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Instantaneous cutting-amount planning for machining deformation homogenization based on position-dependent rigidity of thin-walled surface parts

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ABSTRACT

Thin-walled parts with curved surfaces are widely used in industrial applications, and the surface quality is a basic requirement to ensure the functional performance. Due to the thin-walled and curved geometric features, the rigidity for this kind of parts is not only low but also position-dependent. In this way, the deformation of such parts is easy to vary and complex along the toolpath in the machining process, which results in a poor dimensional quality for the thin-walled parts with curved surfaces. However, it is a novel idea that when the machining deformation is homogeneous, the deformation compensation is easily carried out and the improved machining quality can be obtained for the thin-walled curved surface parts. For the machining deformation is affected by the cutting force and the cutting force is affected by the instantaneous cutting-amount in essence, an instantaneous cutting-amount planning approach based on the position-dependent rigidity of thin-walled curved surface parts is proposed in this study, so as to homogenize the machining deformation thus improving the machining quality. Inspired by the generalized Hooke law, the instantaneous cutting-amount is planned here to be harmonious with the rigidity variation along the toolpath, so that the ratio between the cutting force and the rigidity, i.e. the deformation at certain cutting-position, can be kept as a constant value. For this sake, the instantaneous cutting-amount of thin-walled curved surface parts during the five-axis machining process is first modeled, and then, the position-depended rigidity of the parts is calculated. Finally, the instantaneous cutting-amount is scheduled according to the position-dependent rigidity. Experimental results verify the effectiveness of the presented method in homogenizing of the machining deformation. Achievements of this study are significant for enriching the high-quality machining technique of thin-walled parts with curved surfaces.

1. Introduction

Thin-walled parts with curved surfaces, such as impellers and blades, are widely used in aviation and aerospace fields because of the features of light weight and wide functionality [1]. For the complex characteristics, such parts are commonly machined by the five-axis machine tool, and the surface quality is a basic requirement to ensure the functional performance. Due to the thin-walled and curved geometric features, the rigidity for this kind of parts is not only low but also position-dependent [2]. Therefore, it is readily comprehensible that the machining deformation of the thin-walled curved surface parts is non-ignorable and varies effortlessly with the variation of the cutting position. The variation of the complex machining deformation then will result in the asymmetrical wall thickness of the machined thin-walled parts thus worsening the dimensional quality and the surface smoothness, which eventually weakens the equipment properties where such kinds of parts are utilized [3]. In this way, it is of great importance to choose appropriate control method for the machining deformation, so as to guarantee the machining quality of the thin-walled curved surface parts.

To deal with the machining deformation problem for thin-walled curved surface parts, many studies have been conducted in the past years, and most are focused on the investigation of machining deformation prediction for the accurate compensation. Law et al. [4,5] proposed a machining deformation prediction method and conducted the experimental tests based on different machining paths. It was concluded that when comparing with the straight cutting path, the diagonal cutting path resulted in a smoother machining process and a smaller deformation, which made it easier to compensate the machining deformation error. At last, the machining-error compensation

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method was given to improve the machining quality. Dépincé and Hascoët [6,7] forecasted the machining deformation resulted from the cutter deformation error in the flat-end milling process of the thin-walled workpiece, and a multi-step iteration method was presented to calculate the final compensation value. Chen et al. [8] established a dynamic model to predict the machining deformation of each cutting layer for the thin-wall parts, and the deformation error of the current cutting layer was compensated based on the deformation error of the previous layer. Ratchev et al. [9,10] proposed a multi-level machining error compensation approach that focused on the force-induced error in machining of the thin-walled structures. The prediction algorithm took into account the deformation of the parts in different cutting points of the toolpath, the machining conditions were modified at each step when a local equilibrium between the cutting force and the deformation was achieved, and then the error compensation was achieved through the toolpath optimizing by taking into account the predicted machining deformation error. Guiassa and Mayer [11] proposed a compliance-based model to compute the finishing cut correction through process-intermittent probing feedback. The deflection-induced error was treated using a compliance model and was enriched by the possible change in compliance due to the material removal, while the tool offset induced error was decreased using the mirror-compensation approach. Izamshah et al. [12] developed a finite element analysis processing model to specifically predict the machining deformation or deflection of the thin-walled parts during the end milling, which provided an input for the error compensation. Tang and Liu [13] proposed a static deformation prediction model for the thin-walled parts by using the FEM software ANSYS10.0 to simulate the machining deformation. The results showed that each processing layer should choose a variety of cutting parameters to meet the processing accuracy and efficiency for milling of the thin-wall parts. Li et al. [14] researched the finite element simulation for the machining of large-scale thin-walled aluminum alloy parts in aerospace, and predicted the chip formation and the cutting force. Based on the predicted results, the overall machining deformation was predicted which established the foundation of the deformation compensation for this kind of large-scale thin-wall parts. Yi et al. [15] proposed a new method to compensate the surface error by using the finite element method to predict the machining error and obtained the pre-bending force and the clamping position according to the error prediction results. Tang et al. [16] developed a model to predict the machining deformation, which took multifactor coupling effects, including original residual stresses, clamping loads, milling mechanical loads, milling thermal loads, and machining-induced residual stresses, into account. Bera et al. [17] put forward a cutting force induced machining error compensation methodology by considering tool and workpiece deformations in machining process of the thin-wall components. Kline et al. [18] predicted the surface error based on the model for the cutting force in end milling and the models for cutter deflection and workpiece deflection, and the proposed method which was used predicted the surface error was accurate. Sutherland and Devor [19] developed an improved model for the prediction of the cutting force and the surface error in end milling. Montgomery and Altintas [20] presented an improved model of the milling process for determining the cutting forces in five distinct regions where the cutting edge traveled during the dynamic milling. In which, it could be found that when the tooth passing frequency was selected to be an integer ratio of a dominant frequency for the tool-workpiece structure in milling process, the imprint of vibrations on the finished surface could be avoided. Budak et al. [21–24] developed some models to forecast the cutting force for five-axis milling process which laid the foundation for the machining deformation prediction of flexible plates. They also proposed a method for identifying optimal feed rate and width of cut with given cutter dimensions and cutting constants in order to increase the material removal rate significantly without sacrificing the dimensional accuracy of the finished surface. Sagherian and Elbestawi [25] proposed an enhanced dynamic model for the prediction of the cutting force which took the deflections of the tool and the workpiece into account and simulated the material removal during cutting based on the FEM method.

Based on the above analysis of the methods for dealing with the machining deformation problem of the thin-walled curved surface parts, it can be seen that most of the existing studies focus on building the precise machining deformation models thus providing the deformation compensation approaches. Although the machining deformation compensation can decrease the deformation variation in a certain extent, the dramatic change of the instantaneous cutting-amount may inevitably appear, and then the sharp change of the cutting force is bad for the high quality machining of the thin-walled curved surface parts. In addition, the exact cutting force usually should be obtained when using the machining deformation compensation approaches, and this is a difficult task for the five-axis machining of thin-walled curved-surface parts. Furthermore, there often exists the resistant deformation after one-time compensation, so the compensation values should be solved by the iteration calculations which is not computational efficient.

In the machining process of thin-walled parts with curved surfaces, the machining deformation is affected by the cutting force and the cutting force is affected by the instantaneous cutting-amount in essence. It is just that the machining deformation is quite sensitive to the instantaneous cutting-amount. For thin-walled curved surface parts, the rigidity is not only low but also position-dependent and the instantaneous cutting-amount is varying due to the thin-walled and curved geometric features, which make the machining deformation more complicated. In this way, it is of great importance to choose an appropriate instantaneous cutting-amount planning method for diminishing the deformation fluctuation and guaranteeing the machining efficiency simultaneously, and it is a novel idea that when the machining deformation is homogeneous, the deformation compensation is easily carried out and the improved machining quality can be obtained for the thin-walled curved surface parts.

Inspired by the generalized Hooke law that the machining deformation is proportional to the cutting force and is inversely proportional to the cutting-position rigidity of the machined parts, this study aims at planning the cutting force of the thin-walled curved surface parts according to the position-dependent rigidity, so as to make the ratio between the cutting force and the cutting-position rigidity constant, thus reducing the machining deformation variation. As the cutting force is proportional to the instantaneous cutting-amount [26,27] and in order to directly homogenize the machining deformation of the thin-walled curved surface parts without using precise cutting force or iteration computations, the purpose of this study is equivalent to propose an instantaneous cutting-amount planning method based on the position-dependent rigidity. In this way, an instantaneous cutting-amount planning method for machining deformation homogenization based on the position-dependent rigidity of thin-walled curved surface parts is proposed, so as to make the instantaneous cutting-amount harmonious and the cutting condition more stable. Meanwhile, compared with the geometric characteristic of the thin-walled curved surface parts, the cutting depth in finish machining is very small. Thus, the position-dependent rigidity of thin-walled curved surface parts is mainly affected by the geometric characteristic, and the structural dynamics variation of thin-walled curved surface parts during machining as a result of material removal can be ignored. Based on the above, the machining quality can be improved for the thin-walled curved surface parts. To this end, taking a blade parts as an example in this study, the instantaneous cutting-amount of thin-walled curved surface parts during the five-axis machining process is first modeled taking geometric characteristics of curved surface, machining toolpath, cutting step and feed speed into account, followed by the position-dependent rigidity calculation. After that, the feed speed which directly affects the instantaneous cutting-amount is planned to reduce the deformation variation without decreasing of the machining efficiency, so as to realize