Parameter Optimization of Piston Rod Rough Turning Based on Quadratic Orthogonal Regression

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Abstract: this paper takes the piston rod as the research object and establishes the mechanical model of piston rod. In order to solve the problem that during the piston rod coarse processing, due to the cutting parameters, the cutting force produces radial bending deformation. This paper uses the quadratic orthogonal regression design to optimize the cutting parameters which affect the cutting force and uses the finite element software to optimize the calibration.

1. Introduction

The piston rod used as standard cylinder with SC125×800 standard is used as the research object. The basic size is Φ 32 x 80 mm; length to diameter ratio is 25; and it belongs to the typical slender shaft part class. In the production practice, the main processing process of piston rod is heat treatment, straightening, turning, grinding, polishing chrome, etc., and turning is its processing basis. However, during rough turning of piston rod type slender shaft parts, due to the effect of turning force and its rigidity, it is easy to produce radial bending deformation, geometric error of waist drum and geometrical error of bamboo node, which seriously affects the processing quality. The stiffness of the workpiece is affected by its own material and geometrical dimension and belongs to the inherent characteristics of the workpiece. Therefore, based on the influence of rough turning cutting force cutting parameters as the research object, with the parameters in the ranges recommended by the Metal Cutting Manual, using the method of quadratic orthogonal regression test, this paper optimizes three main parameters including the cutting speed, feed rate, cutting depth, and by using the finite element software to analyze cutting deformation before and after optimization, provides experiment basis for the reliability of optimization results.

2. Piston Rod Turning Mechanics Model

The chunk frequently used for piston rod turning, tailstock tip clamping, positive turning. According to the load condition of piston rod, the mechanical model of piston rod turning is established. See Figure 1. The three-jaw chuck of machine tool spindle can be reduced to a fixed end constraint according to its constraint on the freedom of the workpiece. It restricts the movement and rotation of piston rod along horizontal direction and vertical direction. The top end of machine tool can be reduced to movable hinge support. The tip only limits the movement of the piston rod along the direction perpendicular to the support plane, so that the piston rod can be simplified as the beam structure, forming the super-static and simple beam model.
3. Optimization of Rough Turning Parameters

For the optimization of rough turning process parameters, the paper adopts the quadratic orthogonal regression test design. Orthogonal regression design can design the experimental scheme by using the orthogonal table scientifically before the experiment. It can also analyze the main degree of influence of each related factor on the test results after the experiment and finally get the correct analysis result.

3.1 Evaluation Indicators Determination and Factors Selection

Because the main factor affecting the radial bending deformation of piston rod is turning force, and the factors affecting the turning force mainly include cutting speed, feed speed and cutting depth. Therefore, the maximum bending deformation \( y \) of the piston rod is selected as the evaluation index and the cutting speed \( (X_1) \), feeding speed \( (X_2) \) and cutting depth \( (X_3) \) of the piston rod in the rough process of piston rod are selected as the three factors. The following equation is obtained by quadratic orthogonal regression:

\[
y = a_0 + \sum_{j=1}^{3} b_j x_j + \sum_{i<j}^{3} b_{ij} x_i x_j + \sum_{j=1}^{3} b_{jj} x_j^2
\]  

(2.1)

In the formula, \( a_0 \) is a constant and \( b_j, b_{ij}, b_{jj} \) all are the regression coefficients. \( b_j x_j \) is a linear term, with three in total. \( b_{ij} x_i x_j \) is cross term, with \( t_i = C_3^1 = 3 \) terms in total; \( b_{jj} x_j^2 \) is binomial term, with three in total.

3.2 The Level of Factors Determination and Normalization

First, the upper and lower limits of the three factors of the piston rod test are determined: the object of this study is the piston rod of cylinder (oil cylinder) which is suitable for SC125 x 800, and its diameter ratio reaches 25, which belongs to the typical slender shaft part. Refer to the recommended cutting parameters of the Metal Cutting Manual (third edition) on the long and thin axle thick cars, and determine the range of variation of the cutting speed \( (X_1) \) of the piston rod in the thick car \( (27~37) \text{ m/min} \); the change range of feed velocity \( (X_2) \) is \( (0.3~0.35) \text{ mm/r} \); the variation range of cutting depth \( (X_3) \) is \( (2~4) \text{ mm} \).

According to the factor coding of the control factor \( x_j \), the corresponding calculation formula is:

\[
x_{0j} = \frac{x_{1j} + x_{2j}}{2}
\]  

(2.2)

Where:

\( x_{0j} \) is the zero level of the jth factor;
$x_{0j}$ is the lower level of the $j$th factor;

$x_{0j}$ is the upper level of the $j$th factor;

$$\Delta_j = \frac{x_{2j} - x_{0j}}{\gamma} \quad (2.3)$$

Where:

$\Delta_j$ is the range of the $j$th factor;

$\gamma$ is the star arm (the distance between the asterisk point and the center point), select the basic orthogonal table of $L8(2^7)$, and select $\gamma = 1.215$.

Then normalize the factors:

$$z_j = \frac{x_j - x_{0j}}{\Delta_j} \quad (2.4)$$

The normalized factor level coding is shown in Table 1, and the final test solution is shown in Table 2.

### Table 1. Normalizing Factor Level Coding Table

| Normalized factors | Factor level ($\gamma = 1.215$) |
|--------------------|----------------------------------|
| $z_i$              | $\gamma$ | -1 | 0  | 1  | $\gamma$ |
|                    | 27       | 27.886168 | 32 | 36.113831 | 37 |
| $z_2$              | 0.3      | 0.304431  | 0.325 | 0.345569 | 0.35 |
| $z_3$              | 2        | 2.177233  | 3   | 3.822767 | 4  |

### Table 2. Test Scheme of Piston Rod Rough Turning

| Test No. | $z_1$ | $z_2$ | $z_3$ | Turning rate $v_c (m/min)$ | Feeding rate $f (mm/r)$ | Cutting depth $a_p (mm)$ |
|----------|-------|-------|-------|----------------------------|-------------------------|--------------------------|
| 1        | 1     | 1     | 1     | 36.113831                  | 0.345569                | 3.822767                 |
| 2        | 1     | 1     | -1    | 36.113831                  | 0.345569                | 2.177233                 |
| 3        | 1     | -1    | 1     | 36.113831                  | 0.304431                | 3.822767                 |
| 4        | 1     | -1    | -1    | 36.113831                  | 0.304431                | 2.177233                 |
| 5        | -1    | 1     | 1     | 27.886168                  | 0.345569                | 3.822767                 |
| 6        | -1    | 1     | -1    | 27.886168                  | 0.345569                | 2.177233                 |
| 7        | -1    | -1    | 1     | 27.886168                  | 0.304431                | 3.822767                 |
| 8        | -1    | -1    | -1    | 27.886168                  | 0.304431                | 2.177233                 |
| 9        | 1.215 | 0     | 0     | 37                         | 0.325                   | 3                        |
| 10       | -1.215| 0     | 0     | 27                         | 0.325                   | 3                        |
| 11       | 0     | 1.215 | 0     | 32                         | 0.35                    | 3                        |
3.3 Simulation Test of Piston Rod Based on Orthogonal Test Method

According to the rough turning test scheme shown in Table 2, the simulation test is carried out with ANSYS finite element software, and the results of the simulation test are shown in Table 3. In the process of finite element analysis, the influence of three turning factors is mainly expressed as cutting force. Finite element loading is represented by cutting force. According to the calculating experience formula (2.5), the corresponding cutting force can be calculated, as shown in Table 3.

\[
F_x = 9.81C_{F_x}a_p^{x_F} r^{y_F} v_c^{n_F} K_{F_x} \\
F_y = 9.81C_{F_y}a_p^{x_F} r^{y_F} v_c^{n_F} K_{F_y} \\
F_z = 9.81C_{F_z}a_p^{x_F} r^{y_F} v_c^{n_F} K_{F_z}
\]  (2.5)

\(C_{F_x}, C_{F_y}, C_{F_z}\) depend on the cutting condition and the influence coefficient of the workpiece material;

\(x_F, y_F, z_F\) are the cutting depth \(a_p\) influence indexes;

\(y_F, z_F, x_F\) are the feeding quantity \(f\) influence indexes;

\(K_{F_x}, K_{F_y}, K_{F_z}\) are the correction factor of the cutting condition different from the empirical formula.

| Number | Turning rate \(v_c\) (m/min) | Feeding rate \(f\) (mm/r) | Cutting depth \(a_p\) (mm) | Cutting force \(F_z\) (N) | Maximum bending deformation \(\gamma\) (mm) |
|--------|-----------------------------|---------------------------|---------------------------|--------------------------|-------------------------------------|
| 1      | 36.113831                   | 0.345569                  | 3.822767                  | 1516.48                  | 95.35                               |
| 2      | 36.113831                   | 0.345569                  | 2.177233                  | 863.71                   | 57.45                               |
| 3      | 36.113831                   | 0.304431                  | 3.822767                  | 1423.37                  | 77.83                               |
| 4      | 36.113831                   | 0.304431                  | 2.177233                  | 810.67                   | 46.89                               |
| 5      | 27.886168                   | 0.345569                  | 3.822767                  | 1681.69                  | 103.04                              |
| 6      | 27.886168                   | 0.345569                  | 2.177233                  | 957.79                   | 62.08                               |
| 7      | 27.886168                   | 0.304431                  | 3.822767                  | 1578.43                  | 84.11                               |
| 8      | 27.886168                   | 0.304431                  | 2.177233                  | 898.98                   | 50.68                               |
| 9      | 37                          | 0.325                     | 3                        | 1142.86                  | 69.42                               |
| 10     | 27                          | 0.325                     | 3                        | 1296.31                  | 75.35                               |
| 11     | 32                          | 0.35                      | 3                        | 1257.04                  | 81.12                               |
| 12     | 32                          | 0.3                        | 3                        | 1163.72                  | 63.41                               |
| 13     | 32                          | 0.325                     | 4                        | 1614.81                  | 93.36                               |
| 14     | 32                          | 0.325                     | 2                        | 807.4                    | 50.03                               |
| 15     | 32                          | 0.325                     | 3                        | 1211.10                  | 72.06                               |

3.4 Regression Equation and the Significance Test of Partial Regression Coefficient
Statistical analysis was used to analyze the test results, and the quadratic orthogonal regression equation was obtained as follows:

\[
y = 0.033171 - 0.001291 \left( \frac{x_1 - 32}{4.114} \right) + 0.003510 \left( \frac{x_2 - 0.325}{0.0205} \right) + 0.008378 \left( \frac{x_1 - 3}{0.823} \right) - \\
0.000112 \left( \frac{x_1 - 32}{4.114} \right) \left( \frac{x_2 - 0.325}{0.0205} \right) - 0.000337 \left( \frac{x_1 - 32}{4.114} \right) \left( \frac{x_3 - 3}{0.823} \right) + 0.000837 \left( \frac{x_2 - 0.325}{0.0205} \right) \left( \frac{x_3 - 3}{0.823} \right) + \\
+ 0.000393 \left( \frac{x_1 - 32}{4.114} \right)^2 - 0.000183 \left( \frac{x_2 - 0.325}{0.0205} \right)^2 + 0.000088 \left( \frac{x_3 - 3}{0.823} \right)^2.
\]

The variance analysis table of the quadratic regression equation of the piston rod is obtained, as shown in Table 4.

| Source of variance | Sum of squares (SS) | Degree of freedom (df) | Mean square (MS) | Ratio (F) | P values |
|--------------------|---------------------|------------------------|------------------|-----------|----------|
| \( z_1 \)          | 0.000018            | 1                      | 0.000018         | 121.861221| 0.01     |
| \( z_2 \)          | 0.000135            | 1                      | 0.000135         | 900.110901| 0.01     |
| \( z_3 \)          | 0.000769            | 1                      | 0.000769         | 512.76904 | 0.01     |
| \( z_1z_2 \)       | 0.000000            | 1                      | 0.000000         | 0.675406  | --       |
| \( z_1z_3 \)       | 0.000001            | 1                      | 0.000001         | 6.078716  | 0.10     |
| \( z_2z_3 \)       | 0.000006            | 1                      | 0.000006         | 37.431267 | 0.01     |
| \( z_1z'_2 \)      | 0.000001            | 1                      | 0.000001         | 4.486632  | 0.10     |
| \( z_1z'_3 \)      | 0.000000            | 1                      | 0.000000         | 0.973278  | --       |
| \( z_2z'_3 \)      | 0.000000            | 1                      | 0.000000         | 0.225147  | --       |
| Regression          | 0.000930            | 9                      | 0.000100         |           |          |
| Residual            | 0.000001            | 5                      | 0.0000002        |           |          |
| Sum                 | 0.000930            | 14                     |                  |           |          |

Note: \( F_{0.01}(1,5) = 4.06 \), \( F_{0.01}(1,5) = 16.26 \), \( F_{0.01}(9,5) = 10.16 \)

Variance analysis of regression equation shows that, due to \( z_1z_2 \) (i.e. \( x_1x_2 \) cross term), \( z'_2 \) and \( z'_3 \) (i.e. \( x_2 \) and \( x_3 \) squared terms)'s F test value is less than \( F_{0.1}(1,5) \), so the three items are not significant. All the others are significant or significant, and the regression equation is generally significant.

3.5 Optimization of the Process Parameters of Piston Rod Based on Quadratic Orthogonal Regression Equation

In order to obtain the optimal technological parameters of piston rod rough turning, with cutting speed (X1), feed speed (X2), cutting depth (X3) as the design variables and quadratic orthogonal regression equation as objective function, considering 3 upper and lower bounds of design variables, the optimization mathematical model is set up as follows:
\[
y = 0.033171 - 0.001291 \left( \frac{x_1 - 32}{4.114} \right) + 0.003510 \left( \frac{x_2 - 0.325}{0.0205} \right) + 0.008378 \left( \frac{x_3 - 3}{0.823} \right) - 0.000112 \left( \frac{x_1 - 32}{4.114} \right) \left( \frac{x_2 - 0.325}{0.0205} \right) - 0.000337 \left( \frac{x_1 - 32}{4.114} \right) \left( \frac{x_3 - 3}{0.823} \right) + 0.000837 \left( \frac{x_2 - 0.325}{0.0205} \right) \left( \frac{x_3 - 3}{0.823} \right) + 0.000393 \left( \frac{x_1 - 32}{4.114} \right)^2 - 0.000183 \left( \frac{x_2 - 0.325}{0.0205} \right)^2 + 0.000837 \left( \frac{x_3 - 3}{0.823} \right)^2
\]

\[
\min:\quad \text{s.t.} \quad 27 \leq x_1 \leq 37, \quad 0.3 \leq x_2 \leq 0.35, \quad 2 \leq x_3 \leq 4
\]

The optimal solution \( x_1 = 36.1144, \quad x_2 = 0.3043, \quad x_3 = 2.1622 \) is obtained by using the constraint variable-scale method, and the optimal value of the objective function is:

\[
y \bigg|_{x_1=36.1144, x_2=0.3043, x_3=2.1622} = 0.021645
\]

4. Optimization Parameter Turning Simulation

In order to verify this optimization result, \( x_1 = 36.1144, \quad x_2 = 0.3043, \quad x_3 = 2.1622 \) is used as the turning parameter to carry out the finite element simulation of the rough vehicle. The result \( y = 0.0218 \) of the analysis is consistent with the theoretical optimization result. The simulation results are shown in Figure 2.

![Figure 2. Simulation Results of the Parameters Optimization of Piston Rod Rough Turning](image)

5. Conclusion

In this paper, the main factors affecting the turning force are selected as the evaluation index, including the cutting speed, feeding speed and cutting depth of the piston rod. The finite element simulation test of the orthogonal table is designed. By quadratic orthogonal regression, the maximum radial bending deformation of the piston rod is obtained with the complete quadratic regression equation with the change of the experimental factors and the significance test is carried out. After the establishment of the optimization mathematical model to obtain the optimal technological parameters of piston rod and the parameter optimization, the maximum radial bending deformation of the piston rod is reduced to 0.0216mm, and the maximum bending deformation of the finite element simulation is 0.0218mm. This indicates that the quadratic orthogonal regression optimization method is reasonable and effective, and it can provide a method for improving the quality of the coarse axle parts of piston rod.

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