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NC Milling Process Planning for Thin-Walled Parts with Low Rigidity

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ABSTRACT: To solve the problems that the low rigidity thin-walled part is easy to deform in NC milling process and some parts of the complex surface is difficult to process, this paper points out the measures for increasing accuracy of thin-walled NC machining process from the selection of material and blank, the choice of machine tool, the determination and optimization of the clamping method, the choice of cutting tool, the determination of the tool path, the velocity field distribution of the cutter shaft and the modeling of motion constraint, etc. These theories and methods have certain guiding significance for the efficient numerical control milling of thin-walled parts and they can be used to guide the production practice.

Keywords : low rigidity thin-walled parts; processing technology; NC milling; machining deformation

I. INTRODUCTION

Low rigidity thin-walled parts are widely used in aerospace, mechanical, civil and other fields because of the advantages of light weight and strong carrying capacity[1]. At present, most of these parts are manufactured by NC milling process. In milling process, cutting tool and the workpiece under the influence of cutting force are very easy to produce elastic deformation because the shape of thin wall is complicated, the relative rigidity is low, and the technology is poor. After feeding, the deformation is elastically recovered which resulting in partial material failure to remove and causing the issues such as upper and lower wall thickness difference and the super-size of dimension. The problems greatly reduce the machining precision and surface quality of the workpiece[2].

In recent years, domestic and foreign scholars are researching to reduce parts processing deformation by improving the NC milling process of thin-walled parts with low rigidity. Ye Jianyou et al.[3] indicated that the material, structure, clamping process, residual stress release and redistribution were the main reasons of thin-walled parts deformation. They also summarized the current domestic and foreign researches of thin-walled deformation compensation technology development. Gao Xiang et al.[4] discussed the influence of process route, feeding strategy, cutting parameters and the clamping way which involved in the NC machining of thin wall parts on machining efficiency. They also pointed out technical methods and measures for improving the machining precision and surface quality. RIzamshah et al.[5] analyzed the material removal in NC machining of thin wall parts by using the finite element method, and analyzed cutting parameters by using statistical regression method. Besides, they put forward a method to predict NC machining deformation of thin-walled parts. Yuan Hua et al.[6] put forward the technical scheme to control parts machining deformation and improve the accuracy of the workpiece based on the analysis of main factors of thin-walled parts deformation in milling process.

According to the characteristics of low rigidity thin-walled parts, the paper analyzed the reasons for milling deformation of thin wall parts and put forward the technological measures for improving the precision of thin-walled parts NC machining from the selection of material and blank, the choice of machine tool, the determination and optimization of the clamping method, the choice of cutting tool, the determination of tool path and the velocity field distribution of cutter shaft and the modeling of motion constraint.

II. THE ANALYSIS OF MACHINING QUALITY OF LOW RIGIDITY THIN WALL PARTS

The machining of workpiece is carried out in the processing system composed by the machine tool, the jig, the cutting tool and the part[7]. In the milling process of low rigidity thin-walled workpiece, the main causes of the deformation can be summarized as the initial residual stress, the role of the tool on the workpiece, the loading conditions, the influence of material, the impact of the tool under the knife, etc.[8]. The key to improve the machining accuracy of the thin-walled parts is to take appropriate measures to control and reduce the machining errors caused by these aspects. The NC machining deformation factors of thin-walled parts are as shown in Fig 1.

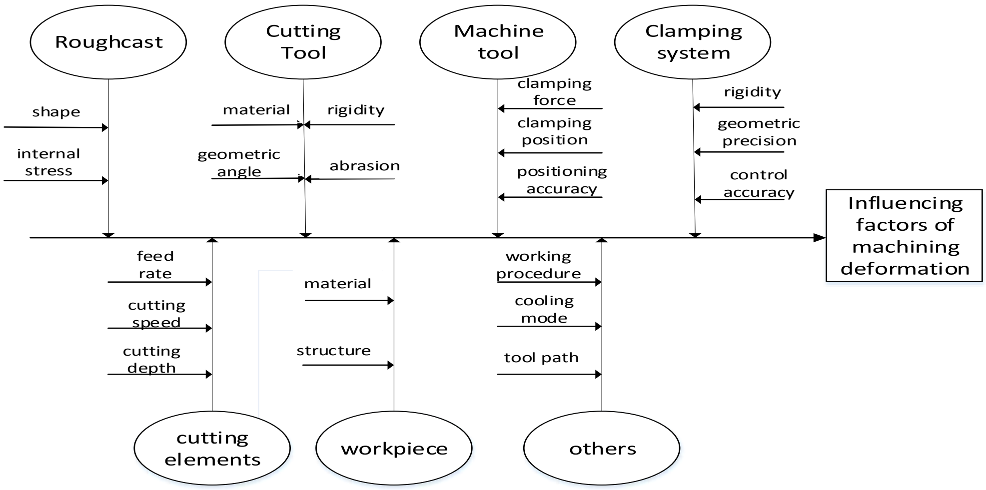

Fig1. Deformation factors of thin-walled parts NC machining

III. PROCESSING TECHNOLOGY OF LOW RIGIDITY THIN-WALLED PARTS

3.1 Selection of materials and blank

Due to the special use of low rigidity thin-walled parts, the material is often required to have high strength, corrosion resistance and good plasticity. The structure of this kind of parts is more complicated and the weight is small. At the same time, high precision, rigidity and strength are required which make the parts easier to be influenced by cutting force, cutting vibration, clamping force and cutting heat. The raw materials which have eliminated internal stress should be as far as possible chosen when choosing roughcast.

3.2 Choice of machine tools

Five axis machining center usually requires only one time to complete the machining of all faces except mounting surface and there is no positioning errors accumulation in the machining process. This kind of machine tool not only avoids multiple clamping but also reduces the cost of the fixture. At the same time, it can improve the efficiency of machining parts and ensure the machining accuracy and quality of the parts. In addition, five axis CNC machine tools can increase the effective cutting edge length and reduce the cost of cutting tools to a certain extent in the process of machining.

3.3 Determination and optimization of clamping scheme

In the NC milling of thin-walled parts with low stiffness, clamping scheme will directly affect machining accuracy, surface quality, labor productivity and production cost. When determining the clamping scheme, the stress and deformation of machining process are analysed and calculated to find the weakest parts of the deformation according to the structural characteristics of parts and processing technology requirements firstly. At the same time, the choice of positioning, clamping as well as clamping force should be focused on to make the integrated force and torque of work pieces as small as possible so as to improve the rigidity and reduce the clamping deformation of parts, and finally achieve the purpose of improving the geometric accuracy of the workpiece.

Under the condition of determined positioning and clamping, the optimization model of clamping point position and clamping force of thin-walled parts can be built with a combination of genetic algorithm and finite element method. The objective function is to minimize the maximum deformation of thin-walled parts. Clamping position and clamping force can be optimized synchronously to make the clamping scheme based on theoretical analysis and quantitative calculation according to the optimization model. The optimization model can be established as follows:

Assuming that there are *p* fixture elements in contact with the workpiece, the cutting force on the workpiece is decomposed into *n* steps. The optimal design variables of optimization model are the position of the clamping point and the number of clamping points. The objective function is described as:

$$Min(\mathrm{Max}(|\triangle_1|,|\triangle_2|,\cdots,|\triangle_k|,\cdots,|\triangle_n|)) \quad (1)$$

In the formula (1), $\triangle_k$ is the cutting force acting on the first *k* step to the point of the maximum deformation of the processing point.

The constraint conditions are:

$$pos(\mathrm{i}) \in \mathrm{V(i)},\quad \mathrm{i}=1,2,\cdots,\mathrm{p} \quad (2)$$

$$\sqrt{F_{xi}^{2}+F_{yi}^{2}} \le \mu_i\,|F_{\mathrm{ni}}|,\ F_{\mathrm{ni}}>0 \quad (3)$$

$$P_{\mathrm{i}}<\sigma_{\mathrm{s}}A_{\mathrm{i}},\ P_{\mathrm{i}}N_{\mathrm{i}}<0 \quad (4)$$

Formula (2) is the position constraint. It indicates that the fixture element should be in the active area of the workpiece. *Pos(i)* is the contact position for fixture element *i* and workpiece. *V(i)* is the effective area of the corresponding positioning surface of the workpiece and the fixture element *i*. Formula (3) is constraint conditions for the stability of workpiece. It indicates that the workpiece and the positioning element cannot be separated from the relative sliding. *Fni* is the normal contact force and μ_i is the friction factor between the fixture positioning element *i* and the workpiece. *Fxi* and *Fyi* are two tangential contact forces of the fixture positioning element *i* and the workpiece respectively. Formula (4) is the constraint conditions for clamping force. It indicates that the clamping force cannot cause the workpiece to produce plastic strain. *Pi* is the clamping force for clamping element *i*. $\sigma_s$is yield stress of workpiece and *Ai* is the contact area of clamping element *i* and the workpiece. Besides, *Ni* is the outer normal direction for the clamping force and the contact surface of the workpiece.

3.4 The selection of machining tool and the optimization method of tool axis vector

InNC machining, the choice of tool type directly affects the range and quality of the machining[10]. In general, the milling cutters are chosen to improve cutting efficiency in rough machining when the machining allowance is relatively large. Ball-end mills are chosen to guarantee the machining accuracy of the workpiece transition surface when the parts are in finishing.

Aiming at the chatter with ball-end mills, cutter axis direction optimization method based on stability can be pointed out. In five axis machining, the intersection region and frequency response function are changed along five axis tool path. It is difficult to judge the stability according to the existing lobe diagram method. So, the five axis machining process is described by the stability equation of frequency domain. The stability of each tool bit is determined by the discrete Nyquist method and then the feasible solution space can be generated. Finally, the direction of the cutter shaft can be selected through the fairness of cutter axis.

3.5 Determination of high speed machining tool path

The main contents of five axis NC milling include the cutting tool, the cutting path and the cutting quantity. The generation of tool path is the basis of NC machining programming. For the complex surface of five-axis NC machining, the rational planning of NC machining process can not be separated from the generation of a reasonable tool path.

3.5.1 Tool path linearization

Discrete straight generatrix can be fitted by rational spline based on the position of discrete points of the curved surface and the distribution of the straight line bus in thin-walleded parts. The idea of quasi linearization of canonical equations can be used to map the rational spline curves in the line space to euclidean space. Then rational ruled surface in the form of tensor product can be obtained. The position of discrete cutter can be obtained from the rational ruled surface offset discrete linear, just as shown in Fig 2:

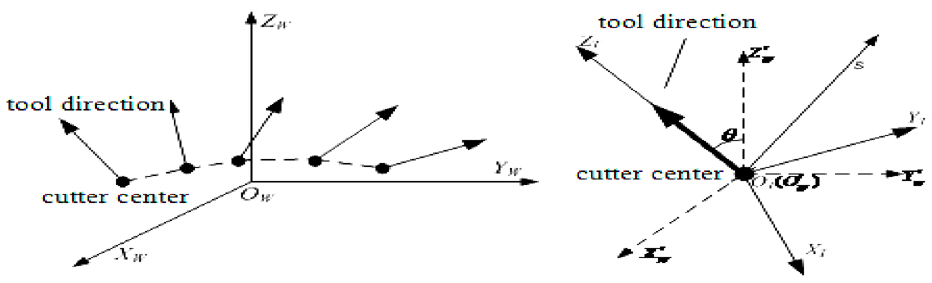

Fig2. Linear description of five axis machining tool bit and expression of dual four element

3.5.2 Tool path of offset double NURBS curve

Expression of cutter envelope surface along the interpolation tool path for cylindrical conical cutter was researched from the line geometry and dual four elements. Linear cutter was fitted by using dual four element B spline vector function to obtain five axis linkage tool B spline motion trajectory based on the error analysis and precision control of the tool path theory. Tool path of offset double NURBS curve which describing the tool center point and the point motion trace of the cutter shaft was obtained after interpolation, just shown as Fig3. And then the motion track of the tool path without interference in high speed machining was obtained[11].

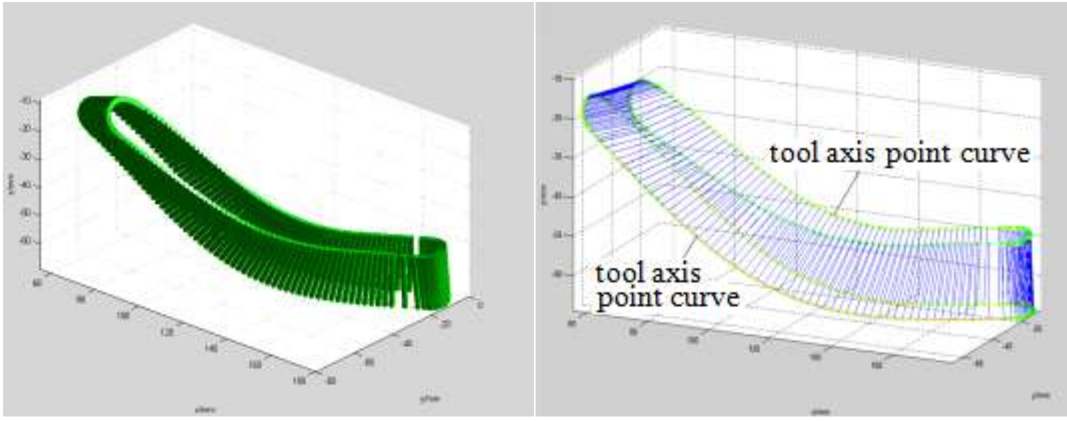

Fig3. Isometric double NURBS tool path simulation

3.5.3 Isometric Double NURBS Cutter Path

The change rule and construction method of surface streamline feature field can be researched based on key data of low stiffness complex thin wall surface. Geometric modeling for complex curved surface is provided to determine the area of the differential system. Among varieties of surface modeling methods, the most studied is NURBS (non-uniform rational B spline). It has ability to describe shape well and can express curves and a variety of free surfaces in a unified form[12].

If the ordered sequence of the known value point is $\{Q_k \mid k=0,1,\cdots,n\}$, a p sub NURBS curve can be constructed to make it through a given value point. Firstly, specify a parameter value $\overline{u_k}$ for each type of value point Q_k. The parameter values corresponding to the first and last points are set to 0 and 1. Then, the rest are decided by chord length parameters method and the appropriate node vector $U=\{u_0,u_1,\cdots,u_k\}$ can be chosen. Among them, $k=n+p+1$. Establishing the following system of linear equations:

$$Q_k = C(\overline{u_k}) = \sum_{i=0}^{n} N_{i,p}(\overline{u_k})\mathrm{P}_i\ , \quad k=0,1,\cdots,n \qquad (5)$$

In practical solution, the node vector *U* is usually determined firstly, and then fitting NURBS curve of value point Q_k can be obtained.

Setting the integral impeller side milling as an example[13], a five axis dual NURBS tool path is shown as Fig4.

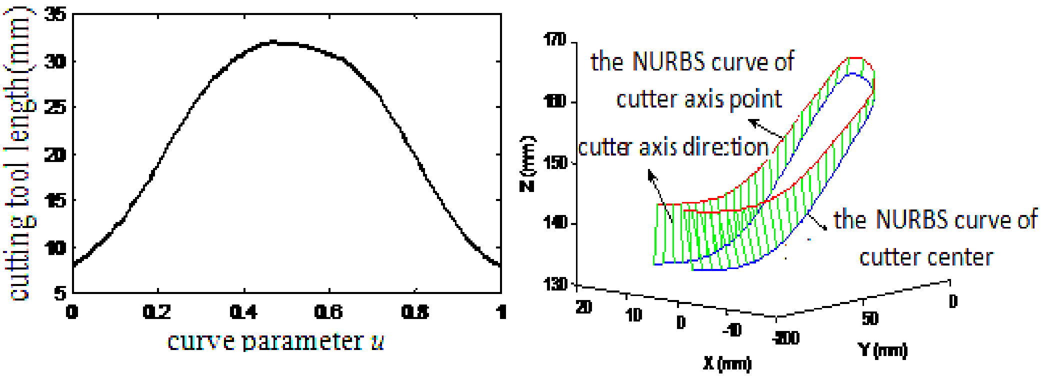

Fig4. Five-axis linkage isometric double NURBS tool path of integral impeller blade side edge machining

3.6 The velocity field distribution and motion constraint modeling of the cutter shaft

3.6.1 Velocity field distribution

Dual NURBS tool path of five axis linkage based on dual four element number representation can be analysed to deduce the velocity field distribution on the rational plane of the cutter shaft and establish the kinematics model of the cutting edge element [14]. The material removal of cutting process and the contact state of tool and workpiece can be researched based on scanning body and instantaneous characteristic line of cylindrical (conical) cutting tools in rational straight line motion. Contact arc length and depth distribution along the cutter shaft can be analyzed and material removal rate per unit time can be denoted by cutter axis scanning area. Feed rate constraint can be obtained to control excessive cutting force and tool breakage caused by material removal rate fluctuation according to the upper limit of the given cutter axis scanning area.

3.6.2 Motion constraint modeling

The relation of the velocity, acceleration, feed rate and feed acceleration of machine tools' each axis in five axis dual NURBS curve interpolation operations can be deduced to make sure that the output command of the interpolation device does not exceed the servo capability of the machine tool according to any given servo capacity constraints. Multiple constraint adaptive feed speed customization model can be established on the basis of motion constraints [15]. Multi constraint adaptive processing uses first order system representation processing and the key factors are adjusted to make it close to the threshold value according to the proportional integral control. Adjusting tool axis motion speed by adaptive controller on the basis of the safety of cutting tools, and machine tools to make sure that the machine tool works in the maximum potential range.

3.7 Process route arrangement

In NC milling, the low rigidity thin-walled parts with precision IT6 or above should adopt the processing route of rough machining - finish machining or rough machining - semi finish machining - finish machining, especially the parts of higher material removal rate. Rough machining uses a relatively large clamping force and cutting parameters to leave appropriate cutting allowance for finish machining. Proper heat treatment process such as cryogenic treatment and aging treatment etc. should be arranged to eliminate the residual stress of the workpiece after the rough machining and before finishing. These measures can significantly improve the dimension stability of low rigidity thin-walled parts. Reasonable cutting dosage and workpiece clamping scheme should be chosen to reduce the clamping and processing deformation and ensure the machining accuracy when the thin-walled parts finishing. Besides, high speed milling(except the special material) and appropriate cooling are widely used to ensure processing quality and reduce the impact of cutting heat on the workpiece when the parts are in finish machining.

IV. CONCLUSION

Low rigidity thin-walled parts are widely used in engineering applications because they have advantages of light weight, high strength, beautiful appearance etc. But the problems of deformation, instability and vibration in processing make them difficult to manufacture. So, it is very important for the artifacts to optimize technology and analysis processing quality. Parts processing technology should be optimized to reduce machining distortion and improve the dimensional accuracy and machining efficiency of thin wall parts as much as possible. The processing stability and quality of low rigidity thin-walled parts in the process of NC machining can be ensured by these improvements.

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