Design and Finite Element Analysis of Axial Low-frequency Vibration Tool-holder

Zhanfeng Liu, Hui Liu*, Dezhong Zhao, Chi Wang, Tianqi Wang, 

Department of Mechanical Engineering, Xi’an Shiyou University, Xi’an, Shaanxi, China

E-mail: 13572896975@163.com, *Corresponding author’s 156237457@qq.com 181020928@stumail.xsyu.edu.cn
190203@xsxyu.edu.cn, 1309473779@qq.com
wangtianqi@xsyu.edu.cn

Abstract—Vibration-assisted drilling can significantly reduce the drilling force and cutting heat during deep hole machining, improve tools life and hole machining quality. As a branch of vibration drilling technology, axial low-frequency vibration-assisted drilling has a broad application prospect in the field of drilling because of its simple structure and easy implementation. A mechanical axial low-frequency vibrating tool-holder (ALVT) is designed, and the overall structure layout and working principle of the vibrating tool-holder are analyzed. The rotary motion of the machine tool spindle is used as the power input to drive the sinusoidal surface to rotate to achieve the amplitude output. The vibrating tool-holder model is simplified, and the ABAQUS finite element software is used to simulate the titanium alloy material for ordinary drilling and axial low-frequency vibration drilling (ALVD), and the axial force and cutting temperature changes are compared and analyzed. The results show that ALVD of titanium alloy can reduce the average axial force by about 47% and the cutting temperature by about 11%, which can significantly improve the drilling conditions and the quality of hole machining.

1. Introduction

As an important processing procedure in the machining process, hole machining is the most widely used technology in the field of mechanical manufacturing. With the increasing application of new materials and difficult-to-machine materials, quality requirements and difficulty of hole processing technology are also increasing, especially in the field of deep hole processing. Deep hole processing has always been a difficult point in mechanical processing. The main reason is that the processing space is closed or semi-closed, which makes it difficult for the chips to be discharged, and the cutting heat to be transferred to the outside of the parts. In severe cases, there may be problems such as chip jamming, burns on the processed surface of the parts, and thermal deformation of the parts [1]. Because of its pulse cutting characteristics, vibration drilling technology can not only solve the problems of difficult chip interruption and chip removal in deep hole machining, but also can significantly reduce drilling force and cutting heat, and significantly improve tool durability [2].

Vibration drilling device is one of the key steps to realize vibration drilling. At home and abroad, many experts and scholars are also devoted to the research of vibration drilling device. Ma Qingyan of North University of China and others designed a mechanical axial deep hole vibration drilling device
using a swing guide rod mechanism [3]. Laporte and others designed a passive axial vibration tool-holder using a sinusoidal washer structure [4]. The main forms of vibration drilling devices include mechanical, hydraulic, ultrasonic, electromagnetic and so on [5-7]. Among them, the mechanical vibration drilling device is widely used due to its simple structure, low cost and convenient operation and maintenance [8]. At present, most of vibration drilling devices in the domestic market are installed on the workbench, and most of them are mainly active high-frequency vibration drilling devices. Although the vibration tool-holders have been used in foreign markets, but due to its confidential core technology and high price, it is difficult to be widely used in China.

Aiming at the above problems, in order to improve the quality of hole processing and reduce the processing cost, this paper designs a fixed-amplitude ALVT. And through finite element simulation, part of the process characteristics of titanium alloy ALVD compared to ordinary drilling are studied.

2. Mathematical model and chip breaking mechanism of axial vibration drilling

The fundamental difference between vibration drilling and ordinary drilling is that a regular and controllable relative vibration is generated between the tool and the workpiece through a vibration device during the drilling process, thereby performing continuous and regular pulse cutting [9]. Fig. 1 shows a schematic diagram of axial vibration drilling.

![Fig. 1 Schematic diagram of axial vibration drilling](image)

In vibration drilling process, the axial displacement of cutting edge can be described by the following equation.

\[ z(t) = f_r \frac{n}{60} + A \sin(2\pi ft) \]  

Where \( f_r \) is the feed per revolution of tools (\( \text{mm} / \text{r} \)), \( n \) denotes the spindle revolutions per minute, \( t \) is the drilling time (s), \( A \) is the vibration amplitude (\( \text{mm} \)), \( f \) is the vibration frequency (Hz).

The axial cutting thickness, that is, the instantaneous feed \( \Delta f_r \) can be as follows:

\[ \Delta f_r = z(t + t_0) - z(t) \]

Where \( t_0 \) is the time (s) required for tools to make one revolution relative to the workpiece, that is, \( t_0 = 1/(n/60) = 60/n \). Substituting \( t_0 \) into equation (2), we get

\[ \Delta f_r = f_r + 2A \sin\left(\frac{\pi f}{n}\right) \cos\left(2\pi ft + \frac{\pi f}{n}\right) \]  

Let \( k = 60f/n = N + i \), where \(-0.5 < i < 0.5\), \( k \) is the number of oscillations of tools in one revolution of the workpiece, called the overlap coefficient [9]. \( N \) is the integer part of \( k \), and \( i \) is the decimal part of \( k \). Equation (3) can be rewritten as

\[ \Delta f_r = f_r + 2A \sin\left(\frac{i\pi f}{n}\right) \cos\left(2\pi ft + i\pi\right) = f_r + 2A \sin\left(i\pi\right) \sin\left(2\pi ft + i\pi + \pi/2\right) \]  

Available cutting thickness shows a regular variation range

\[ \Delta f_{r\text{min}} \leq \Delta f_r \leq \Delta f_{r\text{max}} \]

\[ \Delta f_{r\text{min}} = f_r - 2A \sin(i\pi) \]

\[ \Delta f_{r\text{max}} = f_r + 2A \sin(i\pi) \]
It can be seen that to achieve complete geometric chip breaking, as long as it satisfies
$$\Delta f_{\text{min}} \leq 0$$
which is
$$f_r \leq 2A\sin(nt) = 2A\sin[(60f/n - N)\pi]$$
(6)

Therefore, when the parameters \(f_r, n, A, f\) meet the conditions of equation (6), the drilling process can change from continuous cutting to intermittent cutting [10].

3. Design of ALVT

3.1. The working principle of ALVT

The designed ALVT adopts self-excited vibration mode with the amplitude of 0.06 mm. The circumferential rotation motion of the spindle is transformed into the axial vibration of the tool-holder through the "vibrator" with the end face of a circular sinusoidal surface. No need to add additional excitation devices. The designed device has a simple and compact structure and convenient application. Fig. 2 is the structural diagram of tool-holder with axial low-frequency vibration.

![Fig. 2 Structural diagram of tool-holder with axial low-frequency vibration](image)

1—Input shaft; 2—Shaft sleeve; 3—Circular upper end cover; 4—Case; 5—Tapered roller bearing; 6—Toroidal surface; 7—Roller cage; 8—Roller; 9—Return spring; 10—Centripetal thrust ball bearing; 11—Circular lower end cover; 12—Output shaft; 13—Circlip; 14—Tightening nut; 15—Drilling tool; 16—Positioning lever

When working, the spindle passes through the input shaft 1 and transmits the torque to the output shaft 12 through the spline structure, and drives the drilling tool 15 to rotate through the circlip 13 and the tightening nut 14. The lower surface of the toroidal surface 6 is provided with a toroidal sine curved surface with an amplitude of 0.06 mm and a period of 3. The upper end of the output shaft 12 is internally connected with the input shaft 1 through a spline pair. The upper end-face is provided with a circular groove for placing the roller 8. The lower end-face is provided with a circular groove for placing the return spring 9. During assembly, three identical rollers are installed on the roller cage 7 at equal intervals and placed between the toroidal curved surface 6 and the output shaft 12. Under the action of the return spring 9, the outer surface of the roller is always in contact with the surface of the toroidal curved surface 6 and the surface of the ring groove at the upper end of the output shaft 12. The advantage of this design is that the spindle rotates one circle, and the tool can realize 3 cycles of
vibration drilling.

3.2. The overall installation structure of ALVT
The overall installation structure of ALVT is shown in Fig. 3. The positioning lever of the vibrating tool-holder is fixed in the positioning groove on the outer ring of the machine tool spindle. In this way, the circular upper end cover, the outer ring of tapered roller bearing, the toroidal surface, the case, the outer ring of radial thrust ball bearing and the circular lower end cover are fixed to the outer ring of the machine tool spindle. All of them are forming a structure similar to the stator. The remaining internal parts of the vibrating tool-holder rotate with the spindle of the machine tool. They are forming a structure similar to the mover. When working, under the action of the return spring, the roller always vibrates up and down according to the designed ring-shaped sine curve track, thereby driving the output shaft to vibrate up and down, that is, realize the vibration of the tool and achieve the purpose of vibration drilling.

![Fig. 3 Overall installation structure of tool-holder with axial low-frequency vibration](image)

4. Simulation analysis of ALVD

4.1. Pre-simulation processing
In order to study the technological characteristics of titanium alloy in terms of axial force and cutting temperature when using ALVD technology to make holes, ABAQUS software is used to establish a finite element model of gun drill and workpiece, as shown in Fig. 4. The designed ALVT model is simplified as a gun drill to facilitate the simulation analysis, and the gun drill is set as a rigid body and the workpiece is a plastic body [11]. The workpiece is $\text{aØ14 mm} \times 5 \text{ mm}$ cylindrical Ti6Al4V material blank; the diameter of the gun drill is 10 mm. In order to simplify the model, only part of the gun drill head is taken, and the material is cemented carbide tungsten steel (WC-Co). Table 1 shows the basic parameters of the two materials.

![Fig. 4 Finite element model of gun drill and workpiece](image)
In the finite element analysis, the pros and cons of meshing have a great influence on the simulation results. In order to balance the calculation accuracy and the calculation efficiency, the mesh of the workpiece to be processed is divided into dense mesh [12], and the rest of the mesh is rough. The workpiece mesh type selects an eight-node thermally coupled hexahedral reduction integration element (C3D8RT), and the total number of elements is 104,550. The tool mesh type selects four-node thermally coupled tetrahedral element (C3D4T), and the total number of elements is 66,665.

| Material          | Density (g·cm⁻³) | Elastic Modulus (GPa) | Poisson's ratio | Thermal expansion rate (10⁻⁶°C⁻¹) |
|-------------------|------------------|-----------------------|-----------------|----------------------------------|
| Ti6Al4V           | 4.43             | 110                   | 0.31            | 9.5                              |
| Tungsten steel (WC-Co) | 15.7             | 524                   | 0.24            | 6.3                              |

In vibration drilling process, the velocity \( v(t) \) of drill in the axial direction can be deduced from Eq. (1):

\[
v(t) = f_r \frac{n}{60} + 2\pi f A \cos(2\pi f t)
\]

Define \( n = 1000 \text{ r/min}, f_r = 0.03 \text{ mm/r}, f = 40 \text{ Hz}, A = 0.06 \text{ mm} \) in the above equation, then the axial feed speed is

\[
v(t) = 0.5 + 4.8\pi \cos(80\pi t)
\]

Unit: mm/s.

4.2. Analysis of simulation results

4.2.1. Axial force

In order to compare and analyze the difference between ALVD and ordinary drilling [13], the comparison of the axial force curves of the two drilling methods from the beginning to the stable period of time (0~4 s) was intercepted. As shown in Figure 5.

![Axial force curves of titanium alloy drilling with different processing methods](image)

Fig. 5 Axial force curves of titanium alloy drilling with different processing methods

It can be seen from Fig. 5 that the axial force of ordinary drilling and ALVD gradually increases with the deepening of the gun drill, and finally gradually stabilizes after reaching the maximum value. After the steady state, the axial forces of both will fluctuate up and down within a certain range. The fluctuation range of the former is between 365 N and 665 N, and the latter is between 161 N and 397 N. Compared with ordinary drilling, the axial force fluctuation amplitude of ALVD is smaller, and the drilling is more stable. At the same time, it can be seen from the Fig. 5 that the maximum axial force of ordinary drilling is 665 N, while the maximum axial force of ALVD is 435 N. After reaching the stable stage (between 2.2 s and 4.0 s), the average axial force of the former is 488N, and the latter is
260 N. Compared with ordinary drilling, the average axial force of ALVD is reduced by about 47%.

4.2.2 Cutting temperature
Titanium alloys are usually accompanied by higher cutting temperatures in the machining process. This is due to their lower thermal conductivity. At the same time, higher cutting temperatures will aggravate tools wear, which severely restricts the processing efficiency of titanium alloys [10]. Fig. 6 is showing the cloud chart of the highest cutting temperature in the simulation process of titanium alloy. Fig. (a) shows that the highest cutting temperature of titanium alloys can reach 544 K under ordinary drilling; and the highest cutting temperature is 483 K under ALVD from Fig. (b), which is relatively ordinary drilling fell by 11%. This is due to the intermittent drilling characteristics of axial vibration drilling, which makes tools and workpieces do not work continuously. During the intermittent period, the temperature will drop instantaneously, reducing tools wear and extending the life of the tool.

![Fig. 6 Cloud charts of the highest cutting temperature during titanium alloy drilling simulation process](image)

5. Conclusion
1) A fixed-amplitude ALVT is designed. Its structure is simple and compact, also easy to apply and maintain. It can be directly installed on the spindle of the machine tool without taking up space on the machine tool table and adding additional excitation devices.
2) Based on ABAQUS finite element software, the difference between the axial force and the cutting temperature of the titanium alloy under two different processing conditions is compared and analyzed. The simulation results show that ALVD can effectively reduce the axial force and cutting temperature, and then significantly improve the drilling conditions and improve the quality of hole processing.

Acknowledgment
Funded Project of Xi'an Shiyou University Graduate Student Innovation and Practice Ability Training. (YCS19112030)

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