Int J Adv Manuf Technol (2017) 90:3119–3128
DOI 10.1007/s00170-016-9647-4

ORIGINAL ARTICLE

An adaptive machining approach based on in-process inspection of interim machining states for large-scaled and thin-walled complex parts

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Received: 25 July 2016 / Accepted: 17 October 2016 / Published online: 29 October 2016

Abstract During the machining process of large-scaled and thin-walled parts such as aircraft structural parts, the deformation is a relatively common phenomenon which seriously affects the machining quality of the parts and may lead the parts to be scrapped. In this paper, interim machining states of workpiece are considered in addition to final machining states for deformation control so as to improve the machining quality and part correct rate. It is very important for large-scaled and thin-walled parts to consider the interim machining states, as considerable deformation has always occurred in interim machining states. The difficulties of deformation control of interim machining states contain two aspects: (1) how to assess whether interim machining states can satisfy process requirements for further machining and (2) how to adjust the tool paths adaptively for further machining so as to make the final machining states correct. In order to address the above difficulties, an adaptive machining approach based on in-process inspection of interim machining states for large-scaled and thin-walled complex aircraft structural parts is proposed in this paper. The actual interim machining state is obtained based on in-process inspection of machining states during the machining process; the essential idea of this paper is that the final machining state of the workpiece can be guaranteed by adjusting the tool path based on the inspection of interim machining states, which is realized by coordinating the dimensional tolerance and geometrical tolerance. In order to realize the new idea, the criterion for determining whether the interim machining state is suitable or not for further machining and the concept of expected final state are introduced. Eventually, the large-scaled and thin-walled complex aircraft structural parts can be machined adaptively according to process requirements. A typical large-scaled and thin-walled complex aircraft structural part is used as a case to validate the proposed approach. The results show that the dimensional error is 0.10 mm and the profile error is 0.06 mm, which can meet the machining requirement of large-scaled and thin-walled complex parts.

Keywords Adaptive machining · In-process inspection · Interim machining state · Aircraft structural part

1 Introduction

Large-scaled and thin-walled structural parts are widely adopted by aircraft products so as to improve aircraft performance, while the machining tolerance of the parts is quite tight. Take a typical large holistic structural part for example, the dimension is 4200 × 2600 × 120 mm, the thickness of the thinnest wall is 1.5 mm, the dimensional tolerance is ±0.15 mm, the shape tolerance is 0.2 mm, and the position tolerance is 0.1 mm. Due to the coupling effect of the residual stress of materials, thermal stress, and cutting stress, significant deformation happens after the unloading of fixtures [1], and the maximal deformation of the exampled large-scaled aircraft structural parts can be more than 3 mm; it can lead to undercut or overcut for the part during the subsequent machining process, which has imposed significant challenges to the machining process. Large-scaled holistic structural parts may deform more seriously if they are machined under the clamping state in the whole machining process. In actual manufacturing practice, the parts are always unloaded by

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fixtures during machining process so as to release stresses, and then the machining will be continued.

In order to control machining deformation, the adjustment of tool path during interim machining process is deemed as an effective way. While the difficulty is how to plan the subsequent tool path so as to satisfy both the requirement of machining tolerance and machining process. In order to address the challenging issue, an adaptive machining approach based on in-process inspection of interim machining states for large-scaled and thin-walled complex aircraft structural parts is proposed in this paper.

The actual interim machining state is obtained based on in-process inspection of machining states during the machining process, and the essential idea of this paper is that the final machining state of the workpiece can be guaranteed by adjusting the tool path based on the inspection of interim machining states, which is realized by coordinating the dimensional tolerance and form tolerance. In order to realize the new idea, the criterion for assessing whether the interim machining state is suitable or not for further machining and the concept of expected final machining state are introduced. Eventually, the large-scaled and thin-walled complex aircraft structural parts can be machined adaptively according to process requirements.

2 Literature review

As machining deformation is quite common in machining process, and it has a great effect on part quality, intensive research work has been performed in both the academia and in the industry. The related work can be classified into three categories:

1. Deformation control by off-line prediction. Machining process can be simulated by finite element software tools; thus, the machining deformation of large-scaled and thin-walled complex aircraft structural parts can be predicted so as to control deformation during machining process. Guo et al. [2] proposed a method to predict the milling distortion of aero-multi-frame parts, where the finite element model for milling distortion analysis is established and the prediction analysis of the milling distortion under different milling conditions is carried out. He et al. [3] developed a quantitative analysis method by using finite element modeling to calculate the deformation during machining process of a typical thin-walled structural part. The influence of the residual stress on the part deformation has also been researched by some scholars, where the deformation of the part can be predicted by residual stress analysis. Arrazola et al. [4] presented a prediction method of machining induced residual stresses with finite element-based simulations for nickel-based alloy material. Quach et al. [5] proposed a finite element-based method to predict residual stresses in press-braked thin-walled sections. Yang et al. [1] developed a finite element model to predict machining distortion by considering the effect of initial residual stress for aluminum alloy aircraft monolithic component. Masoudi et al. [6] investigated the correlation between machining-induced residual stresses and distortion in thin-walled workpieces. Wei et al. [7] established a finite element model of original residual stress and proposed a corresponding mend method to control the deflection caused by original residual stress during the actual machining process. Ma et al. [8] presented a finite element analysis approach to predict machining-induced residual stresses and consequent distortion. Zhou et al. [9] developed a finite element method to predict and analyze machining-induced deformation through cutting process modeling, material removal modeling, and the calculation of initial residual stresses in machining process. Due to the impact of unexpected factors, accurate off-line prediction is still a challenge [10], so deformation control based on off-line prediction can only be used as a reference.
2. Deformation control by special machining strategies. The optimization of machining strategies such as machining sequences, tool path, and clamping can be used to control machining deformation. Zhang et al. [11] presented a methodology of minimizing machining distortion based on an accurate cross-sectional residual stress determination, where distortion can be minimized by optimizing the partition of material removal to ensure a symmetrical distribution of residual stress in the part so that the residual stress-induced bending moment could reach self-equilibrium. Ding et al. [12] took a titanium alloy thin-walled web as research object and analyzed the factors of milling deformation. Based on the analysis, the milling process of the titanium alloy thin-walled structure was optimized, including the decrease of cutting force and the increase of processing system rigidity. Gao et al. [13] proposed a deformation control strategy by planning a tool path and an efficient compensation method based on modifying cutter location point. A proper cutting parameter combination which influences the machining deformation directly is obtained based on the established cutting force model. In order to control machining deformation, Li et al. [14] analyzed machining deformation of integral parts with thin walls, where milling process and tool path are optimized. Li et al. [15] established a finite element model to simulate the clamping operation, where the effect of locating positions, clamping sequence, and clamping force on the distortion of thin-walled frame parts is revealed. The deformation can be reduced to some extent by using the special machining strategies, but this method is still limited due to the lack of the exact relationship between machining strategies and deformation.

3. Deformation control by online inspection. Machining error can also be obtained by online inspection, and it can be compensated by tool path adjustment so as to improve machining accuracy [16]. A mirror approach is widely adopted for error compensation based on online inspection [17]. The machining error vector is calculated based on inspection results during machining process, and the tool paths of next machining step are offset in the reverse direction of the error vector. Guiassa et al. [18] proposed an error compensation method where the effect of both changes in final depth of cut and the reduction in part compliance based on online inspection during machining process are considered to compensate the final cut more effectively. Another machining error compensation method is reconstructing machined surface based on the online inspection data, and then new tool paths are generated according to the new surface. Huang et al. [19] proposed an iteration tool path compensation algorithm to compensate the machining error caused by part and cutter deflection by comparing the deviation between the machined surface and the envelope surface, where the machined surface was reconstructed based on an on-machine measurement inspection system. Sortino et al. [20] proposed a workpiece and tool deformation compensation approach based on adaptation of the geometrical 3D CAD model, where the workpiece is measured using an optical method, and then the displacements between the ideal workpiece model and the measured point cloud are calculated. To maintain dimensional accuracy, Kim [21] conducted an investigation on cutting conditions to minimize machining deformation and an analysis on characteristics of cutting signals when machining deformation occurs. Cutting signals for the process are acquired by using an accelerometer and acoustic emission (AE) sensor.

Deformation control by online inspection is an effective way; however, it still has some research gaps for the deformation control of large-scaled parts with thin walls. The deformation is always induced by unexpected factors, so the deformation cannot be compensated directly according to the measured machining error. Although the inspection of interim machining state is an effective way to control deformation, the difficulties of deformation control based on the inspection of interim machining states contain two aspects: (1) how to assess whether interim machining states can satisfy process requirements and dimensional tolerance and form tolerance after further machining and (2) how to adjust the tool paths adaptively for further machining of interim machining states so as to make the final machining states correct. This paper will try to address the above issues.

3 Basic concepts and approach overview

The related basic concepts of this paper are stated in this section so as to help to understand this paper, and the overview of the proposed approach in this paper is also introduced in this section.

3.1 Basic concepts

Interim machining state The interim machining state is defined as one of the machining states of a workpiece from rough machining to finish machining. It includes in-process geometry and machining information of the workpiece. In this paper, the interim machining states mainly refer to the state after rough machining.

Expected final state The expected final state refers to the final state which is predicted by further machining according to the original tool path or the adjusted tool path on the basis of the actual interim machining state.

Process requirements Process requirements refer to cutting constraints of the machining allowance and cutting width or cutting depth of each cutting pass.

Machining error The machining error refers to the deviation between the actual geometric parameters and the corresponding ideal geometric parameters, which includes geometrical dimension error, geometrical shape error, geometrical position error, and so on.

Dimensional error The dimensional error is used to evaluate the deviation between actual sizes and ideal sizes, which is constrained by dimensional tolerance. The dimensional tolerance is defined as an absolute value of the difference between the maximum limit size and the minimum limit size or the difference between the upper tolerance and the lower tolerance.

Shape error The shape error refers to geometric shape error caused by point, line, face, and other geometric elements. In this paper, the least squares plane of an actual inspected surface is deemed as the base level, and the minimum distance between the two tolerant planes which parallel to the least squares plane is deemed as flatness error. The surface profile is used to describe the shape tolerance, which is the area between two symmetrical distribution surfaces. Surface profile error without benchmarks is introduced at length in the following sections.

Position error The position error is defined as the deviation between the actual element and the ideal position which is determined by the benchmark and the theoretical dimension. Position error is constrained by position tolerance.

3.2 Overview of the proposed approach

In this paper, a machining deformation control method is proposed to control the deformation of large-scaled and thin-walled complex aircraft structural parts, as shown in Fig. 1. The essential idea of the proposed method can be described in three steps: (1) assess the interim machining state whether the dimensional error could satisfy the tolerance requirements and whether the machining allowance could satisfy the process requirements. The assessment is made based on in-process inspection results of the actual interim machining state, and the assessment can be used to determine whether the interim machining state is eligible; (2) shape error and position error are calculated on the premise that the dimension error and machining allowance could satisfy the machining requirements; otherwise, the expected final state should be adjusted; (3) If correct final state can be obtained by adjusting the expected final state, the expected final state after adjustment is regarded as the drive geometry for further tool path adjustment. If the expected final state could not be obtained, the interim machining state is not eligible or some special process strategies are required for further machining.

4 Adaptive tool path adjustment method against machining deformation

Machining deformation of large-scaled and thin-walled complex aircraft structural parts is caused by many factors such as cutting forces, residual stress, and uneven properties of

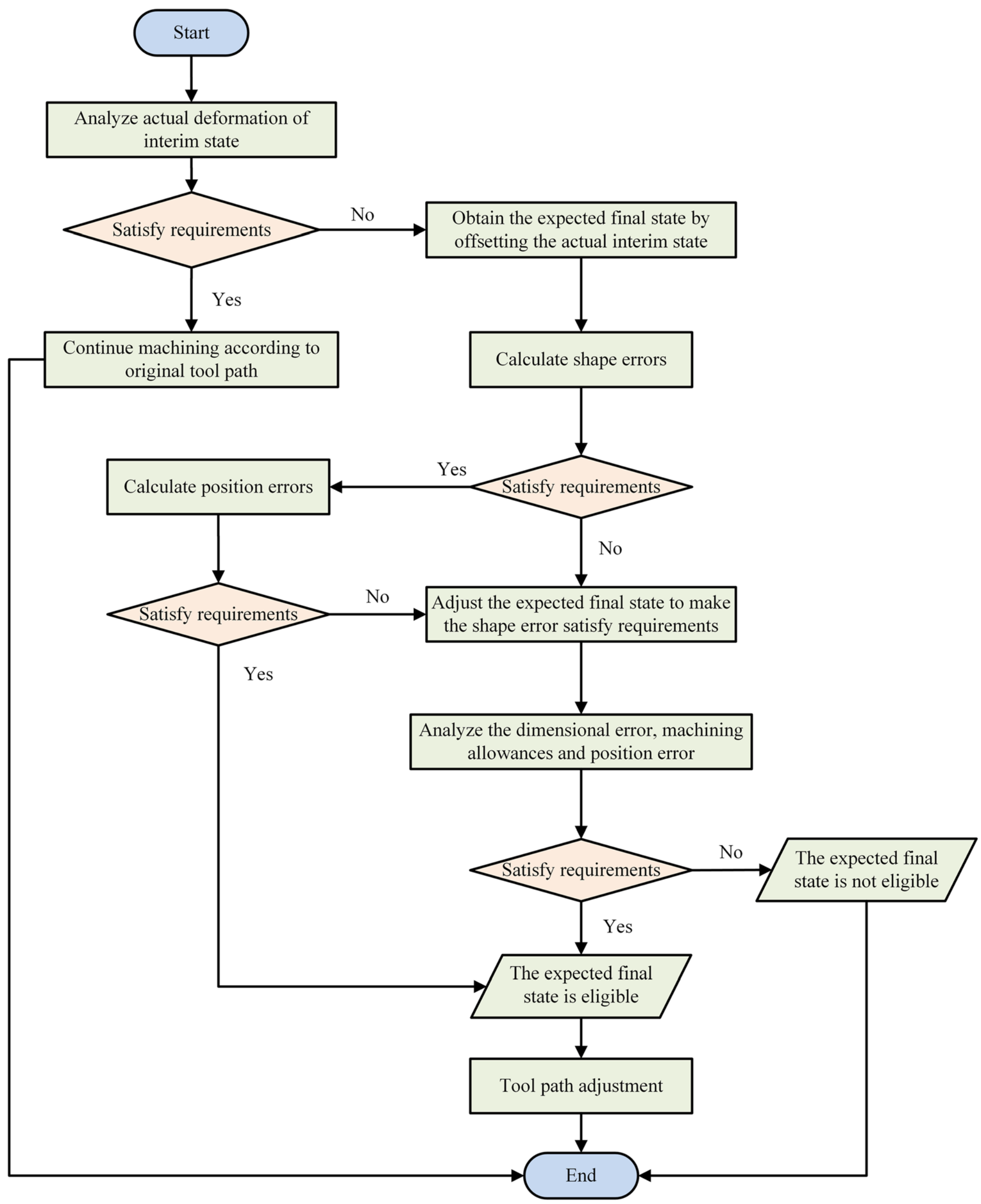

Fig. 1 The workflow of the proposed adaptive tool path adjustment

material. Machining deformation of interim machining states may cause machining errors such as dimensional error, shape error, and position error, which can lead to undercut or overcut and may result in defective parts by further machining, as shown in Fig. 2. It is important to assess whether the interim machining state is eligible or not based on in-process inspection before further machining of the deformed interim machining state. In case that the machining error has been out of machining tolerance, further machining will increase production cost if the interim machining state cannot be assessed correctly.

Tool path adjustment is an effective way to ensure final machining quality if the deformation of a part is in a certain range. An approach of interim machining state error analysis is proposed in this paper, the criterion of whether the further cutting tool path should be adjusted is established by considering the requirements of dimensional tolerance, geometric tolerance, and machining allowance. Drive geometry is constructed for cutting tool path adjustment based on the analysis of interim machining state.

4.1 Machining error analysis of interim machining state

The machining errors of interim machining states can be obtained based on in-process inspection. Machining tolerance is the permissible deviation of actual parameter values with nominal parameter values, which is the criterion for whether the machining errors are acceptable. In numerical control (NC) machining process, every final state of one machining feature has its corresponding tolerance requirements. However, there is no specific definition for interim machining states, which makes it difficult to assess whether the machining errors are acceptable for interim machining states. Because of the complexity of the NC process of thin-walled aircraft structural parts, machining errors are influenced by many factors; the tolerance requirements of interim machining states cannot simply be determined by the tolerance requirements of final machining states. The interactions among the machining errors further increase the assessment difficulty of interim machining states. It is a challenging problem how to establish the criterion to assess whether an interim machining state is eligible.

Machining error calculation is the precondition of interim machining state assessment, the calculation methods of machining errors are analyzed in the following sections.

Thickness is one of the most important dimensions for thin-walled structural parts. There are two thickness measurement methods for interim machining states, one is by ultrasonic thickness sensor and the other one is by calculating the distance between the two sides of the machining feature, and each side is fitted by measurement points. In this paper, the second method is selected for side surfaces. In regarding of bottom sides, the ultrasonic is more feasible, as the inspection of the reverse side is not easy.

The calculation of surface profile is relatively complex, as the actual position and theoretical positions of machining feature are changed due to deformation, which causes the base level and the theoretical plane to be inconsistent. Therefore, the surface profile cannot be calculated according to the actual state and the theoretical surface. The calculation of profile error is composed of two portions: (1) the coordinate transformation matrix is used to transform the actual surface (AS) to a best position and orientation based on minimum zone method; (2) the maximum value of the minimum distances between inspection points and the ideal surface (IS) needs to be calculated, which is the surface profile error. Minimum zone method is the ISO standard to evaluate the profile error of complex surfaces. As shown in Fig. 3, t refers to the profile tolerance.

Let $u=(\Delta x, \Delta y, \Delta z, \alpha, \beta, \theta)$ be a variable of coordinate transformation, u is used to construct a coordinate transformation matrix, the new coordinates of inspection points are obtained by coordinate transformation. The variable of coordinate transformation is expressed with u^* while the workpiece is in the best position and orientation. The minimum distance between the new inspection points and the theoretical surface is expressed with d_j (u^*) when the workpiece is in the best position and orientation. The surface profile error is represented as follows:

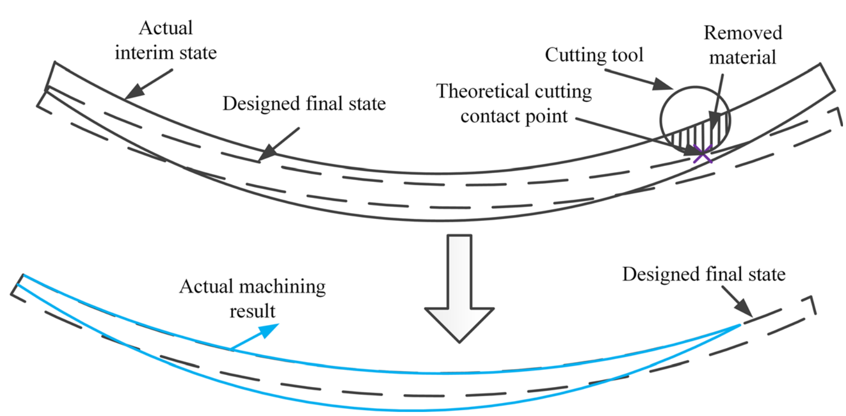

Fig. 2 Overcut due to deformation of interim machining state

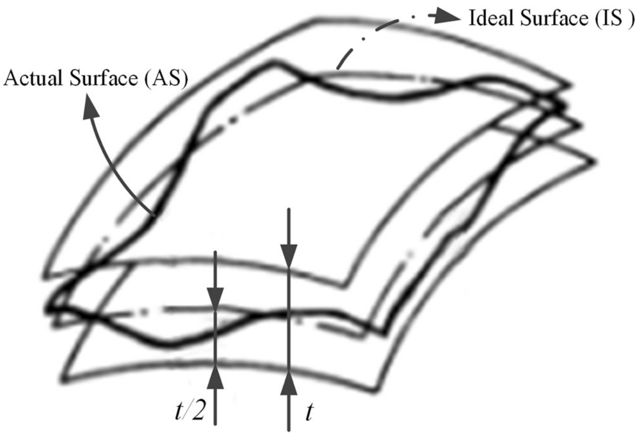

Fig. 3 The schematic diagram of surface profile

$$e = \max_{j=1}^{m} \left(2d_j(u^*)\right). \tag{1}$$

The variable u^* is deemed as the position error when the workpiece is in the best position and orientation during the calculation of shape error.

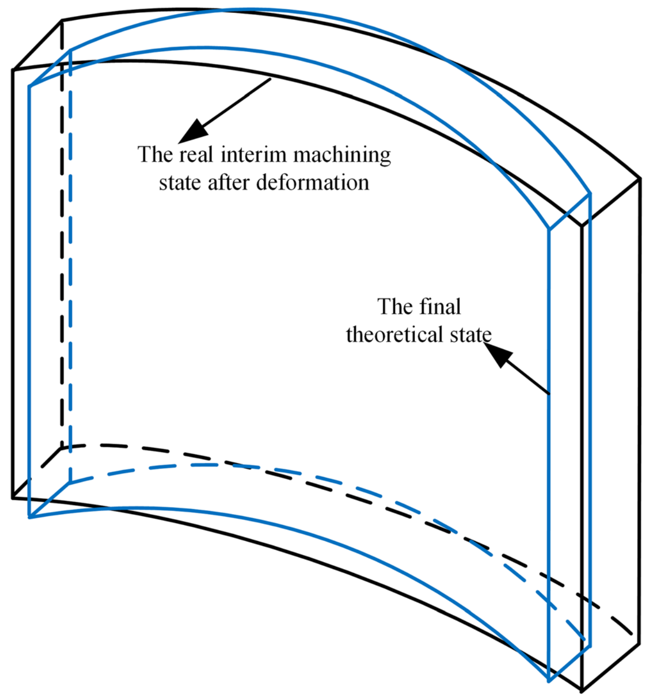

Fig. 4 The deformation of interim machining state

4.2 Criterion of eligible interim machining state

In order to avoid severe deformation caused by stress release after machining process, the fixtures of workpieces need to be unloaded after rough machining, and then workpieces will be fixed again on the workbench. The final machining quality is assessed by the criterion whether the deformed interim machining state is eligible. Figure 4 shows the interim machining state with deformation.

The essential of the assessment of the interim machining state is whether the machining allowance of the interim machining state can envelope the final machining state with tolerance requirements. Not only the tolerances but also the machining allowances of interim machining states need to satisfy process requirements in order to ensure the workpieces' eligibility. In other words, the thickness of the machining feature should be sufficient enough to guarantee that the further machining process is stable, and the thickness value can be provided according to machining experience of different machining features.

According to the conditions mentioned above, the relationship between the actual interim machining state and the theoretical final machining state should be analyzed to assess the interim machining state. The detailed steps are described as follows: (1) calculate the distance between each inspection point of the actual interim machining state and the final machining state. If the inspection point is in the exterior normal direction of the surface of the theoretical final machining state, the orientation distance is set with positive distance (+); otherwise, the orientation distance is set with negative distance (−). (2) if the orientation distance is negative, it shows that the interim machining state cannot envelope the final machining state completely. (3) if the orientation distance is positive, assess whether the distance can satisfy the process requirements for further machining. If not, special machining strategies should be adopted, such as reducing the cutting width or cutting depth. The assessment of the interim machining state is connected with both sides of each feature. For the workpiece with deformation, the surface machining allowance may increase in the direction which is consistent with the deformation direction, while the machining allowance of the other side may decrease.

The ideal solution for the workpieces which have deformed, and the machining allowances that cannot envelope the final machining state, is to adjust the tool path by considering the requirements of geometric tolerance and dimension tolerance. If the adjustment is not feasible, one way is to offset the tool path with the constraints of dimension tolerance requirements and then correct the shape of the workpiece after finish machining. Another way is to press the workpiece to change its shape until it can be machined according to the tolerance requirements and then correct the shape of the workpiece after finish machining. However, the workpieces may deform much more seriously after finish machining if they are clamped with much stress in finish machining, so this approach is not recommended.

4.3 Adaptive tool path adjustment method based on machining features

The idea of tool path adaptive adjustment method for interim machining state for further machining is creating drive geometries based on the inspection points of the interim machining state, and then the new tool path can be generated according to the drive geometries. As it is very difficult to analyze the whole part, the tool path adjustment is analyzed based on machining features which are local shapes with certain machining process.

In order to solve these problems, this paper introduces the concept of expected final state which has been stated in Sect. 3. Firstly, dimensional errors are analyzed to assess whether they can satisfy the tolerance requirements and whether the machining allowances could satisfy the process requirements based on the inspection results of the actual interim machining state, and then the shape errors and the position errors are calculated on the premise that the dimensional error and the machining allowance could satisfy the requirements. If the shape error and the position error cannot satisfy the requirements, the expected final state should be adjusted based on the inspection points of interim machining state. If the expected final state, which can satisfy all the geometric tolerance requirements, can be obtained after adjustment, it can be deemed as the drive geometry for tool path adjustment. If the expected final state cannot be obtained, the interim machining state is not eligible or special machining strategies should be adopted.

As shown in Fig. 5, t_a represents the thickness of the actual interim machining state, t_f represents the thickness of the theoretical final state, S_f represents the surface of the theoretical final state, and S_m represents the surface of the actual interim machining state. The inspection points of the interim machining state are set with $IP = (ip_1, ip_2, \ldots, ip_m)$.

As shown in Fig. 6, *offs* represents the minimum distance between the inspection points of the actual interim machining state (ip_i^a) and the theoretical final state (*tfa*), as represented as follows:

$$\text{offs} = \min\left(\text{dis}\left(ip_i^a, tfa\right)\right), (i = 1, 2 \ldots m). \quad (2)$$

The thickness and machining allowance of the interim machining state can be analyzed based on the inspection points of interim machining state. If they cannot satisfy the requirements, the tool path should be adjusted.

While S_o represents the expected final state after tool path adjustment, $IPo = \left(ip_1^o, ip_2^o, \ldots ip_m^o\right)$ represents the points of the expected final state corresponding to the inspection points of interim machining state.

Shape error can be calculated according to the shape error calculation method after tool path adjustment, which the interim machining state in the best position is expressed by S_o'. If the shape error does not satisfy the requirements, pick up all the points out of the shape tolerance from the state S_o, and offset them in the direction of approaching the theoretical final state. The offset value is the minimum value which can meet the requirements of shape error (S_t).

Let ip_k^o be the points out of the shape tolerance from the state S_o; TI_k represents the surface exterior normal direction of state S_o at the point ip_k^o.

The distance between point ip_k^o and the theoretical final state is represented as d_k; the offset value of point ip_k^o is represented as$off s_k^o$:

$$off s_k^o = d_k - S_t \big/ 2. \quad (3)$$

The point after offset is represented as follows:

$$ip_k^{oo} = ip_k^o \pm off s_k^o \times TI_k \quad (4)$$

where ip_k^{oo} represents the point offset by point ip_k^o, the symbol "±" is determined by the position of the points relative to the theoretical final state; if ip_k^o is inside the theoretical final state, it is denoted with "+"; otherwise, it is denoted with "−"

The points which could not satisfy the shape error requirements should be offset to create a new state S_{oo}; the shape error and the machining allowance of points after offset can be calculated. The thickness of points after offset is represented as follows:

$$t_k = t_{ak} - off s_k \pm off s_k^o \quad (5)$$

where t_k represents the thickness of points after offset and the symbol "±" is determined by the offset direction of each point. If the point ip_k^o is offset along the inside direction of the part, it is denoted with "−"; otherwise, it is denoted with "+".

The machining allowance of points after offset can be represented as follows:

$$a_k = off s_k \pm off s_k^o \quad (6)$$

where a_k represents the machining allowance of points after offset and the symbol "±" is determined by the offset direction

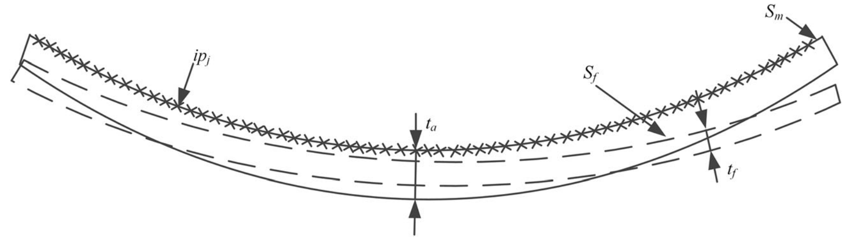

Fig. 5 In-process inspection of interim machining state

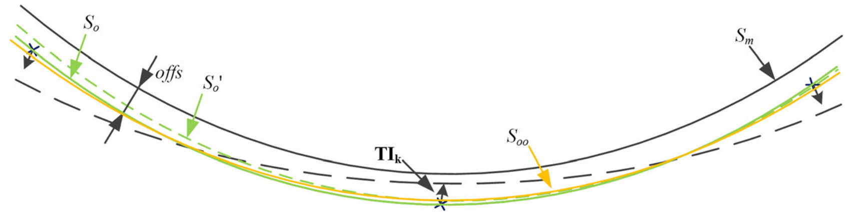

Fig. 6 The expected final machining state after adjustment

of each point. If the point ip_k^o is offset along the inside direction of parts, it is denoted with "+" or it is denoted with "−".

If the dimensional error could satisfy the tolerance requirements and the machining allowance satisfy the process requirements, then the position error after offset is calculated. If the position error could also satisfy the tolerance requirements, the expected final state satisfies the requirements. If the position error does not satisfy the tolerance requirements, the position should be adjusted based on the minimum adjustment principle which makes the position error satisfies the requirements. The position tolerance P_t is represented as follows:

$$P_t = (x', y', z', \alpha', \beta', \theta'). \tag{7}$$

The position error u which can be calculated with the minimum zone method is represented as follows:

$$u = (x^*, y^*, z^*, \alpha^*, \beta^*, \theta^*). \tag{8}$$

The amount of adjustment Δu is calculated as follows:

$$\Delta u = u - P_t. \tag{9}$$

The geometrical transformation matrix TM is constructed by Δu with the method presented above; the new state S_{oo}' is obtained by a coordinate transformation for the state S_{oo}, as represented in Fig. 7.

$$S_{oo}' = S_{oo} \times TM \tag{10}$$

Only the dimensional error and the machining allowance should be calculated as the shape error is constant during the posture adjustment. The consistency between the points of the surface after posture adjustment and the original inspection points has been changed, so the dimensional error and the machining allowance should be recalculated. The calculation approach is stated as follows:

$ip_i^{oo'}$ represents the point of S_{oo}',the machining allowance $a_i^{oo'}$ of point $ip_i^{oo'}$ is shown as follows:

$$a_i^{oo'} = d\left(ip_i^{oo'}, S_m\right). \tag{11}$$

ip_i^* represents the point of surface S_m, which is close to the point $ip_i^{oo'}$, and the initial thickness of point ip_i^* is represented with t_{ai}; the thickness $t_i^{oo'}$ at the current point $ip_i^{oo'}$ is calculated as follows:

$$t_i^{oo'} = t_{ai} - a_i^{oo'}. \tag{12}$$

The problem whether the dimensional error and the machining allowance could satisfy the requirements is analyzed based on the calculations. If an eligible expected final state can be obtained, the interim machining state is eligible; otherwise, the interim machining state is not eligible.

The eligible expected final state can be regarded as a basis to adjust the tool path for further machining. Tool path can be generated based on the surface which is fitted with the adjusted inspection points. If the next machining result is the final state, the adjusted tool path can be generated on the basis of the expected final state directly; otherwise, the expected final state should be offset by a machining allowance distance.

The uncertainty of geometric error is required to make the evaluation of the interim machining state more accurate, as the geometry tolerance analysis based on inspection points involving both measurement uncertainty and algorithm uncertainty which have been researched by some scholars, and it is not elaborated in this paper.

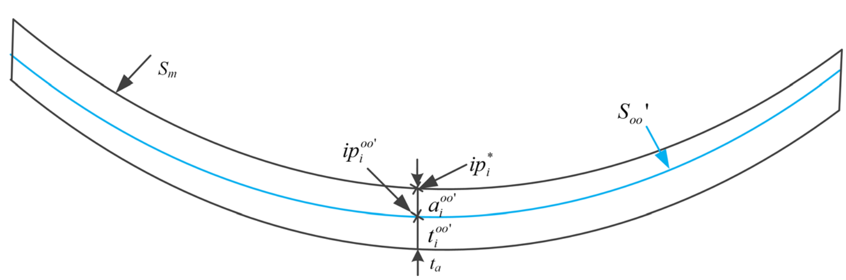

Fig. 7 The expected final machining state adjustment according to position tolerance

5 Case study

A typical large-scaled and thin-walled aircraft structural part is used as an example to verify the proposed approach, as shown in Fig. 8. The material of the part is aluminum alloy; the dimensions of the part are length 2788 mm, width 990 mm, height 50 mm, and thicknesses of the walls are from 1.5 to 3.5 mm. The dimensional tolerance is ±0.15 mm, the profile tolerance is 0.20 mm, and the position tolerance is ±0.10 mm. The part is machined in a 5-axis machine tool. Two main processes are taken, i.e., rough machining and finish machining, and the interim state is inspected after rough machining stage. The inspection is conducted by a contract-type probe, and the distribution of the inspection points is decided according to the surface curvature and machining accuracy.

The actual interim machining state is obtained based on in-process inspection, as shown in Fig. 8. The distance between inspection points and the theoretical final state is calculated based on the assessment of interim machining state. The calculation results show that the maximum distance between inspection points and the theoretical final state is 1.16 mm which suggests that the interim machining state may deform 0.16 mm inward. If the part is machined with the original tool path, the overcut value may be up to 0.16 mm, which makes the dimensional error out of the designed tolerance.

The expected final state can satisfy the requirements of dimensional tolerance, shape tolerance, and position tolerance after tool path adjustment by using the method presented in the paper; and the expected final state can be used as drive geometries for the tool path adjustment for further machining. The new tool path can be generated automatically according to the drive geometries, and, for security consideration, the tool path should be verified by process planners.

Take the point with the maximum deformation for an example, offset the tool path by 0.06 mm in the exterior normal direction of the surface, the undercut value is 0.10 mm, and the dimensional error is 0.06 mm, which can satisfy the tolerance requirements and process requirements.

In actual machining process, the majority of large-scaled and thin-walled parts may deform greatly due to high material removal rate. In summary, the adaptive machining approach proposed in this paper has been validated by the experiment results.

6 Conclusions and future work

This paper proposes an adaptive machining approach based on in-process inspection of interim machining states for large-scaled and thin-walled complex aircraft structural parts. The contributions of this paper to the research literature can be summarized as the following aspects: (1) an assessment criterion for determining whether the interim machining state is suitable or not for further machining is established, which is realized by considering the machining tolerance and machining process requirement based on in-process inspection of interim machining state; (2) an adaptive adjustment approach of the tool paths for further machining of interim machining states is proposed, and an eligible tool path is obtained by adjusting the expected final machining state adaptively by considering the interaction constraints of dimension tolerances, position tolerances, and machining allowances. A typical large-scaled and thin-walled complex aircraft structural part is used as a case to validate the proposed approach. Experiment results show that the dimensional error is 0.10 mm and the profile error is 0.06 mm, which can meet the machining requirement of large-scaled and thin-walled complex parts.

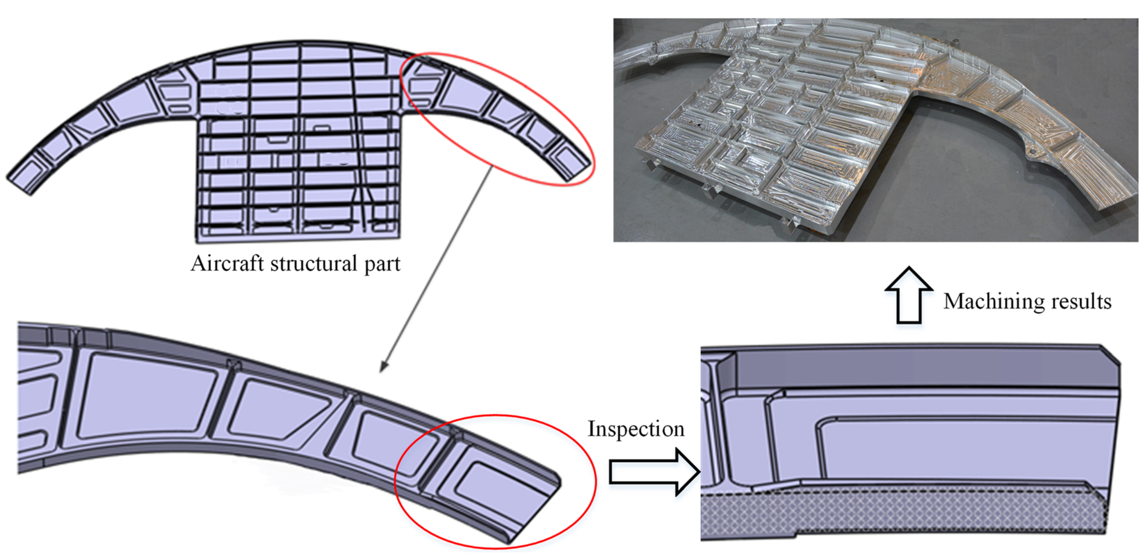

Fig. 8 Case study of an aircraft structural part

Some other in-process inspection methods to improve inspection efficiency will be researched as our future work.

Acknowledgments The research work presented in this paper was primarily supported by the major project jointly funded with the National Natural Science Foundation of China and China Aerospace Science and Technology Corporation (ref. U1537209) and the National Natural Science Foundation of China (ref. 51375239).

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