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Research on precision turning method of slender shaft

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ABSTRACT

Based on the mechanical modeling and force analysis of ordinary turning, the method of slender shaft turning with symmetric dual-tools is introduced, establishing the mechanical model and force analysis of double tools turning, using the finite element method for simulation analysis of both turning machining accuracy, obtaining the turning data through the experiment, drawing the diameter-axis displacement coordinate graph of slender shaft, the results show that turning with symmetric dual-tools can obviously improve the machining accuracy.

KEYWORDS

Slender shaft;
Mechanical modeling;
Dual-tools turning;
Finite element method.

INTRODUCTION

Slender shaft generates bending deformation due to its poor rigidity, weak flexural capacity, the factors of cutting forces, clamping force, vibration, and cutting heat in the turning process, it actually changes the machining position between the parts and the tool, reducing the machining accuracy of the parts, it is difficult to obtain the ideal surface quality and geometry shape, resulting in its processing has been considered the problem in machining process. The traditional methods of solving such problems can be divided into three types: a. increasing parts rigidity, such as installing center rest or follow rest in the process; b. selecting the clamping method, such as elastic rotating top method; c. improving the geometry of the tool. A lot of practice proves that the traditional methods can meet the machining accuracy in certain extent, but it can not achieve greater breakthroughs in the modern production with low-cost, high-volume and high precision. Therefore, through the improvement of traditional processing method, the article proposes symmetric dual-tools turning, using the finite element method for simulation analysis of both turning machining accuracy, obtaining the turning data through the experiment, drawing the diameter-axis displacement coordinate graph of slender shaft, the results show that turning with symmetric dual-tools can obviously improve the machining accuracy.

THE BENDING DEFORMATION MODEL OF ORDINARY TURNING

Due to the bending deformation of feed force F_x along the axis direction acting on the slender shaft can be neglected during the mechanical processing of slender shaft, the bending deformation of machining slender shaft mainly comes from the force F_y, F_z that act on the Y-axis and Z-axis direction. The cutting force changes the actual back engagement of the cutting edge during the machining, affecting the final dimension of the slender shaft, and generating the processing error. In the force analysis, the clamping chuck end is reduced to a fixed end, limiting all degrees of freedom; the end of the thimble is simplified as a rotary hinge, limiting degree of freedom of z-axis direction.

The force model as shown in Figure 1, radial force F_z generates bending deformation in the z direction of the slender shaft. According to the equation of static equilibrium:

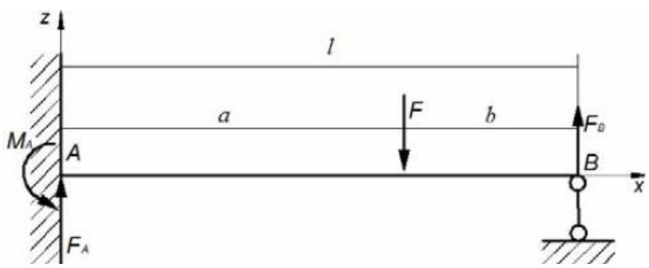

Figure 1 : The bending model of slender shaft under radial force

$$\sum F_Z = F_B + F_A - F = 0 \quad (1)$$

$$\sum M_A = M_A - F\,a + F_B l = 0 \quad (2)$$

Since only two equations to solve three unknown quantity, a deformation equation must be added, using the singular function method to write the deflection curve equation of slender shaft, defining the singular function: if $x > a$, then $< x - a >= (x - a)$

$$EIw'' = F_A < x >^1 - M_A < x >^0 - F < x - a >^1 \quad (3)$$

Integrating the equation (3), we get:

$$EIw' = F_A \frac{< x >^2}{2} - M_A < x >^1 - F\frac{< x - a >^2}{2} + C_1 \quad (4)$$

According to the boundary condition: $x = 0$, $w' = 0$, we get: $C_1 = 0$

Integrating the equation (4), we get:

$$EIw = F_A \frac{< x >^3}{6} - M_A \frac{< x >^2}{2} - F\frac{< x - a >^3}{6} + C_2 \quad (5)$$

According to the boundary condition: $x = 0$, $w = 0$, we get: $C_2 = 0$

Substituting the boundary conditions ($x = l$) into the equation (5), we get:

$$0 = F_A \frac{l^3}{6} - M_A \frac{l^2}{2} - F\frac{b^3}{6} \quad (6)$$

According to the formula of (1), (2), (3), (4), (5), we get:

$$F_A = \frac{Fb}{2l^3}(3l^2 - b^2),\ F_B = \frac{Fa^2}{2l^3}(2l + b),\ M_A = \frac{Fb}{2l^2}(l^2 - b^2)$$

So the differential equation of the deflection curve is:

$$w = \frac{1}{EI}\left[F_A \frac{< x >^3}{6} - M_A \frac{< x >^2}{2} - F\frac{< x - a >^3}{6} \right]$$

Symmetric dual-tools design

The key technology of processing slender shaft is to solve the problem of parts' bending deformation, the main factor of parts' bending deformation is the cutting force of tool, so we can make the following considerations: reducing cutting forces such as the use of small cutting parameters; changing the force distribution acts on the parts such as installing symmetric dual-tools. Thus, on the basis of summing up traditional processing method, the paper presents the program of dual-tools turning slender shaft. The basic structure of dual-tools turning shows in Figure 2.

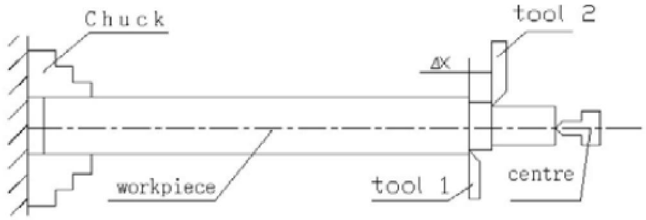

Figure 2 : Symmetric two tools turning structure

Two tools is not fully symmetrical distribution, the axial spacing is Δx, so the original processing is divided into two processing, the cutting force of each tool is reduced.

Symmetric double tools turning mechanics analysis

We know that the cutting force is generated in the turning process, it can be decomposed into an axial cutting force F_x, tangential cutting forces F_z and radial cutting forces F_y, and three forces will cause bending deformation in each direction. Among them, radial cutting forceshas the greatest effect on machining accuracy.

Double-tools turning use the clamping method of elastic rotating top. In the analysis of force, the clamping chuck end is reduced to a fixed end, limiting all degrees of freedom; the other end of the thimble is simplified as a rotary hinge, limiting degree of freedom of y-axis direction. So that it simplifies the problem of a statically indeterminate beam, the simplified mechanical model of dual-tools turning shows in Figure 3.

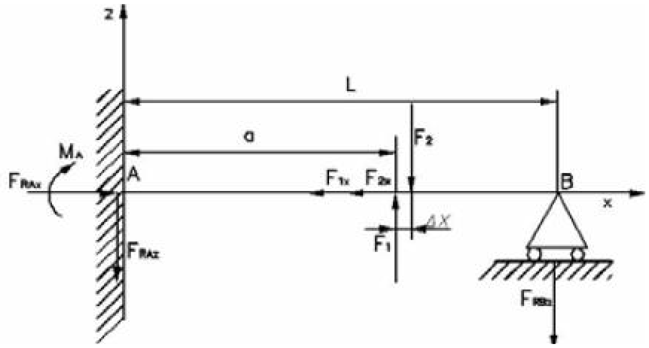

Figure 3 : Symmetric double-tools turning mechanical model

As the coordinates shown in Figure 3, F_1, F_2 represents the radial force of the tools, when the back engagement of the cutting edge of the double tools is not equal, the relationship between them is $F_1 \approx nF_2$, defined the down deflection is negative, $(\omega_B)_{F_1}$, $(\omega_B)_{F_2}$, $(\omega_B)_{F_{Bz}}$ respectively represents the deflection which F_1, F_2, F_{Bz} acts on the terminal B. Because the B end is hinged support, it should not have the vertical displacement, deformation coordination equation is listed:

$$\omega_B = (\omega_B)_{F_1} + (\omega_B)_{F_2} + (\omega_B)_{F_{Bz}} = 0 \qquad \textbf{(7)}$$

$$(\omega_B)_{F_1} = \frac{F_1 a^2}{6EI}(3l - a) \qquad \textbf{(8)}$$

$$(\omega_B)_{F_2} = -\frac{F_2 (a+\Delta x)^2}{6EI}\left[3l - (a+\Delta x)\right]$$

Δx is very small relatively to l, it can be ignored. So:

$$(\omega_B)_{F_2} = -\frac{F_2 a^2}{6EI}\left[3l - a\right] \qquad \textbf{(9)}$$

$$(\omega_B)_{F_{Bz}} = -\frac{F_{Bz} l^2}{3EI} \qquad \textbf{(10)}$$

According to the empirical formula of tool cutting force: $F = C_{F_y} a_p^{xF_y} f^{yF_y} v_c^{nF_Y} K_{F_y}$ in the machining conditions of the same geometry parameters of the tool, workpiece material and the feed speed, the tool cutting force is mainly decided by the back engagement of the cutting edge a_p, because the index xF_y of the back engagement of the cutting edge a_p is close to 1 in general experimental formula of cutting force, so the cutting force F is approximately proportional to the back engagement of the cutting edge , For the convenience of calculation, we assume $a_{p1} = 2d$、$a_{p2} = d$, and let

$$F_1 = 2F_2 \qquad \textbf{(11)}$$

According to the formula of (7), (8), (9), (10), (12) we get:

$$F_{RBy} = \frac{F_2}{2}\left(3\frac{a^2}{l^2} - \frac{a^3}{l^3}\right) \qquad \textbf{(12)}$$

According to the equation of static equilibrium $\sum F_y = 0$, we get:

$$F_{RAy} = F_2 - F_{RBy} \qquad \textbf{(13)}$$

According to the equation of static equilibrium $\sum F_X = 0$, we get:

$$F_{RAx} = F_{1x} + F_{2x} \qquad \textbf{(14)}$$

According to the equation of static equilibrium $\sum M_A = 0$, we get:

$$M_A = F_1 a - F_2(a + \Delta x) - F_{RBy} l$$

Simplification is:

$$M_A = \frac{F_2 l}{2}\left(2\frac{a}{l} - 3\frac{a^2}{l^2} + \frac{a^3}{l^3}\right) \qquad \textbf{(15)}$$

The approximate differential equation of deflection curves at $0 < x < a$ can be written as:

$$EI\frac{d^2 y}{dx^2} = F_{RAy} x - M_A + F_{RAx} y \qquad \textbf{(16)}$$

Formula (10) for second order constant coefficient non-homogeneous linear differential equation, using the boundary conditions: $x = 0, y = 0 and x = l, y = 0$ and mathematical knowledge, we get:

$$w = C_1 e^{kx} + C_2 e^{-kx} + \frac{M_A - F_{RAy} x}{F_{RAx}} \quad 0 \le x \le a \tag{17}$$

Among them:

$$C_1 = \frac{-kM_A + F_{RAy}}{2kF_{RAx}} \quad C_2 = \frac{-kM_A - F_{RAy}}{2kF_{RAx}}$$

Finite element model of the dual-tools turning

The model of simply supported beam is established which is based on the model of double tools turning, it is based on the beam theory, The chuck is simplified as a fixed support, rotary top is simplified as a hinge support, the lengthen of slender shaft is l, Slender shaft is discretized into 10 nodes for analysis by using the finite element method, node number as shown in Figure 4, node 1 is a fixed end, node 100 is Hinged Support, F_1, F_2 is acted on node 7, the dual-tools turning simulation model is shown in Figure 4.

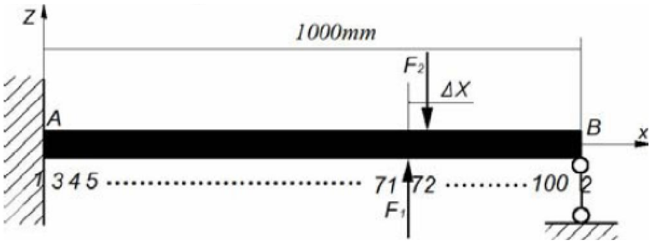

Figure 4 : The symmetric dual-tools turning simulation model

Finite element analysis

Known conditions: The length of slender shaft is 1000 mm, diameter is 50 mm, material is 45 steel, density is $7.8g/cm^3$, Poisson's ratio is 0.3, acceleration of gravity is $9.8N/kg$, rotational speed is $600rad/s$, feed speed is $0.5mm/r$, $E = 2.1e11Pa$. In turning with two tools, the back engagement of the cutting edge of tool 1 and tool 2 is respectively 1.5 mm, 05 mm; the back engagement of the cutting edge is $2mm$, in ordinary machining. In the machining of dual-tools, $F_1 = 107N$、$F_2 = -38.4N$; In the machining of ordinary machining $F=132N$.

Figure 6 is the force deformation of slender shaft after ordinary lathe machining, maximum deformation position of the slender shaft is near the $\frac{l}{2}$, the maximum displacement is 18.4um. Figure7 is the force deformation of slender shaft by turning with two tools, maximum deformation position of the slender shaft is near the, the maximum displacement is 9.84um. Processing the same cutting depth of slender shaft, the maximum deflection of machining with dual-tools （ω_2）is smaller than ordinary machining （ω_1）, the relationship is about $\omega_2 \approx \frac{1}{2}\omega_1$. The simulation results show, slender shaft turning with two symmetric tools meets the machining accuracy.

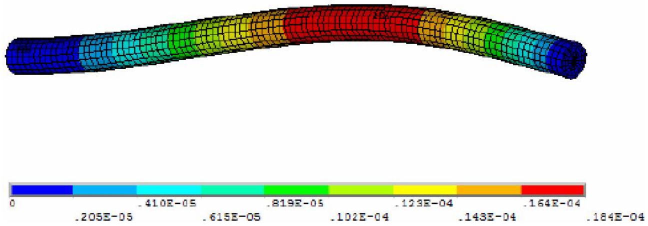

Figure 6 : Part deformation after ordinary machining

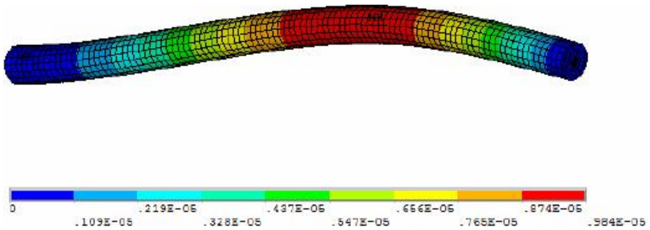

Figure 7 : Part deformation after dual-tools machining

EXPERIMENT

Experiments using NZ-S1500/1000 double turret lathe, material is 45 steel, diameter is 34 mm, length is $700mm$, measurement tools using spiral micrometer caliper. Tool selection: Carbide indexable turning tools; tool geometry: tool cutting edge angle $K_r = 90^0$, rake angle $g_0 = 15^0$, tool cutting edge inclination angle $l_s = 0^0$, tool orthogonal clearance $a_0 = 6^0$; processing parameters: ordinary turning cutting depth $a_p = 2mm$, dual-tools turning cutting depth: $a_{p1} = 1mm$, $a_{p2} = 1mm$; feed speed is $0.6mm/r$; cutting speed is $150m/min$.

The diameter of slender shaft is D=34mm used in

TABLE 1: The experimental data

Abscissa	0	50	100	150	200	250	300	350
Number 1	30.000	30.012	30.021	30.036	30.044	30.055	30.070	30.077
Number 2	30.000	30.005	30.008	30.010	30.013	30.010	30.009	30.005
Abscissa	400	450	500	550	600	650	700	
Number 1	30.082	30.077	30.064	30.055	30.045	30.032	30.024	
Number 2	30.002	29.995	29.992	29.988	29.989	29.990	29.994	

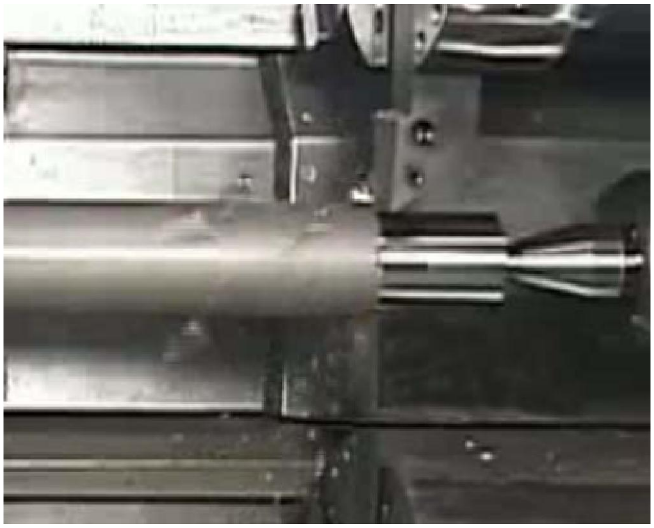

Figure 8 : Machining of ordinary lathe

Figure 9 : Machining of dual-tools

the experiment, the effective length is $l = 700mm$, aspect ratio is 20.58, which is belong to the machining areas of slender shaft, the ideal size of slender shaft processing should be $30mm$, as shown in Figure 8, the experiment number is 1, which is the ordinary machining of slender shaft; as shown in Figure 9, the experiment number is 2, which is the dual-tools turning with slender shaft, the distance of the dual-tools is $\frac{l}{100} = 7mm$, two groups of turning all use the top clamping chuck, after processing, measuring the diameter of the slender shaft in every $50mm$, getting 14 groups diameter data of the slender shaft, measurement results are shown in TABLE 1.

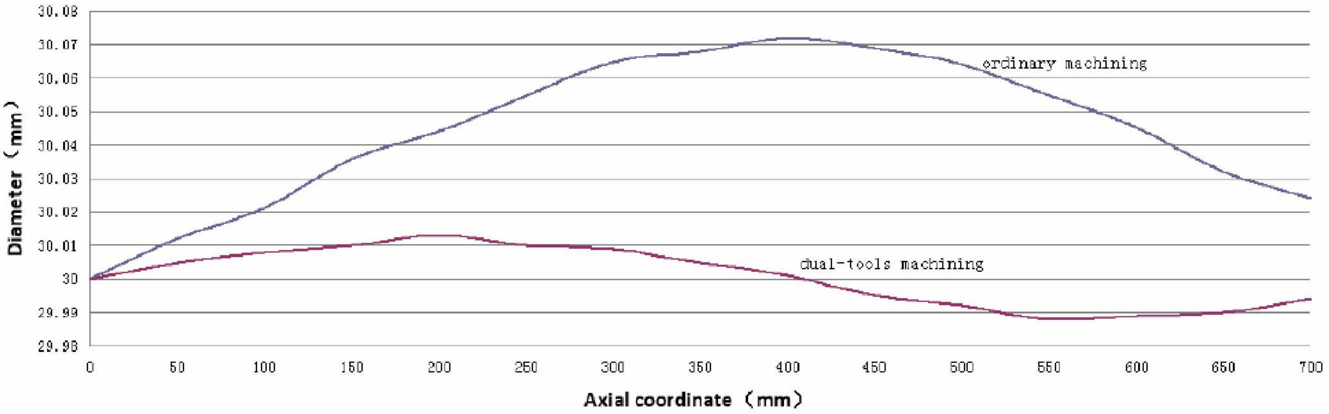

Figure 10 : The date comparison of slender shaft diameter

Using the Excel software, using slender shaft diameter as the vertical axis and the axial coordinates as the abscissa, setting the slender shaft chuck fixed end as the origin of coordinates, drawing the curve of position coordinates in machining slender shaft, as shown in Figure 10.

Although the experimental curves and simulation curves are different, but the overall trend of the curves remained the same, using dual-tools turning is very obvious to improve the machining accuracy of slender shaft, dual-tools turning can meet the design objective to improve the machining accuracy of slender shaft.

CONCLUSION

Slender shaft turning with two symmetric tools effectively solve the problem of bending deformation by changing the distribution of turning forces, it solves the key factors which decide processing dimension error of slender shaft, and significantly improve the machining surface quality and geometrical accuracy.

The cutting force will cause bending deflection ω_1 due to the use of ordinary lathe machines slender shaft, in the same processing condition of the geometric parameters of cutting tool, workpiece material and feed speed, using the dual-tools method to process the same slender shaft, and cutting force relationship between tool 1 and tool 2 is $F_1 = NF_2$, the cutting force causes the parts bending deflection ω_2, from the results of theoretical analysis solution, parts bending deflection is proportional to the force, it can be deduced from the relationship between ω_1 and ω_2, it is approximately: $\omega_2 = \frac{N-1}{N+1}\omega_1$

According to the tool life experience formula $T = \frac{C_T}{v_c^m f^g a_p^h}$ (the value of h is close to 1), in the case of the other factors is constant, double tools turning reduces the back engagement of the cutting edge a_p, and two knives processing at the same time, it greatly reduces the unit energy consumption and cost, improve work efficiency, and meet the production requirements of the modern enterprise.

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