Research on the influence of spindle temperature rise of drilling and tapping machine on machining accuracy

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Abstract. With the progress of science and technology, the improvement of product performance, as well as the improvement of user's requirements for product experience, the accuracy of machine tools and equipment is required to be higher and higher. Spindle is an important component of high-speed drilling and tapping machine. The change of its temperature directly affects the accuracy of machining size and appearance of machine equipment. This paper mainly studies the causes of spindle temperature rise and the methods to prevent excessive temperature rise.

1. Introduction

High speed drilling and tapping machine can be used for drilling, tapping, milling and continuous smooth curve processing, with high speed, high precision and high efficiency. The machine adopts the cross sliding table structure, the motion form is that the worktable moves along the X and Y directions, the column is fixed, and the spindle box drives the spindle to move along the Z direction. On the premise of small size and weight of parts, the cross sliding table structure is easy to achieve the requirements of high precision and high dynamic performance of the machine tool, and the whole machine structure is simple.

At present, the spindle speed of drilling and tapping machine at home and abroad is generally high, most of them are 20000 rpm, a few are 24000 rpm or 30000 rpm. The high-speed rotation of spindle core, with large angular acceleration and linear velocity, makes the spindle temperature rise too high, which has always been a stubborn disease of drilling and tapping machine manufacturers. Only by controlling the temperature rise of the spindle of drilling and tapping machine, the dimensional accuracy and appearance accuracy of the machine can be guaranteed. The machining dimensional accuracy includes dimensional tolerance, form and position tolerance, etc., while the appearance accuracy is mainly manifested in the surface roughness, surface knife lines, etc.

In the solution of spindle temperature rise, the current methods mainly include adding z-axis grating ruler, system adaptive thermal compensation and other measures to ensure the machining accuracy of the machine. For the above two measures, the accuracy of grating ruler is very high, but the cost is high; the self-adaptive thermal compensation requires high quality for early data acquisition, later data maintenance and technical personnel. The above two solutions are the follow-up remedial
measures for the spindle temperature rise, and do not solve the machining error caused by the spindle heating at the source.

2. Cause analysis of temperature rise

Cause analysis of temperature rise the main factors of spindle temperature rise are high-speed rotation of bearing, repeated compression of spring during tool change, and cutting heat conduction to spindle.

2.1. Bearing transmission

At present, the spindle bearings of drilling and tapping machines in the market are mostly two groups of angular contact ceramic bearings, which are arranged face to face. Ceramic bearings are widely used in high-speed drilling and tapping machine spindle because of their high temperature resistance, cold resistance, wear resistance, corrosion resistance, magnetoelectric insulation, oil-free self lubrication, high speed and other characteristics. Heat generation and heat transfer of bearing components are important factors affecting the working performance and service life of high-speed rolling bearing. In the process of high-speed movement of spindle, with the increase of rolling bearing speed, the overall temperature of bearing and grease increases through friction heat generation and heat transfer.

2.1.1. A subsubsection.

In high-speed rotation, friction between ceramic bearing elements is the main heat source of bearing temperature change. Therefore, in order to calculate the heat transfer mechanism of ceramic bearing, it is necessary to obtain the heating condition of each element of ceramic bearing.

When the spindle moves at a high speed, the outer ring of the rolling bearing is stationary, and the ceramic ball and the outer ring have a compound motion of relative sliding and rolling.

\[ Q_1 = \int_0^{\tau_0} \tau_q v_q d_1 \]  

Where: \( \tau_q \) - shear stress between roller and outer ring  
\( v_q \) - sliding speed of rolling element relative to outer ring

When the rolling element rotates around the axis at high speed, the rolling element itself rotates and generates heat by friction with the inner raceway:

\[ Q_2 = M_q \omega_q t \]  

Where: \( M_q \) - Friction torque of rolling element  
\( \omega_q \) - Angular velocity of rolling element rotation

When the rolling element is running, it drags relative to the lubricating oil, and the heat generated is as follows:

\[ Q_3 = \frac{1}{2} d_q \bar{f}_x |\omega_q - \omega_p|^{0.61} \]  

Where: \( d_q \) - Diameter of rolling element  
\( \bar{f}_x \) - Average value of rolling element diameter and rolling element friction  
\( \omega_q \) - Rotating angular velocity of lubricating oil  
\( \omega_p \) - Circumferential angular velocity of rolling element

Other fever:

\[ Q_4 = Q_1 + Q_2 \]  

Where: \( Q_4 \) - Friction and heat generation between rolling element and cage  
\( q_2 \) - The friction between cage and grease generates heat

The above are the four forms of spindle ceramic bearing heating, and the total heating amount is:
The heat transfer of high-speed ceramic bearings can be divided into three basic types: convection, conduction and radiation. Through the above three forms, the overall temperature of the spindle increases.

2.2. Frequent tool change

The advantage of drilling and tapping machine lies in the speed of drilling and rigid tapping, and the tool changing speed is the basic attribute of drilling and tapping machine. The tool changing speed of drilling and tapping machine of Shenyang machine tool is 1.4s of tool to tool. According to the preliminary statistics of tool changing times in 2 hours in the fifth sequence of certain project of Shenzhen certain company, the table is as follows:

| Process | Tool change times |
|---------|-------------------|
| Process 1 | 245               |
| Process 2 | 256               |
| Process 3 | 180               |
| Process 4 | 108               |
| Process 5 | 705               |

In the ideal spring compression, only elastic deformation will occur, and the kinetic energy will be completely transformed into the elastic potential energy of the spring. But in practice, in addition to the elastic deformation, there is also a small plastic deformation in the compression process of the spring. Part of the kinetic energy is transformed into the elastic potential energy through the elastic deformation, and the other part is transformed into its internal energy through the plastic deformation:

\[ Q' = \sum_{i=1}^{4} Q_i \]  

(5)

Where:
- \( Q' \): Tool change times
- \( Q_i \): Heat produced by plastic deformation of a tool changing spring

2.3. Cutting heat

When drilling and tapping machine cutting metal, in the cutting area, if it is dry cutting, the temperature is 200-300 °C; if it is wet cutting, the temperature is 50-80 °C. In this cutting area, the cutting edge will cause the workpiece material to deform and cut off. In the milling process, the milling cutter teeth cut in and out of the workpiece intermittently, and the temperature of the cutting edge will rise and fall alternately. With other conditions unchanged, the higher the cutting speed (s) will produce more heat; the higher the speed feed (f) will increase the area of the cutting edge affected by high temperature. Generally speaking, in the intermittent cutting condition dominated by high-speed milling, the selection of cutting edge groove, cutting speed, feed rate and back feed rate of the cutting tool has different degrees of influence on the generation, absorption and control of heat.

2.3.1. Cutting edge groove

It is helpful to control the heat generation to select the proper geometric angle of the milling cutter body, the shape of the cutting edge slot, the number of cutting edges and whether the coating is applied. The hardness of workpiece material and its surface condition determine the selection of tool rake angle. The tool with positive rake angle produces less cutting force and heat, and can also use higher cutting speed. The groove shape of the cutting edge can cause and control the cutting action and cutting force, thus affecting the generation of heat. The standard milling cutter is divided into 2-edge, 3-edge, 4-edge and 6-edge. The more the number of edges, the higher the tool strength, but the less conducive to chip removal and heat removal. In general, the standard uncoated alloy tool is selected for processing aluminum alloy, magnesium alloy and die casting aluminum, and the coated alloy tool
is selected for processing iron, steel, copper and other products. The strength of uncoated tools is lower than that of coated tools, but uncoated tools are sharper than coated tools and more conducive to heat removal.

2.3.2. Selection of cutting parameters
The cutting parameters include cutting speed, feed rate and back feed rate. Increasing the cutting parameters will usually produce more cutting heat, reduce the processing time and improve productivity, but reduce the service life of the tool and the machining accuracy of the workpiece. At this time, reducing the cutting parameters can reduce the temperature to an acceptable level. In machining, it is necessary to select the appropriate cutting parameters.

Generally, the whole machining system will absorb the heat generated in the metal cutting process. 85% of the heat goes into the chip and cutting fluid, about 8% into the workpiece, 5% into the tool, and 2% into the air. Among them, 20% of the heat into the tool goes into the spindle taper hole, and then transfers to the interior through heat transfer. The heat is \( Q'' \)

To sum up, in the process of drilling and tapping machine, the heat generated by the spindle temperature rise is:

\[
Q = Q' + Q'' + Q''' = CMT
\] (7)

3. Influence of temperature rise

3.1. Machining accuracy
As the first choice of 3C industry, high-speed drilling and tapping machine is a kind of high-precision processing equipment integrating speed and precision. The spindle is the core component of high-speed drilling and tapping machine to provide processing initiative. In the process of machine tool operation, the thermal error of machine tool caused by thermal deformation of structure can not be ignored. The research shows that the thermal error accounts for 70% of the total error of the machine tool. Among them, the spindle thermal elongation error is particularly prominent. Along the axis of the spindle, the drilling and tapping machine is in Z direction, which is also the processing error sensitive direction. The accuracy of the spindle has a very important impact on the whole machining process, only high-precision spindle can process high-precision parts. In this paper, the spindle thermal elongation is tested, and the data are shown in the figure below.

![Fig. 1 Statistical chart of spindle temperature rise and thermal elongation](image)

According to the above values, when the temperature changes from room temperature to 90 \(^\circ\)C, the thermal elongation value of the spindle fluctuates to 0.023mm, and the temperature changes most obviously between 45 \(^\circ\)C and 75 \(^\circ\)C. During the process of drilling and tapping machine, the thermal elongation of spindle affects the Z value. With the increase of processing time, the larger the thermal elongation value is, the more influence the machining accuracy of the processed parts.

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3.2. Service life of spindle bearing

The relationship between bearing life and load can be expressed as follows:

$$L_{10} = \left( \frac{f_t C}{P} \right)^e$$

Where:
- $L_{10}$ - Basic rated life
- $f_t$ - The temperature coefficient is selected as shown in Table 2
- $C$ - Basic dynamic load rating
- $P$ - Equivalent dynamic load
- $e$ - Life factor

Table 2 Temperature coefficient table

| Temperature /°C | $f_t$ |
|-----------------|-------|
| <120            | 1     |
| 125             | 0.95  |
| 150             | 0.9   |
| 175             | 0.85  |
| 200             | 0.8   |
| 225             | 0.75  |
| 250             | 0.7   |
| 300             | 0.6   |

It can be seen that the service life of bearing decreases with the increase of temperature, and the higher the temperature is, the greater the gradient of decrease is.

3.3. Service life of tool magazine

Most of the existing drilling and tapping machines in the market are of turret structure. The tool magazine has the characteristics of fast tool changing speed and rapid response, but compared with the manipulator tool magazine, the tool clamp is relatively weak. At present, the maximum speed of drilling and tapping machine is 20000 rpm, which needs 3000 n pulling force in high-speed operation. According to the theory of molecular motion, molecules are always in irregular motion, and the higher the temperature is, the more intense the molecular thermal motion is. With the increase of the spindle temperature and the larger tensile force, it is easier to make the toolholder and spindle cone hole adhere. In the process of continuous "high speed rotation adhesion tool change high speed rotation adhesion tool change", the tool holder is under the action of large intermittent load, which makes the tool holder stick. The fatigue failure at the root of the tool holder will not only affect the service life of the tool holder and tool magazine, but also cause abnormal noise of the tool magazine.

![Stress diagram of spindle taper shank](image)
4. Analysis of measures

4.1. Select appropriate processing parameters
The cutting parameter is the main source of axial and radial force on the spindle. In order to make full use of the cutting performance of the cutting tool and machine tool, the reasonable cutting parameter can be selected in the process of machining, and the higher productivity and lower processing cost can be obtained on the premise of ensuring the processing quality. For different machining properties, to make the cutting parameters for cutting is to determine the cutting depth reasonably on the basis of selecting the tool material and geometric parameters. Feed \( f \) and cutting speed \( v_c \).

In rough machining, high metal removal rate and necessary tool life should be ensured as far as possible, so the maximum cutting depth is generally preferred \( d_p \). Secondly, select a larger feed rate \( f \), and finally determine the appropriate cutting speed \( v_c \) according to the tool life requirements. In addition to leaving finishing allowance, all the allowance should be cut off as far as possible in one milling. When the machining allowance is too large, the stiffness of the process system is low, the power of the machine tool is insufficient, and the tool strength is not enough, the tool can be moved several times.

The machining allowance of semi-finish machining and finish machining is generally small and can be cut off at one time, but sometimes in order to ensure the machining accuracy and surface quality of the workpiece, secondary milling can also be used. When milling for many times, the cutting depth of the first cutting should be larger, generally 2/3~3/4 of the total machining allowance.

The finishing allowance of drilling and tapping machine is mostly between 0.03-0.08, and the workpiece is processed by one milling, with high rotation \( v_c \). Large feed \( f \), small cutting amount \( d_p \). To ensure the processing of high-quality products.

Only by selecting reasonable cutting parameters can the performance of the machine be brought into full play, and at the same time, the temperature of the main shaft will not rise too much due to the excessive bearing force of the main shaft, which will affect the machining accuracy of the machine.

4.2. Optimize the installation mode of spindle bearing
Reasonable installation and debugging methods, suitable installation tools and dust-free workshop environment are the necessary conditions for bearing to obtain higher speed, lower temperature rise and higher accuracy. It is very important to optimize the installation method of the spindle bearing to improve the service life of the spindle. Assuming that the material of the spindle is of the same material, the optimized installation method can ensure the uniformity of the radial and axial force of the spindle bearing, such as hot installation method, uniform pressure installation method and so on. The precision of ceramic bearing is grade 6, that is to say, the machining precision of inner axis and outer axis assembled with spindle bearing is grade 6 respectively, so as to ensure that the subsequent dynamic balance reaches grade G0.4. The spindle bearing of high-speed drilling and tapping machine is installed with interference fit. When the spindle diameter \( D \) is not less than 80mm, the thermal installation method is adopted, and it is heated to 80 °C for installation.

High speed drilling and tapping machine spindle bearing preloading method, can improve the stiffness of the bearing, but the preloading and should be moderate, otherwise the work done by bearing friction will be converted into heat, which will lead to excessive temperature rise of the spindle, resulting in damage to the bearing system, drilling and tapping machine spindle according to experience, preloading 500kg-800kg is more appropriate.

4.3. Installation of spindle oil cooler
Spindle is an important part of drilling and tapping machine. Due to the high rotation speed of the spindle of drilling and tapping machine, the rotation speed of the spindle of conventional drilling and tapping machine is 20000 rpm, a large amount of heat is generated during operation, which causes the temperature rise of the spindle, thus affecting the normal work of the spindle. At present, some
domestic machine tool factories have installed oil cooler on the spindle. Under the action of the oil pump, the cooling oil of the oil cooler is forced to flow between the outer ring of the spindle and the spindle box. According to the second law of thermodynamics, where there is a temperature difference, there must be heat transfer, and the temperature is always transferred from the high temperature object to the body temperature object, that is, the heat of the spindle is transferred to the cooling oil, and then the cooling oil enters the oil cooler, which is cooled by the compression pump, so as to be recycled.

4.4. Reasonable use of cutting fluid
Controlling the heat generated in metal cutting will reduce the heat transfer to the spindle direction and cool the heat source, so as to effectively reduce the temperature rise of the spindle in unit processing time. Cutting fluid and cutting oil can not only ensure the accuracy and surface finish of the workpiece, but also effectively control the heat of machining.

5. Conclusion
In the process of high-speed drilling and tapping machine operation, with the increase of operation time and speed, the spindle temperature rise is more obvious, which not only affects the service life of drilling and tapping machine, but also affects the dimensional accuracy and surface roughness of the product. This paper introduces three main factors that affect the spindle temperature rise of drilling and tapping machine, and three measures to prevent excessive temperature rise of spindle, which provides reference for the research and application of spindle temperature change of high-speed drilling

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