Analysis of Turning Process of Slim Shaft Based on Finite Element Method

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Abstract: Based on the analysis of turning bending deformation of the ordinary turning (forward) machining method of the slender shaft, a reverse turning machining method of the slender shaft is proposed, the bending deformation analysis of the reverse turning of the slender shaft is performed, the finite element method is used. The machining accuracy of the two turning solutions is simulated respectively. Finally, it is verified through experiments that reverse turning can improve the turning accuracy of slender shaft parts to a certain extent.

1. Introduction
For shaft parts with an aspect ratio greater than 20, they are collectively referred to as slender shafts. Due to their poor rigidity, slender shaft parts are prone to bending deformation during turning, and it is difficult to obtain the ideal machining size\(^1\), which is considered to be turning. At present, domestic and foreign researches on the improvement of machining precision of slender shafts are mainly divided into two categories, namely: 1) Change the work piece clamping method, and improve the traditional chuck-top clamping to two top clamping. 2) Change machining process parameters such as cutting force. Based on the mechanical modeling and force analysis of traditional turning methods, this paper proposes a machining method for reverse turning and establishes a mechanical model for reverse turning to analyze its machining characteristics. The element method\(^2\) analyzes and compares the simulation results of two kinds of turning machining accuracy, and points out that the reverse turning method can improve the turning precision of slender shaft parts to a certain extent.

2. Bending deformation analysis of slender shaft turning

2.1. Analysis of bending deformation in forward turning
The work piece is clamped using the traditional chuck-top clamping method, which can be simplified to solve a one-time statically indeterminate beam problem\(^3\), and its mechanical model is shown in Figure 1. During forward turning, the turning tool starts from the machine tool feeds in the direction of the chuck. The cutting component force \(F_x\) causes the work piece to be pressed. For the slender shaft, it will cause obvious bending deformation; \(F_y\) causes the work piece to bend, affecting the work piece processing error.

According to the basic theory of material mechanics, the reaction force at point B can be written as:

\[
F_B = \frac{F_x^2}{2l^2} \left(3 - \frac{x}{l}\right)
\]

According to the mechanical balance equation \(\Sigma y = 0\), the reaction force at point a is obtained as:
\[ F_A = F_y - \frac{F_y x^2}{2l^2} (3 - \frac{x}{l}) \]

**Figure 1.** Force analysis of forward turning of a slender shaft

According to the coordinates set in Figure 1, the winding degree is negative. Therefore, if \( F_x \) is specified to make the work piece pressurized, the bending moment equation on the section at a distance \( x \) from the A end is:

\[ M(x) = F_A x - F_y y, (0 \leq x \leq 1/2) \]

The approximate differential equation of the torsion curve \( y(x) \) is:

\[ y''(x) = \frac{d^2 y}{dx^2} = \frac{M(x)}{EI} \]

In the formula, \( E \) is the elastic modulus of the material; \( I \) is the moment of inertia of the section with respect to the \( x \)-axis; finishing:

\[ EI y''(x) = \frac{F_y}{2l^2} (x^4 - 3lx^3 + 2l^2 x) - F_y y \]

\[ k^2 = \frac{F_x}{EI}, T = \frac{F_y}{2l^2 EI}, p = \frac{3F_y}{2lEI}, Q = \frac{lF_y}{EI} \]

make:

\[ y''(x) + k^2 y = Tx^4 - px^3 + Qx \]

The general solution of equation (1) is:

\[ y = C_1 \cos(kx) + C_2 \sin(kx) + \frac{T}{k^2} x^4 - \frac{p}{k^2} x^3 - \frac{12T}{k^4} x^2 + (6\frac{p}{k^3} + \frac{Q}{k^2}) x + \frac{24T}{k^6} \]

Substitute the boundary conditions:

When \( x = 0, y = 0 \),

\[ C_1 = -\frac{24T}{k^6} \]

When \( x = 1 \) and \( y = 0 \),

\[ C_2 = \frac{1}{\sin(kl)} \left[-\frac{T}{k^2} l^4 + \frac{p}{k^2} l^3 + \frac{24T}{k^4} l^2 - (6\frac{p}{k^3} + \frac{Q}{k^2}) l - \frac{24T}{k^6} + \frac{24T}{k^6} \cos(kl)\right] \]

So the special solution of equation (2) is:

\[ y(x) = -\frac{24T}{k^6} \cos(kx) + \frac{1}{\sin(kl)} \left[-\frac{T}{k^2} l^4 + \frac{p}{k^2} l^3 + \frac{24T}{k^4} l^2 - (6\frac{p}{k^3} + \frac{Q}{k^2}) l - \frac{24T}{k^6} + \frac{24T}{k^6} \cos(kl)\right] \times \sin(kx) \]

\[ + \frac{T}{k^2} x^4 - \frac{p}{k^2} x^3 - \frac{12T}{k^4} x^2 + (6\frac{p}{k^3} + \frac{Q}{k^2}) x + \frac{24T}{k^6} \]  

\( (0 \leq x \leq 1/2) \)
2.2. Analysis of bending deformation in reverse turning

The mechanical model is shown in Figure 2. In reverse turning, the turning tool is fed from the machine tool chuck to the tail stock. At this time, the cutting force \( F_x \) in the cutting direction causes the work piece to be stretched without radial bending deformation. At this time, the bending deformation of the work piece can be considered to be caused only by \( F_y \). Using the same method, the equation of the bending curve of the work piece can be obtained as:

\[
y = \frac{F_y}{2l^2EI} \left( \frac{x^6}{30} - \frac{3l}{20} x^4 + \frac{l^3}{3} x^3 \right) - \frac{13F_y l^3}{120EI} x \quad (0 \leq x \leq 1/2)
\]

3. Finite element analysis of slender shaft turning

Known conditions: the length of the work piece is 800mm, the diameter is 30mm, the aspect ratio is 26.67, the diameter is greater than 20, which belongs to the slender shaft. The work piece material is 45 steel, the density is 7800kg / m\(^3\), the poisson ratio is 0.3, and the elastic mold the quantity \( E = 210\text{GPa} \). In this simulation analysis, the slender shaft is separated into 80 nodes along the axial direction. Using ANSYS software, the tool acts on the slender shaft 1/4, 1/2, 3/4. The analysis\(^4\) was performed at 4 places, the slender shaft bending deformation was obtained, as shown in Figure 3.

![Bending deformation at 1/4](image1)
![Bending deformation at 1/2](image2)
![Bending deformation at 3/4](image3)

Figure 3. Bending deformation of the slender shaft during forward turning

Using the same method to perform reverse turning analysis on the slender shaft using the ANSYS, the reverse turning bending deformation map of the slender shaft is obtained, as shown in Figure 4.
The above simulation results are analyzed and calculated, the forward and reverse turning bending deformation parameter table of the slender shaft is obtained, as shown in Table 1:

| Cutting direction | Bending deformation at different positions (mm) |
|-------------------|-----------------------------------------------|
|                   | 1/4               | 1/2           | 3/4               |
| Forward turning   | 0.101             | 0.115         | 0.0445            |
| Reverse turning   | 0.0995            | 0.108         | 0.0427            |

It can be seen from Table 1 that no matter the forward turning or reverse turning, the maximum bending deformation of the slender shaft appears near 1/2 of the shaft length\(^{[5]}\); comparing the forward and reverse parameters, it is found that whether 1/4 locations, 1/2 locations and 3/4 locations, the bending deformation of reverse turning is about 5% smaller than that of forward turning. It can be seen that the reverse turning solution can improve the machining accuracy of slender shaft turning to a certain extent.

4. Experimental demonstration

4.1. Experimental conditions
Machine tool: CK360; test piece: 45 steel, work piece size Φ32 × 800mm; turning tool: carbide steel YT15; measuring tools: V-type iron, dial indicator, magnetic stand, etc.

4.2. Experimental parameter
Clamping method: chuck-top installation; spindle speed: 600r / min; back feed amount: 1mm; feed speed: 80mm / min. In order to eliminate errors caused by manual feed speed difference during forward and reverse turning in the experiment, the same CNC lathe was used, and the same cutting parameters were used to complete the turning of the slender shaft.

4.3. Measurement of experimental results
(1) When measuring, support both ends of the journal on the V-shaped iron;
(2) The shaft is divided into 4 measurement sections along the length direction. The surface of the measurement point must be selected on a smooth shaft section or machined surface without burrs, pits,
blisters, or pits;

(3) Divide the shaft end face into 8 equal parts as the measurement points, and the initial "1" is the key point of the key-way on the shaft.

(4) Install the dial indicator at each axial length measurement position. The measuring rod should pass perpendicular to the shaft surface and center through the axis. Adjust the small pointer of the dial indicator to the middle of the range, and adjust the large pointer to "0". Turn it slowly for 1 week, and the dial indicator hands should return to the starting value.

(5) Measure and record the dial indicator readings point by point. According to the record, calculate the sloshing value of the axis in the same section, and take 1/2 of the value as the bending value of the section. The measurement results are shown in Table 2.

|     | 1/4          | 1/2          | 3/4          |
|-----|--------------|--------------|--------------|
| 1   | 0            | 0            | 0            |
| 2   | 6            | 5            | 6            |
| 3   | 11           | 10           | 12           |
| 4   | 17           | 15           | 18           |
| 5   | 23           | 21           | 24           |
| 6   | 16           | 15           | 18           |
| 7   | 11           | 10           | 12           |
| 8   | 6            | 5            | 6            |
| Sway value | 0.23     | 0.21     | 0.24     |
| Bending value | 0.115 | 0.105 | 0.120 |

From the results, it is known from the comparison of experimental measurement data that reverse machining of slender shafts can achieve better machining accuracy, which is basically consistent with the results of finite element analysis.

5. Conclusion
Simulation and experimental results show that the method of turning slender shafts by reverse turning can improve the turning accuracy of slender shafts to a certain extent, providing a theoretical basis for reverse turning of slender shafts, and the reliability of finite element method in the analysis of slender shaft turning is also verified.

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