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ORIGINAL ARTICLE

An approach for improving the machining efficiency and quality of aerospace curved thin-walled parts during five-axis NC machining

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Abstract

The processing of aerospace thin-walled parts with complex curved surfaces can hardly realize both high precision and high efficiency. It is challenging to choose the optimal processing scheme under the limited technological condition. This study proposes a tool path optimization for five-axis numerical control based on Mastercam numerical control programming software. Numerical control program is introduced to VERICUT software to implement simulation optimization through different cutting parameters. Different tool paths of surface processing are optimized to select the optimal cutting trajectory with the highest processing efficiency and the optimal surface quality. On this basis, with processing productivity as the object function, the processing parameters are optimized through control variable method to determine the optimal cutting force and cutting thickness on the premise of guaranteeing the processing quality (cutting force), so that both processing efficiency and processing quality can be perfected. Through experiments, the machining efficiency is increased by 61.5% after two optimization operations, and the machining quality is improved effectively (the average cutting force of finishing is reduced by 76.6% to the largest extent). This not only meets the requirements of processing precision and maximizes the efficiency of processing but also provides a reference for the further application of key parts in aerospace and some other fields.

Keywords Aerospace thin-walled parts · Tool path optimization · Optimization of cutting parameters · Processing efficiency · Surface quality

1 Introduction

Thin-walled parts with complex curved surfaces are characterized by high strength, light material, and excellent bearing capacity, and have been widely used in various fields, such as aerospace and automobile industry. Since thin-walled parts are weak and likely to be deformed, it is difficult to control the machining accuracy [1]. With the continuous development of numerical control processing technology, the variety of thin-walled parts with curved surfaces has been increased, and the requirement for product performance is further improved. This paper studies thin-walled parts with "X"-curved surface composed of "X" surface parts and rectangular base with non-uniform thin-wall thickness. Such thin-walled parts have a series of characteristics, like complex shape and structure, low stiffness, and small wall thickness. How to improve the machining accuracy and machining efficiency of thin-walled parts with curved surface is still an important research and development direction.

In recent decades, many scholars have studied and explored this issue, and have made a series of progresses in theory. The cutting parameter, as indispensable optimization target in the machining process of parts with curved surface, is the main factor affecting size, shape precision, and surface quality [2–6]. Ribeiro et al. [7], changed the parameters of cutting speed, feed speed, radial depth, and axial depth in milling process, and analyzed the influence of each parameter on the surface quality through Taguchi method. The results show that the interaction between the radial depth and the axial depth has the most significant influence on the surface quality. In terms of processing parameters, Suresh et al. [8] developed a two-order mathematical model through response surface method (RSM) to predict surface roughness, and tried to optimize the target function of the surface roughness

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prediction model through a genetic algorithm, obtaining the minimum and maximum values of surface roughness and the optimal cutting parameters. Combined with two artificial intelligence methods (artificial neural network and genetic algorithm), Kant and Sangwan [9] developed a prediction and optimization model which can replace the conventional method to predict the optimal value of the processing parameters and optimize the surface quality. Cus and Balic [10] put forward the gene expression programming method to predict the influence of cutting speed, feed speed and cutting depth on surface roughness of milling. Tandon et al. [11] proposed an artificial neural network to predict cutting force. In the case of milling, particle swarm optimization algorithm was used to optimize multiple processing parameters simultaneously, so that the quality of the machined surface was substantially improved. Yan et al. [12] put forward a transformation algorithm which could satisfy the error constraint, generate the curvature continuous double NURBS tool paths, smooth the local corner and improve the machining quality. Rao and Pawar [13] studied the application of non-traditional optimization methods in the optimization of multi-feed milling parameters, which greatly improved the surface quality and processing efficiency of the parts. Many scholars have studied the optimization of cutting parameters, and important theoretical progress has been achieved. Although a great number of mathematical models have been established, there are still a lot of inadequacies in the application of actual production. For example, the theory of optimizing the objective function of the mathematical model is not perfect, and the actual needs cannot be satisfied by only considering the optimization of the cutting parameters. Therefore, some scholars began to study the tool path planning.

Tool path planning is always the key technology in the machining process of parts with curved surface, and it is also the main factor affecting the processing efficiency [14, 15]. Hauth et al. [16] and Feng et al. [17] put forward a constant scallop height tool path generation method, which has been widely used in the industrial field. Sun et al. [18] reconstructed the topological relation of the mesh surface, and simplified the intersection point solving process of the section and the triangular mesh surface. Ma et al. [19] proposed an optimization method of tool-path parameters for curved surface by the construction of cutter location mesh units. An adaptive uniform tool path generation method for complex surface with adjustable density was proposed in [20]. Lin et al. [21] put forward a non-retractable tool path generation method, which regarded the tool path planning task as a traveling salesman problem. Malhotra et al. [22] introduced a three-dimensional tool path generation for single point incremental forming. Zhang and Tang [23] presented an optimal tool path generation model for a ball-end tool which strives to globally optimize a tool path with various objectives and constraints. Cao et al. [24] proposed a tool path optimization algorithm for free-form surface NC machining. By calculating and optimizing the step distance and line spacing in the processing path in the feed path through, the problem of tool redundancy and tool missing can be effectively avoided, and the machining efficiency can be improved. Bi et al. [25] developed a new five-axis path smoothing algorithm for the high speed machining of the linear five-axis tool path. The new double Bezier transformation method can smooth the machine tool axis trajectory of both translation path and rotation path. The new path smoothing has obvious advantages in the feed smoothness and processing efficiency in the original linear interpolator. Some scholars have optimized cutting parameters to improve the processing efficiency. Savadamuthu et al. [26] put forward an optimization model based on genetic algorithm to optimize the processing parameters of turning process, which significantly improved the processing efficiency considering the constraints of technology and materials. Kara and Budak [27] simulated and experiment with a model on a multi-task numerical control machine tool to study the influence of material removal rate and cutting force on the machining efficiency and tool wear. Many scholars have made significant progresses in tool path optimization, and established a variety of mathematical models. However, few scholars have optimized both the cutting parameters and the tool path. Obviously, the actual demands cannot be satisfied by simply considering a single optimization method. Moreover, there are some problems in the traditional optimization strategy, such as human experience interference and the long computation time. These factors make it difficult for the existing mathematical models to be used in actual production.

In view of the above deficiencies, this paper studies the machining accuracy and processing efficiency of the five-axis machining of thin-walled parts with complex X-curved surface in the machining process. Based on the simulation analysis through cutting software, an approach was proposed to optimize the cutting paths of different types of tools through Mastercam numerical control programming software. The cutting path with the highest processing efficiency and the optimal surface quality was selected. In addition, the cutting parameters of the optimal tool path were optimized through VERICUT software. The optimization of tool path and cutting parameters was comprehensively considered to make up for the deficiency of a single optimization method in the actual cutting process. Finally, sample experiments were carried out to verify the validity of the proposed method.

2 Methodology

2.1 Experimental procedure

There are many factors to be considered in the cutting process of complex thin-walled parts, such as tool process parameters, path, fixture, and machine tool, which is time-consuming. The accuracy is affected by various complex factors. It should be noted that the experiment in this section is used only to verify the time consumption of cutting, especially the influence of different processes. The final machining accuracy is tested on three coordinates. In this experiment, the process parameters of X-shaped thin-walled part are processed. Software simulation and experimental processing are implemented by setting tool path and cutting parameters according to experience method, and the simulation time and the error of the actual processing time are obtained. The simulation time is programmed through Mastercam software based on the processing technology of the parts, and the NC file is gotten through VERICUT software cutting simulation. The actual processing time is conducted with experiment processing through Mikron five-axis machining center HEM 500U machine tool. Aeronautical thin wall should have the performance of light quality, high strength, and resistance to deformation. The most commonly used material is aluminum alloy 7075, which has been extensively used in various fields because of its high intensity, easy processing, and wear resistance (Table 1).

According to the size of the part, the blank size is 150(mm) × 150(mm) × 40(mm). On the basis of the processing requirements, the groove surface is surface A, and the crest surface is surface B. Surface B is milled by surface as the reference surface. Roughing, semi-finishing, and finish machining should be carried out to meet the requirements of precision. The most commonly used tool path is roughing of surface through the curved surface channel. Radial milling is used in semi-finishing and finish machining. Surface B is processed through parallel milling. Cutting parameters and cutting tools for machining thin-walled parts with curved surface are as shown in Table 2. Moreover, Table 3 lists the process parameters and cutting tools of hole processing.

The three kinds of tools needed in processing the parts are shown in Fig. 1. Combined with the above cutting parameters setting, the surfaces and holes of the parts are experimentally processed. According to the characteristics of the part, it can be divided into surface A and surface B. The thinnest position and its thickness are shown in Fig. 2. The machining process of the thin-walled parts is shown in Fig. 3.

2.2 Process modeling

After the workpiece, tool, and milling path are determined, the production efficiency is mainly affected by cutting parameters such as cutting speed, feed rate, cutting depth, and cutting width. VERICUT optimization module is adopted in this study. The optimization targets include constant removal rate, constant cutting thickness, and constant cutting force. The optimized tool path does not change the original machining path, and it is only a set of optimized parameters based on the given model and setting. The feed speed or cutting speed is recalculated on the premise of guaranteeing the maximum machining efficiency and the cutting speed.

2.2.1 Machine constraints

In the optimization analysis, the optimization variables are limited by spindle speed, feed amount, feed force and power of the machine tool. Therefore, the following constraints need to be met:

1. The spindle speed n satisfies the constraint of the spindle speed of the machine tool.

$$g_1(x) = \frac{n_{\min}\pi d}{1000 \times 60} - x \leq 0 \tag{1}$$

$$g_2(x) = x - \frac{n_{\max}\pi d}{1000 \times 60} \leq 0 \tag{2}$$

where

$n_{\max}$ is the maximum spindle speed of machine tool
$n_{\min}$ is the minimum spindle speed of machine tool

2. Feed amount f satisfies the constraint of machine tool spindle feed.

$$g_3(x) = f_{\min} - x \leq 0 \tag{3}$$

Table 1 Material properties sheet of aluminum alloy 7075

Alloy grade	Chemical composition (%)								Other impurities (%)		
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Single	Sum	Al
7050	≤0.4	≤0.5	1.2–2.0	≤0.3	2.1–2.9	0.18–0.28	5.1–5.6	≤0.2	0.05	0.015	Margin

Table 2 Processing parameters of surface machining

Process	Tool	Feed rate (mm/min)	Cutting speed (r/min)	Reserved value (mm)	Feed value (mm)
Surface A roughing	φ12-mm flat tool	600	5500	2	2
Surface A semi-finishing	φ6-mm ball tool	500	10,000	0.25	0.5
Surface A finishing	φ3-mm ball tool	300	18,000	0	0.25
Surface B roughing	φ12-mm flat tool	700	6000	2	5
Surface B semi-finishing	φ6-mm ball tool	600	18,000	0.25	0.5
Surface B finishing	φ3-mm ball tool	300	24,000	0	0.25

$$g_4(x) = x - f_{\max} \leq 0 \tag{4}$$

where

$f_{\max}$ is the maximum feed amount of machine tool
$f_{\min}$ is the minimum feed amount of machine tool

3. The cutting force satisfies the constraint of the maximum feed force of the cutting.

$$g_5(x) = C_{F_c} a_p^{X_{F_c}} f^{Y_{F_c}} v_c^{Z_{F_c}} K_{F_c} - F_{\max} < 0 \tag{5}$$

where $F_{\max}$ is the maximum cutting feed force.

4. The cutting power P satisfies the constraint of the maximum power of the machine tool.

$$g_6(x) = \frac{F_c v_f}{1000} - \eta P_{\max} \leq 0 \tag{6}$$

where

$P_{\max}$ is the maximum machine tool power
F_c is the cutting force
η is the effective coefficient of machine tool

2.3 Optimization modeling

The traditional optimization algorithms include genetic algorithm, particle swarm optimization, and artificial neural network, which are likely to be disturbed by human experience because of the long computing time. These factors make it difficult to use traditional algorithms in actual production. VERICUT optimization module can avoid the above problems, and it is more convenient. The constant removal rate, constant thickness cutting and constant cutting force optimization models are analyzed as below.

1. Optimization of cutting mode of constant volume removal rate.

When Eq. (7) is satisfied, namely, the constant volume removal rate is greater than the actual removal rate, the feed speed is increased. When Eq. (8) is satisfied, namely, the constant volume removal rate is smaller than the actual removal rate, the feed speed is decreased. In this way, a stable volume removal rate can be maintained. The actual removal rate should be equal to the set constant removal rate so as to guarantee table cutting condition. The optimization model is mainly applied to the huge change of material cutting allowance, especially in the roughing stage. This optimization method can effectively protect numerical control machine tools, and a large amount of cutting can be avoided. Meanwhile, it contributes to increasing the service life of the tool. The mathematical expression is:

$$g_7(x) = Q - Q_b < 0 \tag{7}$$

$$g_8(x) = Q_b - Q < 0 \tag{8}$$

where

Q is the actual removal rate
Q_b is the constant volume removal rate

Table 3 Processing parameters of hole drilling

The type of hole	Tool	Feed rate (mm/min)	Cutting speed (r/min)
φ12.5-mm center hole	φ12.5-mm drill	400	1200
φ7-mm holes	φ7-mm drill	200	5500
φ13-mm holes	φ13-mm drill	300	5500

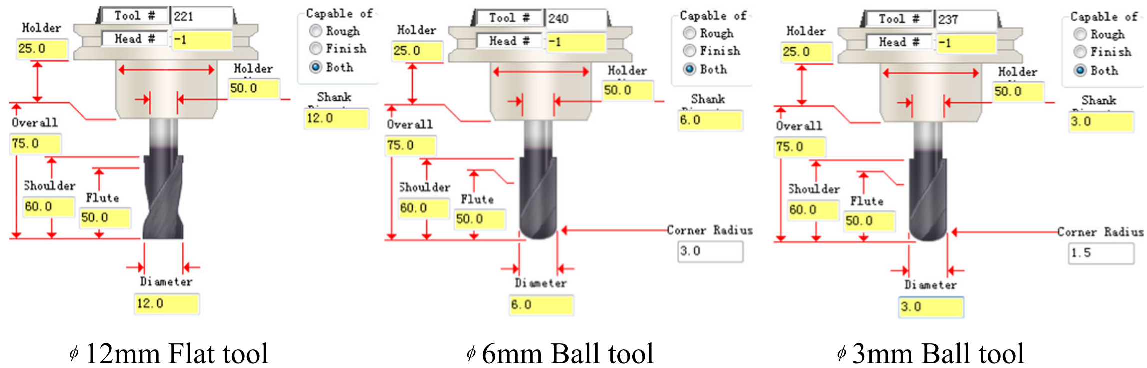

Fig. 1 Setting of tool modeling

2. Optimization of cutting mode with constant thickness.

The cutting model and cutting thickness are optimized and analyzed through VERICUT optimization. When Eq. (9) is satisfied, namely, the actual cutting thickness is greater than the constant cutting thickness, the feed speed is decreased. In the case that Eq. (10) is satisfied, namely, the actual cutting thickness is smaller than the constant cutting thickness, and the feed speed is increased. In cutting process, the constant cutting thickness and stable cutting force are maintained dynamically by changing the feed rate. The mode is mainly suitable for semi-finishing and finish machining, and can improve the processing efficiency and the surface quality of the parts. The mathematical expression is:

$$g_{10}(x) = h_c - h < 0 \tag{9}$$

$$g_{11}(x) = h - h_c < 0 \tag{10}$$

where

h_c is the constant cutting thickness
h is the actual cutting thickness

3. Optimization of cutting mode with constant cutting force.

When Eq. (11) is satisfied, namely, the constant maximum cutting force is greater than the actual cutting force, the feed speed is decreased. Otherwise, the feed speed is increased. In cutting process, the constant cutting thickness is maintained by changing the feed rate. Setting constant cutting force can improve the surface quality of the workpiece, and avoid the damage to parts because of excessive force on the tool. The mode is mainly suitable for semi-finishing and finish machining. The mathematical expression is:

$$g_{12}(x) = F_m - F < 0 \tag{11}$$

$$g_{13}(x) = F - F_m < 0 \tag{12}$$

where

F_m is the constant maximum cutting force
F is the actual cutting force

In order to solve the problem of tool path and cutting parameter optimization in practical production, this paper

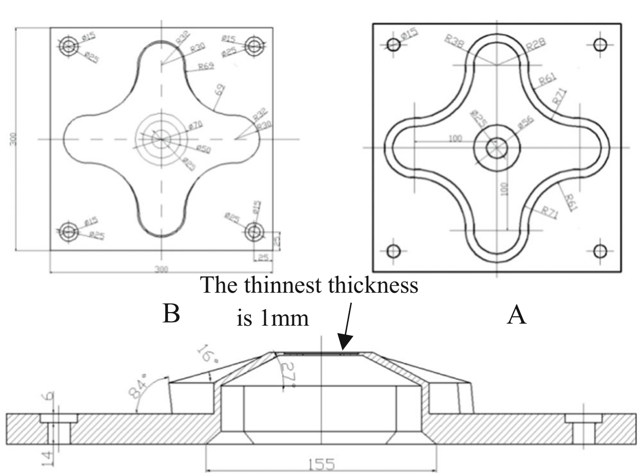

Fig. 2 Thin-walled features

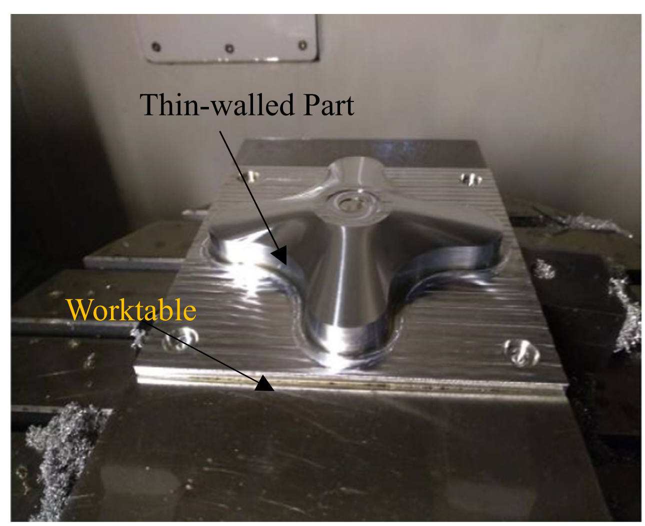

Fig. 3 Machining of thin-walled part

takes "X"-curved thin-walled parts as the research object. Firstly, Mastercam software has different kinds of tool path and powerful curved surface machining function; it can basically meet the requirement of machining any complicated part. Then, the influence of cutting tool paths on machining efficiency and surface quality is explored by VERICUT software. Finally, the cutting parameters are optimized. The effects of cutting depth, cutting width, and cutting thickness on machining efficiency and surface quality are explored. Both Mastercam and VERICUT software can satisfy the simulation processing of any part. Therefore, this method is applicable not only to the "X"-curved thin-walled parts, but also to other complex curved thin-walled parts, which can be applied to the processing of complex thin-walled surface in the field of aerospace. The overall optimization flow chart is as shown in Fig. 4.

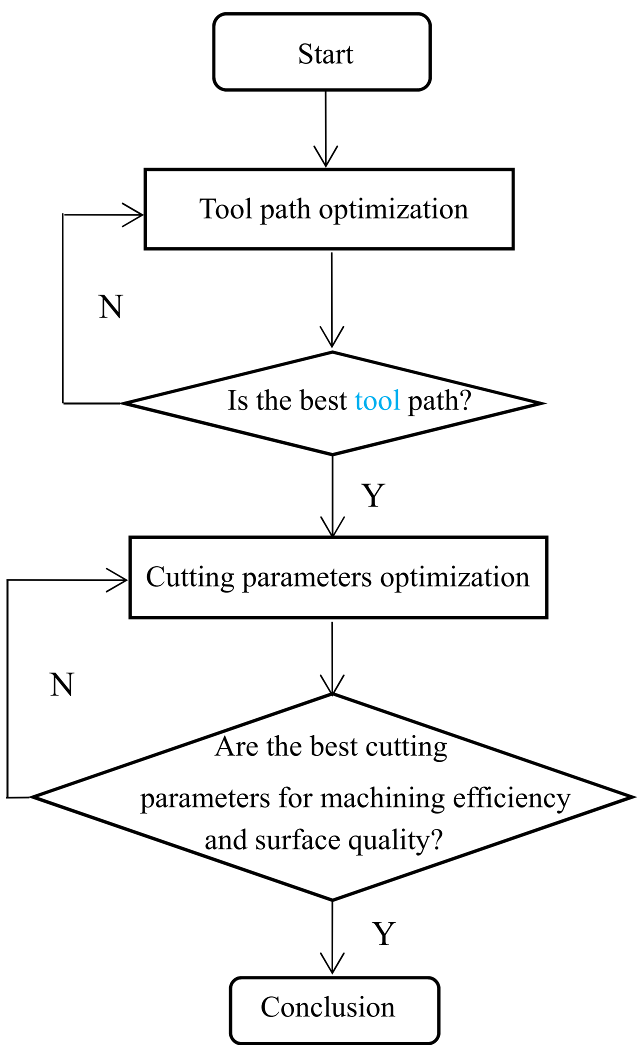

Fig. 4 Optimization process flow chart

2.4 Simulated procedure

The optimization analysis module of this paper includes the analysis of tool path and milling parameters. The tool path in the Mastercam software is used to simulate each tool path. The processing time and cutting force of each path are obtained through VERICUT for further comparison so as to select the tool path with the highest machining efficiency and moderate cutting force. Based on the tool path, the constant cutting thickness and constant cutting force in the VERICUT optimization module are used for analysis. On the premise of guaranteeing the cutting force, the processing time required for each parameter scheme is compared to choose the most efficient cutting scheme.

2.4.1 Simulation of tool path optimization

Tool path is an important determinant of the machining efficiency and surface quality after setting the workpiece, cutting tool, cutting parameters, and machine tools. The common tool path is: milling, radial milling, contour milling, and grooving milling. According to the applicable situation of each tool path and the structural features of surface A surface of the thin-walled parts with curved surface, the tool paths which preliminarily conform to the roughing of surface A include roughing radial milling, roughing parallel milling, roughing contour milling, and roughing grooving milling. The corresponding tool path diagram is as shown in Fig. 5.

Similarly, the features of surface B of the thin-walled parts are analyzed. The grooving milling which is only suitable for processing groove is firstly excluded. Therefore, there are three kinds of roughing suitable for surface B, namely, roughing parallel milling, roughing radial milling and roughing contour milling. The tool path is as shown in Fig. 6.

The tool paths of semi-finishing (semi-F) and finish machining are preliminarily the same. Surface A and surface B are conducted with semi-finishing machining through radial milling and parallel milling. Finish machining parallel milling and finish machining radial milling are carried out for surface A and surface B. The tool path can refer to the roughing tool path scheme.

2.4.2 Setting of process parameter scheme

Numerical control machining primarily aims to ensure the surface quality of the machined parts. The smallest thickness of the thin-walled part with curved surface is only 1 mm, which raises high requirements for cutting force. The excessive cutting force will cause the deformation of parts and even breakage because of residual stress in machining. In order to avoid part deformation in the processing, the constant cutting force is adopted for optimization analysis. According to the requirements of the process, the maximum cutting force of the

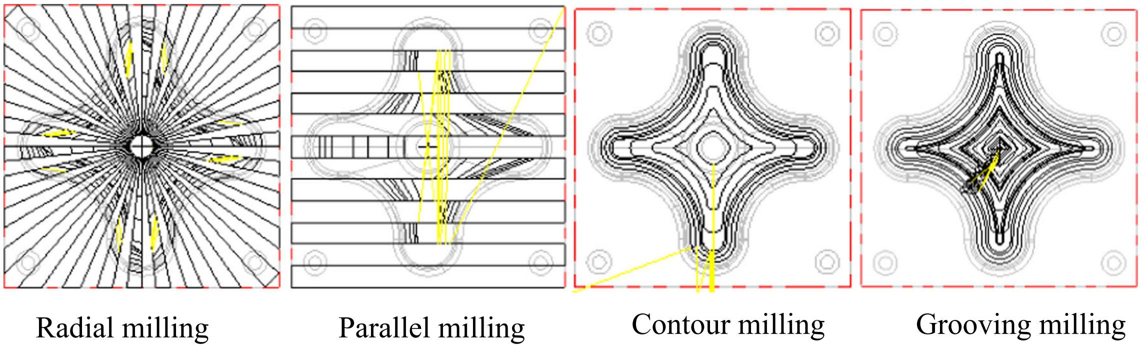

Fig. 5 Surface A roughing tool path

finish machining should not exceed 15 N. The requirements for semi-finishing and roughing are relatively low. In this paper, the cutting force of roughing is not greater than 200 N, and the cutting force of semi-finishing is not greater than 100 N. On the premise of ensuring the surface quality of the parts, the processing efficiency is further optimized through constant cutting thickness in this paper. Several parameter schemes are set for cutting depth, cutting width and cutting thickness, respectively. The specific scheme parameters are as shown in Table 4.

3 Results and discussions

3.1 Comparison between the experimental and simulated results

In order to verify the effectiveness of this method, the process of initial experimental processing is used, and other tool and process parameters can be referred to Section 2. Combined with the simulation analysis, the experiment and the simulation processing time are compared as shown in Table 5.

According to Table 5, compared with the simulation results, the actual errors of surface A and surface B in experiment relative to that of the simulation are $\delta_a = \frac{13}{203} \times 100\% = 6.4\%$ and $\delta_b = \frac{17}{214} \times 100\% = 7.9\%$, respectively. According to experiment results, the simulation results have high matching precision, which proves the effectiveness of the simulation method. Therefore, this method will be further used to analyze the optimization of the machining quality and machining efficiency.

3.2 Influence of tool path on machining time and cutting force

The path optimization model proposes several tool paths suitable for the machining of thin-walled parts. In actual processing, the commonly used tool paths are selected according to the experience, and the optimal path is selected after trial cutting for multiple times. However, this method is time-consuming, laborious and costly, and it fails to get the optimal path. In this case, software simulation is required to analyze the optimal tool path with the shortest cutting time and the minimum cutting force.

The maximum cutting force and machining time in each manufacturing procedure of surface A are shown in Fig. 7. Figure 8 shows the maximum cutting force and machining time in each process and finish machining of surface B.

According to Fig. 7, under the same parameters, the simulation time of processing surface A through four tool paths of radial milling, parallel milling, contour milling, and grooving milling is 61, 18, 25, and 20 min, respectively. The maximum

Fig. 6 Surface B roughing tool path

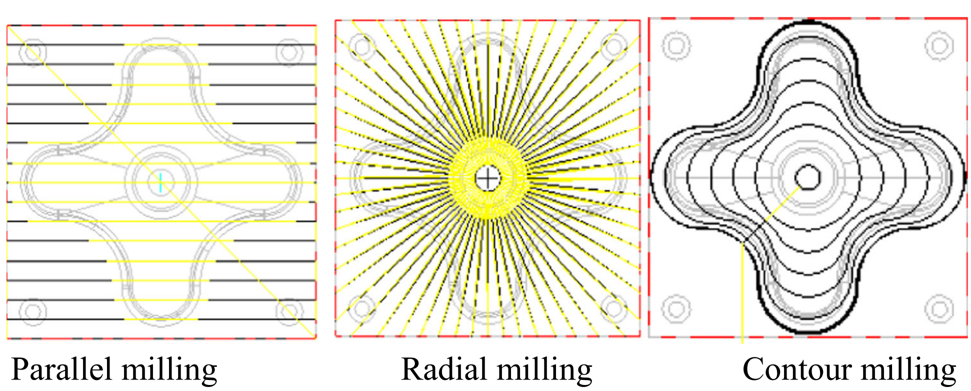

Table 4 Processing parameter scheme

	Roughing				Semi-finishing				Finishing			
Scheme	I	II	III	IV	I	II	III	IV	I	II	III	IV
Cutting depth (mm)	4.0	3.0	2.0	1.0	1.0	0.8	0.6	0.4	0.4	0.3	0.2	0.1
Cutting width (mm)	8.0	7.0	6.0	5.0	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5
Cutting thickness (mm)	0.1	0.09	0.08	0.07	0.05	0.04	0.03	0.02	0.02	0.015	0.01	0.005

Table 5 Comparison of experimental and simulation processing time

	A	B	Total processing
Simulation time (min)	216	231	447
Experimental time (min)	203	214	417

cutting forces are 368, 652, 902, and 274 N. Generally speaking, the tool path with the shortest machining time and smallest cutting force will be selected so as to realize higher processing efficiency. Smaller cutting force can decrease the wear of cutting tool and enhance the quality of the machined surface. In contrast, surface A is machined through roughing machining grooving milling to realize the highest machining efficiency and optimal surface quality. Similarly, semi-finishing and finish machining of surface A adopt parallel milling to obtain the optimal effects. Figure 8 shows that the simulation time of processing surface B through three tool paths of radial milling, parallel milling, and contour milling is 45, 76, and 16 min, respectively. The maximum cutting forces are 326, 30, and 410 N.

The time consumption of radial milling is the longest, while contour milling consumes the shortest time. However, the greatest drawback of contour milling is that it cannot process the flat parts, and the cutting force is too large. Therefore, the best choice is the roughing parallel milling with shorter time and the minimum cutting force. In the same way, semi-finishing radial milling and finish machining parallel milling are most suitable for the semi-finishing and finish machining of surface B.

Based on the above results, it can be concluded that rough machining grooving milling, semi-finishing parallel milling, and finish machining parallel milling are the optimal tool paths for surface A. The optimal tool paths for surface B are roughing parallel milling, semi-finishing radial milling, and finish machining parallel processing. The comparison of cutting force and time consumption before and after the optimization is shown in Fig. 9.

As shown in Fig. 9, the processing time of surface A and surface B through the optimized tool path is 155 and 171 min, and the processing efficiency is increased by 28.2 and 25.9% respectively. In addition to the increase of processing efficiency, the maximum cutting force has been reduced to a certain extent after path optimization. The average cutting force after optimization is slightly larger than that before the optimization because of self-rotation and uneven cutting force in the cutting process. The tool path before optimization is likely to cause serious tool wear, poor surface quality, and low machining efficiency.

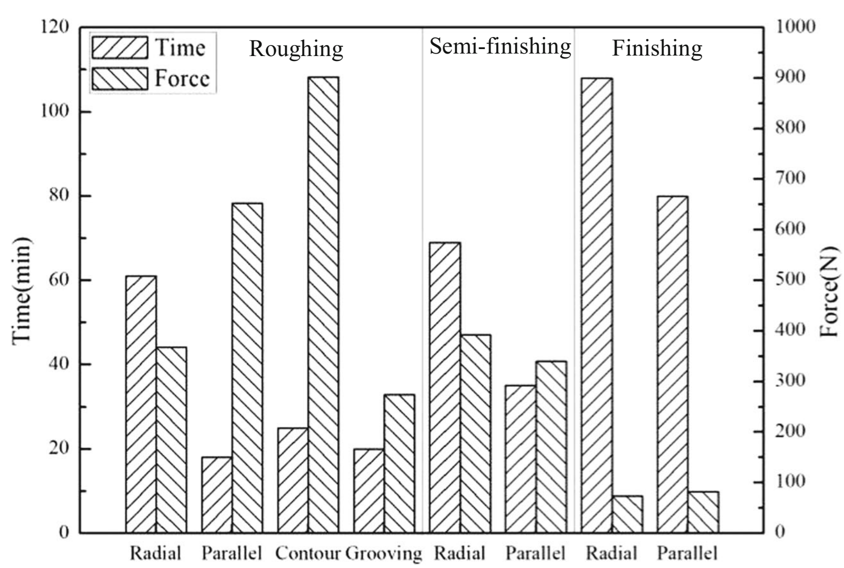

Fig. 7 Surface A machining maximum cutting force and processing time

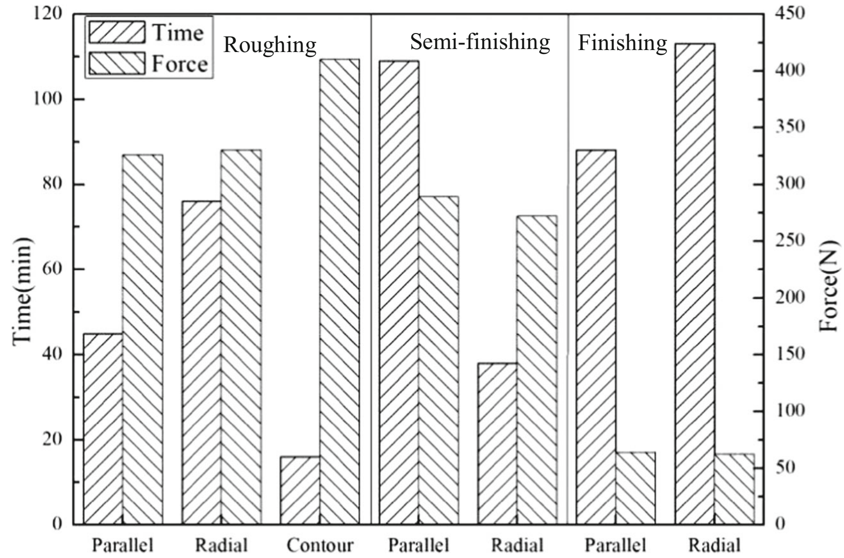

Fig. 8 Surface B machining maximum cutting force and processing time

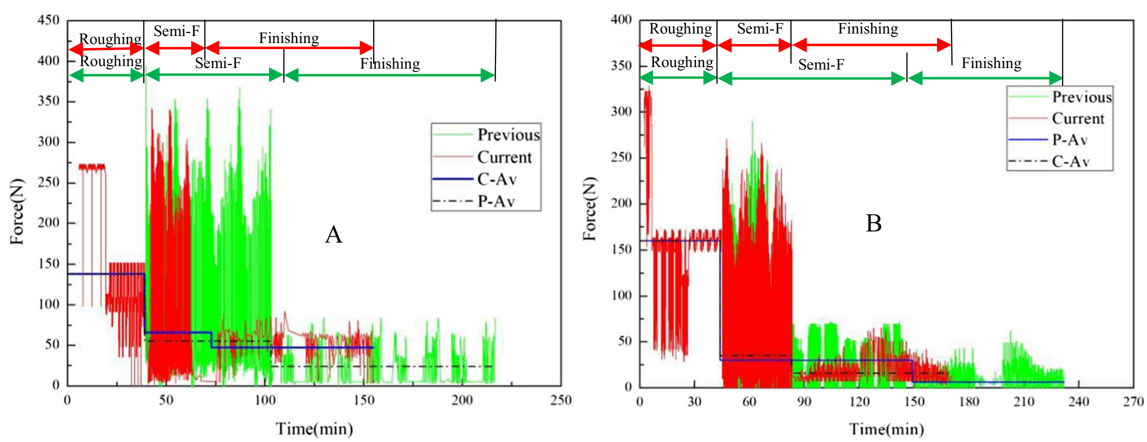

Fig. 9 Surfaces A and B optimization before and after the cutting force and time

3.3 The influence of cutting parameters on machining time

After the milling path and the maximum cutting force are determined, cutting parameter is the main factor that affects the machining efficiency. By simulating each scheme in Table 4, the simulated processing time in each scheme is obtained, as shown in Table 6.

The efficiency of processing surface A is the highest in scheme I, and the efficiency of processing surface B is the highest in scheme III. Time consumption and cutting force before and after optimization are compared as shown in Fig. 10.

After the optimization, the maximum cutting force is obviously reduced and the processing efficiency is greatly improved. The constant cutting force is used as the optimization model; it is mainly suitable for finishing. So the average cutting forces of the roughing and semi-finishing (semi-F) are slightly greater than the average cutting force before the optimization. After the optimization, the average cutting forces of finish machining of surface A and surface B are 11 and 10 N, which are decreased by 36 and

Table 6 Comparison of different schemes simulation processing time

	Scheme I	Scheme II	Scheme III	Scheme IV
Surface A simulation time (min)	61	62	67	80
Surface B simulation time (min)	117	116	109	119

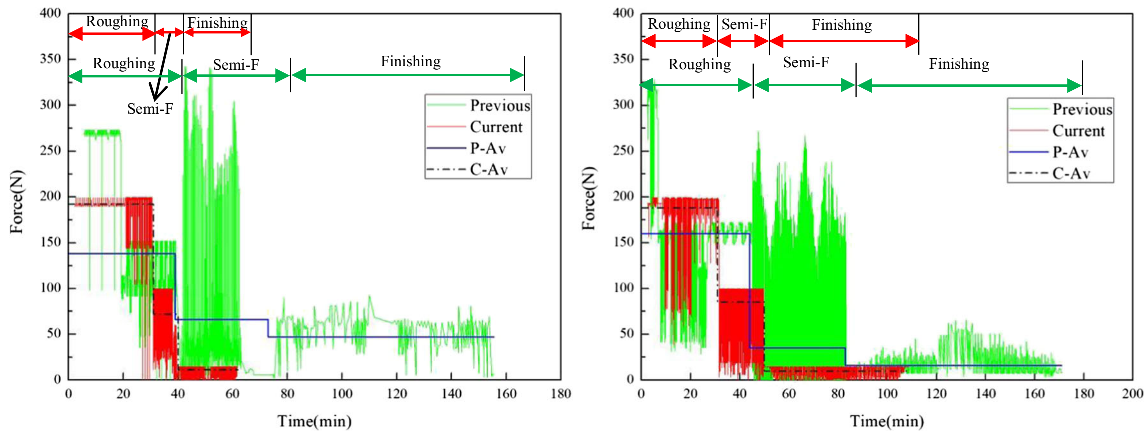

Fig. 10 Surfaces A and B optimization before and after the cutting force and time

6 N compared with those before the optimization. Moreover, the optimized cutting force is more stable, and the wear of the tool is substantially decreased.

3.4 Case experiment verification and result analysis

According to the above results, the optimized milling path should be assigned to the machined surfaces as follows: Grooving milling is conducted in the roughing, and parallel milling in the semi-finishing and finishing for surface A. The parallel milling is conducted in the roughing and finishing, and radial milling in the semi-finishing for surface B. Cutting parameters: surface A selects scheme I; surface B selects scheme III. The machine tool is the same as the above. The related cutting tools and processing parameters are shown in Table 1~Table 3. The comparison between the optimized simulation time and experimental processing time is shown in Table 7.

According to Table 7, the errors of the actual time and the simulation of the A surface and the B surface are $\delta_a = \frac{6}{56} \times 100\% = 8.9\%$ and $\delta_b = \frac{8}{101} \times 100\% = 7.9\%$, respectively. The actual total processing time after the optimization is 157 min. Compared with the actual processing time before the optimization, the processing efficiency is increased by 61.3%.

Finally, the precision of the machined parts is tested. This paper uses the Sheffield three-coordinate measuring machine (CMM) for the fixed point scanning of the thin-walled parts. The distribution of the measurement points is shown in Fig. 11. The machining accuracy of parts is tested, as shown in Fig. 12. After repeated measurements and fixed point measurement, the error value of the "X-shaped" specimen in the five-axis numerical control machine tool is about 0.023 mm. Therefore, the numerical control machine tool has a high machining precision, and it can process high precision parts. The requirement for precision (0.05 mm) in design drawing is fully satisfied. In this paper, the influence of tool path and cutting parameters on machining efficiency and cutting force of thin-walled parts in machining process is analyzed synthetically by using Mastercam and VERICUT software. By comparing the simulation analysis and experimental data, the optimal tool path and cutting parameters are obtained respectively, so that the machining efficiency is greatly improved. Meanwhile, optimization of cutting force by using VERICUT software, not only the cutting force is obviously reduced but also the cutting force becomes more stable, which ensures the machining accuracy of thin-walled parts. Finally, the experimental results show that this method is effective and feasible.

Table 7 Comparison of optimized simulation and experimental processing time

	A	B	Total processing
Simulation time (min)	61	109	171
Experiment time (min)	56	101	157

4 Conclusion

There are a great number of factors affecting the quality and efficiency of machining aerospace thin-walled parts, particularly the tool path and process parameters. Researchers have carried out a great number of theoretical and experimental studies in order to realize the comprehensive control of product quality and efficiency. Effective methods have been put forward. This paper proposed a comprehensive analysis method for five-axis machining thin-walled parts with curved surface, the following conclusions are summarized.

(1) Mastercam software was used to simulate and analyze the tool paths, and explore the influence of tool path on machining time and surface quality. By analyzing the case results, the total processing efficiency was increased by 27.1% compared with that before the optimization.

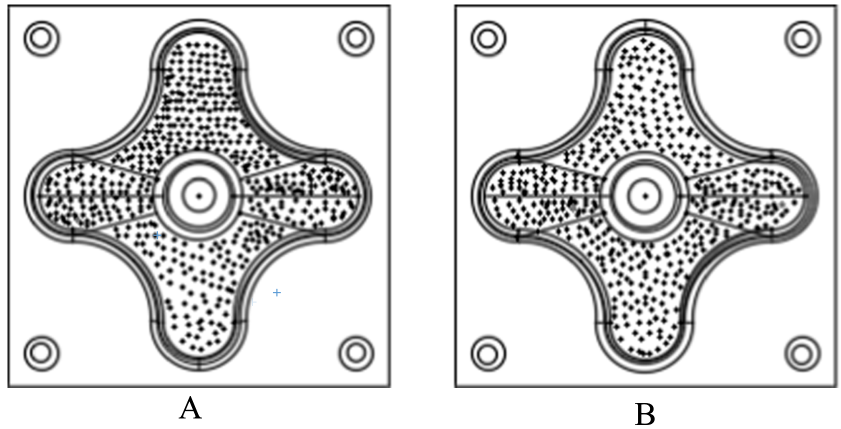

Fig. 11 Measurement points distribution

(2) This paper uses the optimization module of constant cutting force in VERICUT software to control the cutting force. After repeated simulation and analysis of the results, using the NC program optimized by constant cutting force, not only the cutting force becomes smaller, the machining efficiency is also greatly improved, but also the cutting force is more uniform, which can reduce the wear to the tool. It can improve the service life of tools.

(3) In addition to cutting path and cutting force factors, cutting parameters are also very important factors affecting the machining efficiency and precision of thin-walled parts. In this paper, VERICUT software is used to optimize cutting depth, cutting width and cutting thickness. Through simulation and result analysis, the total processing efficiency is increased by 34.2%, which further verified the experiment results. The accuracy of the X-shaped thin-walled parts processing through this optimization method is in line with the production requirements.

(4) A comprehensive analysis method for five-axis machining of curved thin-walled parts is universal, which is applicable not only to the "X"-shape specimen, but also to other complex curved thin-walled parts, which can be applied to the processing of complex thin-walled surface in the field of aerospace.

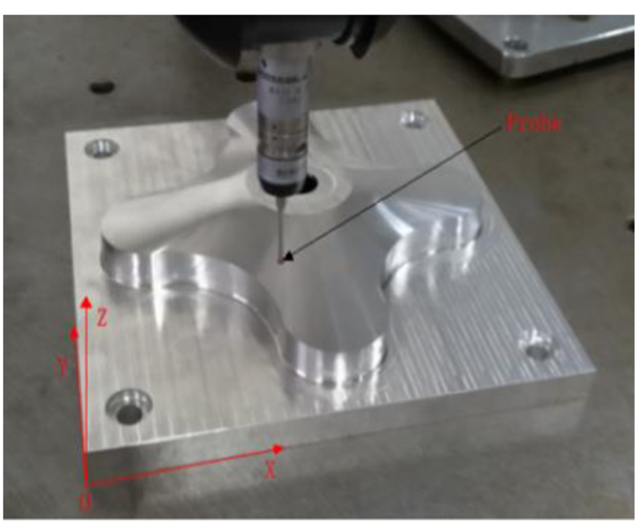

Fig. 12 Precision measurement by CMM

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