

Construction and Analysis of Cutting Force and Stability Prediction Model in CNC Milling Thin-Walled Parts Machining

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Abstract. Thin-walled parts are widely used in precision instruments, automobiles and other fields for their high strength, light weight and other characteristics. However, in the process of CNC milling, as the thickness of the parts decreases, their rigidity gradually decreases, resulting in the machining process is very easy to produce vibration, and even chatter, which seriously affects the accuracy and surface quality of the parts. Traditional manufacturing methods usually use conservative cutting dosage to reduce vibration, but this greatly limits the performance of CNC machine tools and cutting tools. In order to solve this problem, this paper thoroughly investigates the dynamic characteristics of the cutting process of thin-walled parts, and constructs a cutting force and stability prediction model. Through a combination of theoretical analysis, experimental verification and numerical simulation, this paper comprehensively analyses the impact of cutting parameters, tool geometry, workpiece material properties and other factors on cutting force and machining stability. The research results not only help to improve the cutting theory of thin-walled parts, but also provide an important technical support for the realisation of high-efficiency and high-precision machining. The results of this paper show that by optimising the cutting parameters and tool geometry, the cutting force can be effectively reduced and the machining stability can be improved, so as to achieve efficient and high-precision machining of thin-walled parts. In addition, this paper also explores the causes and mechanisms of vibration in the machining process, providing a theoretical basis for the development of targeted vibration control measures. The research in this paper is important for promoting the development of thin-walled parts machining technology, not only helps to improve the processing efficiency and quality of parts, but also helps to promote the manufacturing industry to a more efficient, more precise direction.

Keywords: thin-walled parts; CNC milling; cutting force prediction; machining stability.

1. Introduction

With the rapid development of modern industrial technology, thin-walled parts have been widely used in precision instrumentation, automotive manufacturing and other fields because of their high strength, light weight and other significant advantages. However, in the process of CNC milling, thin-walled parts, due to their weak structural characteristics, the rigidity of the thickness decreases significantly, which leads to the machining process is very easy to generate vibration, and in serious cases, even chatter, greatly affecting the machining accuracy and surface quality of the parts.

Traditional machining methods usually use conservative cutting dosage to reduce vibration, but this method not only restricts the performance of CNC machine tools and cutting tools, but also reduces the machining efficiency. Therefore, how to effectively predict and control the cutting force and machining stability has become a key issue to improve the quality and efficiency of thin-walled parts machining.

In order to solve this problem, this paper thoroughly investigates the kinetic characteristics of the cutting and machining process of thin-walled parts, aiming to construct accurate cutting force and stability prediction models. Through this study, we expect to gain a deeper understanding of the effects of cutting parameters, tool geometry, workpiece material properties and other factors on cutting force and machining stability, so as to provide theoretical support for optimising machining parameters and improving machining efficiency and quality.

2. Research Background And Significance

Thin-walled parts play an indispensable role in modern industrial manufacturing due to their unique advantages such as high strength, light weight and compact structure. Especially in the fields of precision instrumentation and automobile manufacturing, thin-walled parts have been widely used due to their excellent performance. However, despite the many advantages of thin-walled parts, they face a series of challenges in the machining process.

During CNC milling, as the thickness of a part decreases, its rigidity decreases accordingly. This reduction in rigidity results in parts that are susceptible to external factors such as cutting forces and cutting heat during the machining process, resulting in vibration[1]. More seriously, when the vibration reaches a certain level, it may also trigger vibration phenomenon, that is, the parts in the machining process of self-excited vibration, this vibration will lead to a serious decline in machining accuracy, and may even damage the surface quality of the parts. Thin-walled, shaped features, high machining accuracy requirements, machining process complexity, long production cycle, how to improve machining accuracy?

Miscellaneous, long production cycle, how to improve the efficiency of machine tool machining under the condition of ensuring the accuracy of the parts, is an urgent problem to be solved[2]. Aero-engine blade is a typical thin-walled structural components, as shown in Figure 1.



Figure 1 Aero-engine blade

In order to solve this problem, conventional manufacturing methods usually use conservative cutting dosages to reduce vibration. This approach reduces cutting forces by lowering parameters such as cutting speed and feed, thereby reducing the likelihood of vibration. However, while this method is effective to a certain extent, it greatly limits the performance of CNC machine tools and cutting tools. With the continuous improvement of modern industrial requirements for machining accuracy and efficiency, traditional manufacturing methods have been difficult to meet the needs of actual production[3].

Therefore, an in-depth study of the dynamics of the cutting process of thin-walled parts and the construction of accurate cutting force and stability prediction models have become an urgent problem for the current manufacturing industry. Through this study, we can more comprehensively understand the influence of cutting parameters, tool geometry parameters, workpiece material properties and other factors on cutting force and machining stability, so as to optimise machining parameters and improve machining efficiency and quality. At the same time, this will also lay a solid foundation for promoting the manufacturing industry in the direction of more efficient and more precise development.

3. The Research Content And Method

In order to solve the vibration and chattering problems caused by the reduction of rigidity of thin-walled parts in CNC milling, this paper not only thoroughly investigates the dynamics of the cutting process, but also constructs an accurate cutting force and stability prediction model. Through careful theoretical analysis, rigorous experimental verification and advanced numerical simulation, this paper aims to comprehensively and deeply reveal the influence mechanism of cutting parameters, tool geometry parameters, workpiece material properties and other factors on cutting force and machining stability, and accordingly propose optimisation strategies to achieve the goal of efficient and high-precision machining[4]. At present, in the industrial field, many critical parts often have thin-walled, shaped and other characteristics, because of practical needs, mostly aluminium alloys, titanium alloys and other materials with low density, low stiffness and easy deformation[5]. In the actual production processing, there are many factors affecting the processing deformation of low-stiffness parts, mainly workpiece material properties, cutting parameters, fixtures, blank residual stress and machining paths, etc., and there is a coupling relationship between the factors, so it is difficult to analyse the processing deformation of low-stiffness parts[6]. Thin-walled parts deformation factors affecting Figure 1.2 shows. Elimination of such deformation from the principle of roughly divided into the selection of conservative machining parameters, process route compensation and manual calibration.

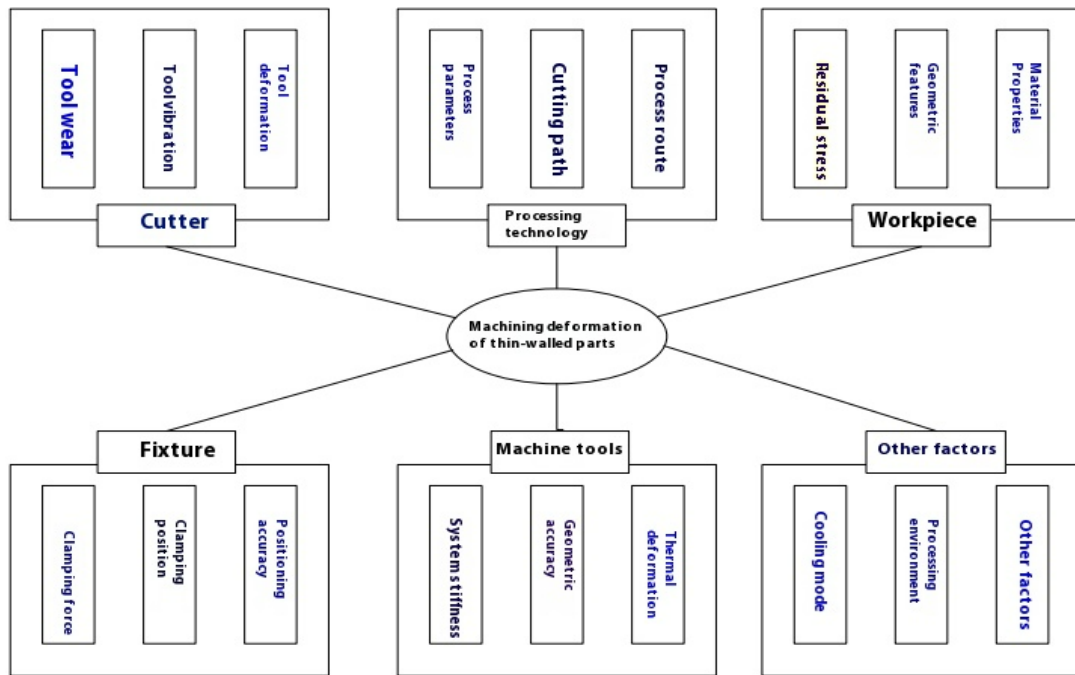


Fig. 2 Influence factors of thin-walled parts machining deformation

In terms of theoretical analysis, this paper not only establishes a mechanical model of the cutting process based on the basic principles of cutting processing, but also further considers the heat-force coupling effect in the cutting process. By analysing the effect of cutting heat on material properties and cutting force, this paper reveals the complex relationship between cutting temperature and cutting force and machining stability[7]. In addition, for the structural characteristics of thin-walled parts, this paper also explores in detail the deformation mechanism of the parts during the cutting process and the dynamic mechanism of vibration generation, which provides a solid theoretical foundation for the subsequent experimental verification and numerical simulation.

In terms of experimental verification, a series of precise cutting experiments are designed in this paper to ensure the accuracy and reliability of the experimental results by strictly controlling the experimental conditions. In the experiments, this paper not only examines the effects of single factors such as cutting parameters, tool geometry and workpiece material properties on cutting force and machining stability, but also investigates the interaction between these factors. The experimental

results not only verify the accuracy of the theoretical analysis, but also provide rich data support for the subsequent numerical simulation. As shown in Figure 3, the cutting force image, selected from the actual milling force data in a period of smoother data, from the figure can be seen that the milling force has the characteristics of cyclical, fluctuating large. In the experiment, the frequency of the force measuring instrument is very high, 0.0001s to read a set of data, so that the whole process can be analysed in a more detailed way, and further processing is needed after the data collection, such as correcting the data drift problem, etc., to remove the influence of unstable factors in the processing of the data, and to ensure the accuracy of the analysis.

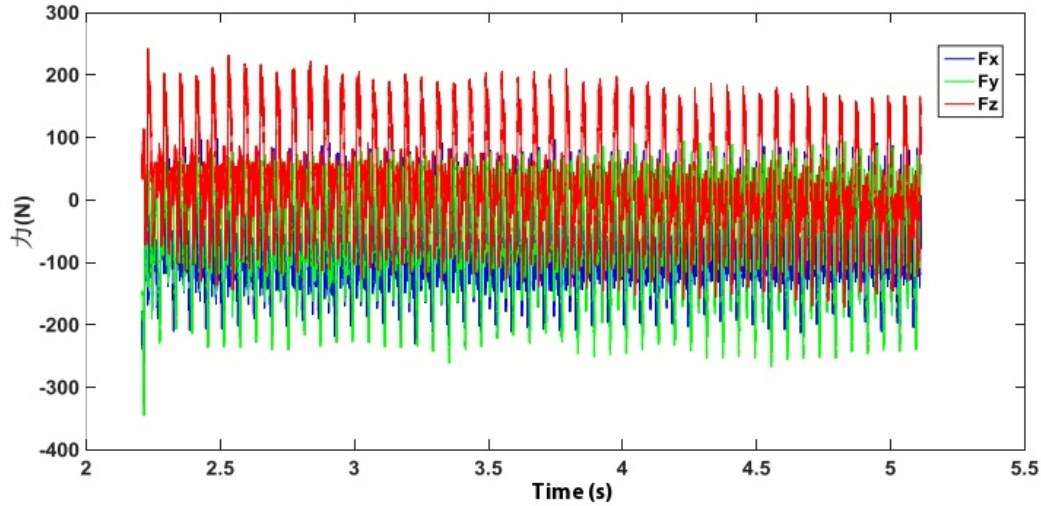


Fig. 3 Cutting force image

In terms of numerical simulation, the milling force data obtained from this experiment through the dynamometer include the time and the size of the milling force in three directions, according to the figure it is relatively obvious to see that the cutting force has the characteristics of cyclicity and fluctuation, this is because the milling cutter rotation leads to the cutting edges involved in the cutting in the change, there are peaks in a complete cycle, the previous equivalent cutting force values are calculated according to the average value for processing, but In actual machining, considering tool wear, machining vibration and machine tool error and other factors, the actual cutting volume will be higher than the average value. Therefore, the experiment will be the average value of each cutting volume peak as the equivalent cutting force, the cutting force expression is.

$$F_i = \frac{1}{n} \sum_{j=1}^n F_{ij} \quad i = x, y, z$$

In the above equation, F_i is the magnitude of the cutting force, n is the number of extreme points, and F_{ij} is the extreme value of the local cutting force in an actual sampling interval. After obtaining the experimental output and processing it, the cutting force corresponding to each parameter combination is obtained, as shown in Table 1.

Table 1 Cutting force data of orthogonal experiment

序号	$F_x(N)$	$F_y(N)$	$F_z(N)$
1	24.952	22.156	36.138
2	53.579	41.669	62.926
3	77.578	40.894	86.847
4	137.825	62.397	175.167
5	171.599	80.063	250.637
6	60.034	41.426	57.549
7	92.342	8.581	60.314
8	182.964	333.842	570.216
9	87.063	67.242	106.534
10	53.969	32.364	84.573
11	47.621	80.625	77.361
12	42.561	37.534	63.967
13	54.134	8.144	41.193
14	62.403	8.786	60.334
15	72.648	152.171	222.876
16	46.397	20.209	68.932
17	80.075	151.223	209.186
18	87.212	112.896	183.542
19	208.071	39.102	123.514
20	139.775	52.221	133.549
21	157.748	82.535	105.263
22	162.991	62.011	175.294
23	68.951	16.973	99.564
24	69.809	129.175	262.953
25	296.587	318.279	323.219

Through the above research, this paper not only reveals the influence mechanism of cutting parameters, tool geometry parameters, workpiece material properties and other factors on cutting force and machining stability, but also proposes corresponding optimisation strategies[8]. These strategies not only help to reduce cutting force and improve machining stability, but also help to improve machining efficiency and quality. In addition, the research results of this paper also help to improve the theory of thin-walled parts cutting machining and provide new ideas and methods for the development of the manufacturing industry. Through the research in this paper, we expect to promote the progress of thin-walled parts machining technology and contribute to the development of modern manufacturing industry.

4. Research Results And Discussion

In the previous study, we have thoroughly explored the effects of cutting parameters, tool geometry parameters, workpiece material properties and other factors on cutting force and machining stability by combining theoretical analysis, experimental verification and numerical simulation. Now, we will elaborate and discuss the research results in detail.

Firstly, we found that the cutting parameters have a significant effect on cutting force and machining stability. By adjusting the parameters such as cutting speed, feed and depth of cut, we can effectively control the magnitude of cutting force and the stability of the machining process. Specifically, appropriate reduction of cutting speed can reduce the cutting force, but too low cutting speed may lead to low machining efficiency; and increase the feed volume can improve the machining efficiency to a certain extent, but too large a feed volume may also lead to an increase in cutting force and machining stability decline. Therefore, in actual machining, we need to choose the right combination of cutting parameters according to the specific situation to achieve efficient and stable machining.

Secondly, tool geometry has an important influence on cutting force and machining stability. Factors such as tool geometry, cutting edge angle and cutting edge sharpness will directly affect the cutting force and vibration during the cutting process. By optimising tool design, we can further reduce cutting forces and improve machining stability. For example, the use of smaller cutting edge angles

and sharp cutting edges can reduce the cutting force; and the use of reasonable tool materials and coating technology can also improve the wear resistance and vibration resistance of the tool.

In addition, workpiece material properties are also one of the key factors affecting cutting force and machining stability. The properties of different materials such as hardness, toughness and thermal conductivity will affect the cutting force and machining stability during the cutting process. Therefore, when machining different materials, we need to select appropriate cutting parameters and tool types according to the properties of the materials to ensure the smooth machining process.

During the discussion, we also found some interesting phenomena and laws. For example, in some cases, an appropriate increase in the depth of cut can improve machining stability; while in other cases, too large a depth of cut may lead to a sharp increase in cutting force and a decrease in machining stability. These phenomena indicate that the effects of cutting parameters and tool geometry on cutting force and machining stability are complex and variable, and need to be considered and optimised according to specific situations.

Finally, we put forward some optimisation suggestions based on the research results. For example, in actual machining, we can select appropriate cutting parameters and tool types according to the size, shape and material properties of the workpiece; at the same time, by real-time monitoring of the cutting force and vibration during the cutting process, we can timely adjust the cutting parameters and tool status to ensure the stability and efficiency of the machining process. In addition, we can further study the heat-force coupling effect and tool wear mechanism in the cutting process to further improve the machining quality and efficiency.

In summary, through the in-depth study and analysis of factors such as cutting parameters, tool geometry parameters and workpiece material properties, we have revealed their influence mechanisms on cutting force and machining stability, and put forward corresponding optimisation suggestions. These research results will not only help to improve the theory of cutting and machining of thin-walled parts, but also provide new ideas and methods for the development of the manufacturing industry.

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