Influence of contact parameters on the wear characteristics of fixture-bar friction pair in low-stress cropping

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Abstract
A new structure of grooved fixture with a cambered surface is proposed to reduce wear of bar surface caused by a fixture in low-stress cropping. Using the finite element method (FEM) and orthogonal experiment, the optimal contact parameter combination of cambered grooving fixture is obtained. The radial wear degree is proposed to evaluate the surface quality of bars under four contact conditions. Results show that the friction pair under the A4B1C2D1E4 combination of contact parameters has the best wear reduction effect and the lowest radial wear degree, which is 0.0469 mm², and 34.50% lower than ones of line contact, respectively. The cropping platform based on acoustic emission-stress–strain is established to study the influence of roughness Ra on the comprehensive wear state of friction pair. It is pointed out that under the different contact conditions, when Ra = 0.4 μm, the acoustic emission characteristic parameters meet the minimum level and the comprehensive abrasion state of the friction pair is optimal.

Keywords Low-stress cropping · Fixture-bar friction pair · Archard model · Radial wear degree · Acoustic emission (AE)

1 Introduction

Precision cropping is widely used in aerospace, mechanical standard accessories, electronic components, etc., which is the first process of metal forming [1, 2]. Now the trend of precision cropping methods is green and efficient low-stress cropping [3–5]. The low-stress cropping process is as follows: first of all, the annular V-groove is prefabricated on the surface of the bar to realize the regular action of the spindle assembly. Secondly, through the cropping die of the electro-hydraulic control system, the rotating bending load is applied to the bar to change the stress state at the tip of the V-groove of the bar so that the fatigue crack gradually expands inward. Finally, continuous, efficient, and controllable cropping is accomplished. However, under the existing low-stress rotating bending loading condition [6], the line contact form of the fixture-bar friction pair causes the bar to produce a slight shake relative to the fixture, and the reaction force of the fixture also produces unstable extrusion deformation on the bar surface. These deficiencies not only lead to uneven grinding marks on the bar surface but also appear to collapse the angle of the bar and poor surface quality [7, 8]. At the same time, the impact vibration caused by friction and wear also affects the working stability of the cropping machine [9]. Therefore, it is very significant to study the influence of fixture contact parameters on the wear characteristics of friction pairs under different contact conditions.

Highlights
• A new fixture with cambered surface grooves for low-stress cropping is proposed.
• The radial wear degree is proposed to evaluate the wear characteristic of the metal bar.
• Radial wear degree under optimal combination is the minimum, which is 0.0469 mm².
• AE parameters are used to study the effect of roughness on the wear state of a friction pair.

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friction and wear properties of nickel matrix composites from room temperature to 600 °C, and obtained that the friction coefficient of the composites increased first and then decreased with the increase of temperature. Gong et al. [12] established the wear mechanism diagram of copper-based friction clutch material under the oil lubrication condition according to the measured wear rate, and divided it into super mild, mild and severe wear characteristics, and gave the linear equation of regional transition. Mukhacheva et al. [13] applied the Kragelsky yield criterion to study the friction and wear properties of medium carbon steel after carbonitriding in urea electrolyte. The consequence showed that the wear resistance of the steel was increased by 40% after carbonitriding at 750 °C for 7 min and a sliding speed of 0.4–0.55 m/s. Medabalimi et al. [14] used the pin-on-disk tribometer to evaluate the friction and wear behavior of partial oxidation of flame sprayed Ni–Fe–Si coating on the microstructure of the coating. The results specified that the wear rate of the coated steel was 5 times lower than that of the uncoated steel at 600 °C, and the wear rate and friction coefficient of the coating decreased with the increase in temperature. Lu et al. [15] studied the effect of pre-impregnated silicone layer on friction and wear properties of paper-based friction materials. The upshot expressed that the addition of a small amount of silicone into the paper-based friction material could improve the static friction coefficient of the paper-based friction material and reduced the dynamic friction coefficient and wear rate of the paper-based friction material. When the content of silicone was 7.5%, the paper-based friction material had the highest static friction coefficient and the best stability. Slawomir et al. [16] studied the effect of graphite surface texture on dry plane contact friction reduction performance of graphite-steel sliding pair and tested four different types of texture surface of graphite disk with the diameter of 100 mm and thickness of 10 mm. The results showed that the convergence direction of the bottom texture had a great influence on the dispersion of the friction coefficient. The disc texture with the bottom step parallel to the herringbone arm had a high stability and low friction coefficient, and the friction was small when the angle between the arms was 120°.

It can be found that the current research mainly focuses on the wear mechanism of friction pairs under the different materials and environmental conditions, while the influence of contact parameters on the wear characteristics of friction pairs is ignored. Therefore, this paper designs a new structure of fixture contact cambered surface based on the principle of tribology and uses the method of combining orthogonal test and finite element simulation to study the influence of fixture contact parameters on the wear characteristics of friction pair and obtains the optimal combination of contact parameters. The evaluation index that affects the wear characteristics of the friction pair is proposed. On this basis, the cropping test is carried out by combining AE and stress–strain measurement technology to further determine the surface quality parameters of the bar under the optimal wear characteristics, and the SEM is used to analyze the micro-wear mechanism of the friction pair in order to comprehensively improve the surface quality of the metal bar.

The low-stress cropping machine is based on hydraulic compensation, which makes full use of stress concentration effect, hydraulic compensation technology, and centrifugal effect to precisely crop metal bar and tube. It is mainly composed of six parts: frequency conversion motor, hydraulic transmission system, double slider mechanism, cropping die, mobile fixture mechanism, and frame, as shown in Fig. 1(a). In the cropping process, one end of the bar with a V-shaped groove is put into the cropping round hammer, and the other end is fixed with a fixture. Then the three-phase AC motor drives the hammer head to rotate at a high speed through the spindle. Due to the high speed of the hammerhead, its smaller mass and radius of rotation produce a larger centrifugal force, which makes the slider slide eccentrically under the action of centrifugal force. At the same time, the hydraulic cylinder supplies oil to make the round slider slide in the radial groove so as to compensate for the centrifugal force. Under the combined action of centrifugal force and hydraulic compensation force, cracks at the tip of the V-shaped groove initiate and propagate stably along the desired path, thus achieving low-stress brittle fracture [17]. In the process of cropping, the fixture and the bar are in contact and shake, which makes the bar wear greatly and largely determines the surface quality of the bar. Among them, the mobile fixture mechanism of the low-stress cropping machine is mainly composed of a mobile fixture, a guide pillar, a VH-305 hydraulic chuck, a bar, and a fixed fixture, as shown in Fig. 1(b). The enlarged diagram of contact principle between the fixture and the bar is shown in Fig. 1(c). The yellow line is the bar, the overlapping part of the blue and yellow lines represents the contact zone between the fixture and the bar, and the pink arrow represents the extrusion deformation zone on the surface of the bar after being stressed. At the beginning of the contact, the fixture and the bar are in line contact under the combined action of hydraulic compensation force of hammer head and centrifugal force, while the bar near the fixture end shakes slightly, and the reaction force of fixture produces continuous extrusion on the bar surface, causing obvious wear and extrusion deformation. Moreover, under the condition of line contact, during the circumferential loading process, the shaking of the bar relative to the fixture will be more severe, making the extrusion wear of the bar surface more serious [18], as shown in Fig. 2. Therefore, it is of great significance to study the influence of contact parameters on the wear characteristics of friction pairs under the different contact conditions.
2 Materials and methods

2.1 Establishment of finite element analysis model of friction pair

Because the contact parameters between fixture-bar will affect the surface quality of the bar, a new type of contact cambered structure of hydraulic clamping claw is designed according to the tribology theory. The main V-grooves and the auxiliary friction increasing grooves of equal width are set on the cambered surface of the clamping claw, which is made of wear-resistant materials, and the rounded corners are arranged on the V-groove edge to reduce the contact wear of the fixture-bar friction pair. The combined fixture-bar model is divided into three contact zones according to the working state: the hydraulic compensation force $F_h$ of the hammer head on the bar is taken as the benchmark; the clamping claws are marked as 1~3 clockwise respectively; the corresponding contact zones between the clamping claws and the bar are I~III, respectively. The finite element model of the fixture-bar friction pair is shown in Fig. 3(a), and the contact parameters are shown in Fig. 3(b). Among them, the linear contact model and the cambered grooving contact model only have different contact conditions, which can be done by referring to Fig. 1.

2.1.1 Wear simulation based on Archard model

Using Archard wear simulation analysis method, the fixture material is low carburizing steel of 20CrMnTi; the bar material is No. 45 steel; the hammer head material is GCr15. The performance parameters of these materials are shown in Table 1.

Because of the complex structure of the fixture’s contact surface and the existence of an irregular small surface, it can only be divided into the tetrahedral grid by the automatic division method, and the grid quality can be controlled by improving the cell size. Using the multi-zone...
method, the bar and bearing are set as a hexahedral grid and the face meshing is used to ensure the uniformity of the end face mesh shape. The mesh unit size is controlled to be 0.15 mm. After solving, the model is symmetrically divided into 82,167 units, 118,637 nodes, and the grid quality is high with the highest value of 0.99972 and the average value is 0.84472. The multi-zone meshing model is shown in Fig. 4.

One end of the bar is clamped by the hydraulic clamping claws; the clamping force $F_{b} = 10$ kN; the bearing hammer head acts on the other end of the bar; the rotational speed is 600 rpm. Under the joint action of the centrifugal force $F_{c}$ generated by the spindle driving the rotation of the hammer head and the hydraulic compensation force $F_{h}$ generated by the feeding cylinder pushing the hammer head sliding, the rotary bending loading of the hammer head on the bar is realized. At the same time, motion joints are established to apply the corresponding load and speed, and the end face of the bar moves axially. Archard wear model [19] is used, and its form is shown in Eq. (1):

$\dot{V} = \frac{K}{H} P_{n}^{m} v_{rel}^{n}$

where $\dot{V}$ is the wear volume (mm$^3$); $K$ is the coefficient of wear; $H$ is the material hardness (MPa); $P$ is the normal contact pressure (MPa); $v_{rel}$ is the relative motion velocity of friction pair (m/s); $m$ is the contact pressure index; $n$ is the relative velocity index.

Table 1  Performance parameters of material

| Material   | Mechanical parameters |
|------------|------------------------|
|            | $\rho$ (g/cm$^3$) | $E$ (GPa) | $v$ | $\sigma_y$ (MPa) | $\sigma_b$ (MPa) | $H$ (HRC) |
| No. 45     | 7.89                  | 210       | 0.269 | 355  | 600       | 25        |
| GCr15      | 7.83                  | 209       | 0.30  | 518.42 | 861.32    | 48        |
| 20CrMnTi   | 7.80                  | 207       | 0.25  | 835   | 1080      | 42        |
2.1.2 Comparative analysis of simulation results

The transient dynamic analysis of the friction pair is carried out, and the correlation results of the friction pair under the linear contact and cambered surface contact for 10 s are obtained as follows.

Figure 5(a) and (b) are the equivalent stress of the bar under linear and cambered contact condition, respectively. Figure 5 shows that under the same working condition, the deformation of the extrusion surface at the bar clamping end is different due to different contact forms of the fixture, thus affecting the stress state of the bar. Under the linear contact condition, the bar has a slight torsional deformation due to the centrifugal force acting on the bar, and then an approximate linear stress change zone is slightly wider than the contact surface of the claw appearing at the bar clamping end, and the stress zone is relatively uniform. The maximum equivalent stress of the bar appears at the contact point between the bearing and the bar, and its value is 1476.9 MPa. Under the cambered surface contact condition, the maximum equivalent stress of the bar appears in the same position as that of the linear contact. However, since the normal contact load applied is the same, and the contact zone is larger, and the stress value is lower than that of the linear contact [20], which is 1089.1 MPa.

According to the nephogram of the axial sliding distance of the bar in Fig. 6, under both linear contact and cambered contact, the maximum occurs in the contact zone between the fixture and the bar. The difference is that the maximum axial sliding distance of the bar clamping end is 18.70 μm in the linear contact. In the cambered contact, because of the existence of auxiliary friction increasing grooves on the fixture contact surface, the axial sliding of the bar is effectively reduced. Therefore, the maximum axial sliding distance of the clamping end is 8.11 μm, which is significantly lower than one of the linear contact conditions.

By comparing the wear volume curves Fig. 7(a) of the two contact conditions, it is indicated that the change trend of the wear volume curves of the bars is roughly the same. The volumetric wear rate of the three contact zones of the fixture-bar friction pair increases rapidly in 0 ~ 3 s, then decreases gradually in 3 ~ 6 s, and remains basically unchanged with the increase of time after 6 s. According to the typical wear process curve [21], under the condition of constant working conditions, 0 ~ 6 s is the period when the running stage of the friction pair approximately ends, and 6 ~ 10 s is the stable wear stage when the friction pair is working normally. Therefore, the result of the wear curve is reasonable. According to the comparative analysis, in the linear contact, the maximum wear volume in the contact zone 3 of the friction pair at 10 s is 0.61904 mm³; the minimum wear volume in the contact zone 1 is 0.40502 mm³. In cambered surface contact, the maximum wear volume in the contact zone 2 of the friction pair is 0.55829 mm³ at 10 s; the minimum wear volume in the contact zone 1 is 0.49480
mm³. By comparing the friction stress curve Fig. 7(b), it is found that the friction stress of the friction pair changes uniformly in the case of linear contact. Under the combined action of centrifugal force and normal contact pressure, the bar will undergo slight torsion, and extrusion deformation makes the contact zone of friction stress increase. Under the same contact pressure, the friction stress will decrease, which causes the bar to slide slightly in the radial and axial direction, thus increasing the wear of the bar surface. Among them, the maximum average friction stress in contact zone 2 at 10 s is 36.2211 MPa; the minimum average friction stress in contact zone 3 is 13.1469 MPa. In cambered surface contact, due to the effect of the main V-groove and the auxiliary friction-increasing groove on the bar surface, the friction stress of the bar increases as a whole compared with that of the linear contact, and the circumferential torsion and axial sliding of the bar are improved. Among them, the maximum average friction stress in contact zone 1 is 51.6070 MPa; the minimum average friction stress in contact zone 2 is 15.1038 MPa.

By comparing the simulation results, it can be seen that the wear volume of the bar in cambered surface grooving contact is lower than that in the linear contact, and the torsion and axial sliding effect of the bar are significantly reduced, which improves the surface quality of the bar. Therefore, it is reasonable to design the fixture’s contact
surface and optimize the contact parameters to improve the wear characteristics of the friction pair.

2.2 Optimal combination of contact parameters of cambered surface fixture

According to the simulation results, under the same rotational speed and load condition, although the wear reduction effect of cambered grooved contact is better than that of line contact, the influence of fixture contact parameter combination on the wear characteristics of friction pair is not considered. Therefore, the orthogonal experiment is designed to further optimize the contact parameters of the cambered surface grooving fixture model, so as to obtain the optimal combination of contact parameters of the cambered surface grooving fixture.

2.2.1 Orthogonal experimental design scheme

The orthogonal experiment is designed in order to optimize the fixture contact parameters that affect the wear
characteristics of the fixture-bar friction pair. It is divided into several parts: the test objective is to reduce the wear degree of friction pair; the evaluating indicators are wear of volume and average axial sliding distance of bar; the electing factors and levels are as shown in the following Tables 2 and 3. Design L₁₆⁴⁵ orthogonal test table to analyze the test results through range. Finally, obtain the optimal combination of factors and levels [22].

### Table 2 Contact parameter factor level table

| Levels | Factors |
|--------|---------|
|        | Groove depth $h$ (mm) | Groove width $b$ (mm) | Fillet radius $r$ (mm) | Angle $\alpha$ (°) | Number of friction increasing grooves |
| 1      | 1.5     | 1.4 | 0.2 | 45 | 3 |
| 2      | 2.0     | 1.7 | 0.3 | 60 | 6 |
| 3      | 2.5     | 2.0 | 0.4 | 75 | 9 |
| 4      | 3.0     | 2.3 | 0.5 | 30 | 12 |

2.2.2 Orthogonal optimization results of fixture contact parameters

The simulation results of 16 groups of orthogonal models under the cambered surface grooved contact are carried out, and the relevant wear results of friction pairs are shown in Table 4.

Table 5 shows the optimization results of contact parameters of friction pair under cambered contact. In order to show the friction and wear characteristics of bar more intuitively, the average axial sliding distance and the wear volume of bar surface are selected as the evaluation indexes of orthogonal test. The optimal level and the primary and secondary factors are obtained by using the comprehensive balance range analysis method [23], and then the optimal combination of fixture contact parameters in this table is obtained. In Table 5, A, B, C, D, and E represent groove depth, groove width, groove edge fillet radius, friction increasing grooves angle, and the number of friction increasing grooves, respectively, and $k_1$, $k_2$, $k_3$, and $k_4$, respectively, represent the average value of the test data when the factor is taken at the corresponding level. $R$ is the range value of each factor to the test index. The influence degree of each factor on the test index is determined by the range value.

It can be seen from Table 5 that the most important factor affecting the axial sliding distance of the bar surface is the number of auxiliary friction increasing grooves, and its range value $R = 37.33$. The second influencing factors are the groove depth and width. According to Tables 2 and 3, the increase in the number of auxiliary friction grooves can effectively reduce the axial sliding of the bar surface and the wear loss of the friction pair. The groove width is the most important factor affecting the wear extent of bar, and the range value is $R = 0.5594$. The second influencing factors are groove depth and the number of auxiliary friction grooves. Because the contact deformation is considered in the simulation model, the wider the V-shaped groove is, the smaller of contact zone between the two friction pairs is. Under the same normal load, the friction stress of the contact surface magnifies and the wear extent increases [24, 25]. And the auxiliary friction increasing grooves can increase the fastening state of the friction pair,

### Table 3 Orthogonal test table of contact parameters

| Orthogonal group | Groove depth $h$ (mm) | Groove width $b$ (mm) | Fillet radius $r$ (mm) | Angle $\alpha$ (°) | Number of friction increasing grooves |
|------------------|-----------------------|-----------------------|-----------------------|-------------------|---------------------------------------|
| 1                | 1.5                   | 1.4                   | 0.2                   | 45                | 3                                     |
| 2                | 2.0                   | 1.7                   | 0.3                   | 45                | 6                                     |
| 3                | 2.5                   | 2.0                   | 0.4                   | 75                | 9                                     |
| 4                | 3.0                   | 2.3                   | 0.5                   | 30                | 12                                    |
| 5                | 2.0                   | 2.0                   | 0.4                   | 60                | 12                                    |
| 6                | 1.5                   | 2.3                   | 0.3                   | 60                | 9                                     |
| 7                | 3.0                   | 1.4                   | 0.4                   | 60                | 6                                     |
| 8                | 2.5                   | 1.7                   | 0.5                   | 60                | 3                                     |
| 9                | 2.5                   | 2.3                   | 0.2                   | 75                | 6                                     |
| 10               | 3.0                   | 2.0                   | 0.3                   | 75                | 3                                     |
| 11               | 1.5                   | 1.7                   | 0.4                   | 75                | 12                                    |
| 12               | 2.0                   | 1.4                   | 0.5                   | 75                | 9                                     |
| 13               | 3.0                   | 1.7                   | 0.2                   | 30                | 9                                     |
| 14               | 2.5                   | 1.4                   | 0.3                   | 30                | 12                                    |
| 15               | 2.0                   | 2.3                   | 0.4                   | 30                | 3                                     |
| 16               | 1.5                   | 2.0                   | 0.5                   | 30                | 6                                     |
reduce the surface wear caused by the axial movement of the bar surface, and play a role in reducing the wear.

Regarding the results of the axial sliding distance of the bar surface, the combination of the better level column is A4B1C4D1E4; as for the results of wear volume, the combination of the column of better level is A4B1C2D2E3. Therefore, A4 is the best groove width, and B1 is the best groove depth. Combined with the analysis of the range value, the influence of the groove edge fillet radius (C) on the axial sliding distance and the wear volume ranks fifth, and there is an influence value C3 between the axial sliding distance C2 and C4, and the wear volume C2 is the best, followed by C4. Considering the two indexes comprehensively, the groove edge fillet half diameter C3 is appropriate; the influence of friction increasing groove angle D on the axial sliding distance and wear volume is the fourth; and the gap between the axial sliding distance D1 and D2 is large, while the gap between the wear volume D1 and D2 is small. Considering the two indexes comprehensively, the effect of friction groove angle D1 is better. The influence of the number of auxiliary friction grooves E on the axial sliding distance is the first, the influence on the wear volume is the second, and E3 is better than E4 in terms of wear volume. Comprehensive consideration, E4 level is better for auxiliary friction increasing groove. The optimal combination of fixture contact parameters under cambered surface grooved contact is A4B1C2D1E4. That is when the groove depth h is 3.0 mm; the groove width b is 1.4 mm; the groove edge fillet radius r is 0.3 mm; the auxiliary friction increasing groove angle α is 45°; the number of auxiliary friction increasing grooves are 12, and the friction pair has the best wear characteristics.

### 2.3 Experimental verification of wear characteristics of friction pair contact parameters

#### 2.3.1 Establishment of radial wear degree model and AE model of micro-convex body

The optimal combination of cambered contact parameters of the fixture is obtained through an orthogonal experiment, which needs comparative analysis. According to Table 4, the boundary values of axial sliding distance and wear volume are in different orthogonal groups. Therefore, it is necessary to establish a radial wear degree model and an AE model of micro-convex body.
to establish comprehensive evaluation indexes of axial sliding distance and wear volume, so that the test data can better reflect the wear characteristics of the bar surface. The initial contact length of the fixture bar is set as $S_0$, since the friction pair is continuous contact, and the initial contact section of the fixture bar is regarded as a wear element. After the time interval $\Delta t$, the average sliding distance of the wear element is $\bar{S}$. After 10 s, the average axial sliding distance of the bar is $S = \sum \Delta \bar{S}_i$. The ratio of wear volume $V$ to the average axial sliding distance $(S_0 + \bar{S})$ of the bar is defined as the radial wear degree $\lambda$ of the bar. The boundary value of $\lambda$ is obtained through analysis as the comparative analysis group of the fixture, and the model of radial wear degree is shown in Fig. 8.

The existence of a micro-convex body on the surface of the friction pair is the direct reason for the difference in surface roughness. In the relative motion, the elastic deformation occurs in the collision between the micro-convex bodies, and the continuous signal is released to reflect the wear state of the friction pair at this time. Therefore, in order to study the friction and wear characteristics of friction pair, continuous signal parameters related to the elastic deformation of the micro-convex body between contact faces are constructed to characterize the wear characteristics of friction pair. Combined with Hertzian contact theory and Greenwood–Williamson contact model, Fan et al. [26] established the relationship between the elastic deformation of micro-convex body on the contact surface and the AE characteristic signal parameter RMS [27] that characterized the wear characteristics of friction pairs. As shown in Eq. (2),

\[
V_{\text{rms}} = \sqrt{\frac{2K_K K_w N w v}{R_1^2} \int_0^\infty (z - y)f(z)dz}
\]

where $f(z)$ is Gaussian probability density function of the contour height of the contact surface; $y$ is the distance from convex surface to ideal plane (mm); $K_K$ is the ratio of elastic energy of contact peak converted to AE signal; $K_w$ is conversion rate of AE measurement system sensor to AE signal; $N$ is total number of contact peak points between the contact zones of two friction pairs; $w$ is load borne by peak point (N); $v$ is surface sliding speed of friction pair (mm/s).

According to Eq. (2), for the conventional sliding friction process, when the normal load and rotational speed are fixed, the AE characteristic parameter $V_{\text{rms}}$ formed by the elastic deformation of the micro-convex body between friction pairs is mainly affected by the contact characteristic parameters on the surface of the friction pairs. Therefore, the continuous AE characteristic signal parameter $V_{\text{rms}}$ can be used to well characterize the friction and wear characteristics of the material, and the surface quality of the fixture under the optimal wear characteristics can be determined to guide the cropping experiments.

The simulation results of wear volume and axial sliding distance of 16 groups of models are substituted into the radial wear degree model of bar, and the results are obtained as shown in Table 6. The radial wear degree $\lambda$ of orthogonal group 11 is the largest and that of orthogonal group 12 is the smallest at 10 s. According to the wear characteristics of fixture-bar friction pair, the friction and wear tests are carried out on claws with four different contact conditions: optimal combination of cambered contact parameters, line contact, orthogonal groups 11 and 12.

### 2.3.2 Experimental materials and methods

In the experiment, different bar materials also affect the surface wear morphology of the bar. Because different materials exhibit different mechanical properties under the same load, and also result in different damage mechanisms and different wear morphologies on the surface. The research object of this paper is the fixture contact parameters. The

| Orthogonal group | Radial wear degree $\lambda$ (mm²) | Orthogonal group | Radial wear degree $\lambda$ (mm²) |
|------------------|-----------------------------------|------------------|-----------------------------------|
| 1                | 0.0661                            | 9                | 0.0788                            |
| 2                | 0.0678                            | 10               | 0.0718                            |
| 3                | 0.0620                            | 11               | 0.0925                            |
| 4                | 0.0636                            | 12               | 0.0454                            |
| 5                | 0.0628                            | 13               | 0.0645                            |
| 6                | 0.0565                            | 14               | 0.0540                            |
| 7                | 0.0469                            | 15               | 0.0748                            |
| 8                | 0.0769                            | 16               | 0.0809                            |

Fig. 8 Model of radial wear degree of bar
material of bar is No. 45 steel, which is the most commonly used, and the size of single section bar is length \( L = 40 \text{ mm} \) and diameter \( D = 15 \text{ mm} \). The size of fixture is length \( L = 30 \text{ mm} \) and the actual contact length \( l = 25 \text{ mm} \) with the width \( B = 25 \text{ mm} \) and the height \( H = 52 \text{ mm} \). The material of fixture is 20CrMnTi. The contact parameters of the fixture under the four different contact conditions selected in Table 6 are different. In order to meet the experiment requirements of fixture-bar friction pair, the initial roughness of the contact surface between the fixture and bar manufactured by the manufacturer is required to be 0.8 \( \mu \text{m} \), as shown in Fig. 9. The mechanical property parameters of materials are shown in Table 1.

KM-001 Rotary bending low-stress cropping machine [28], DS2 full information acoustic emission signal analysis system and stress–strain gauge are used to verify the cropping experiment. And, the cropping principle is shown in Fig. 10, and the construction of the experimental platform is shown in Fig. 11. The strain gage is connected to the stress–strain gauge and affixed near the contact zone of bar and bearing. Half-bridge compensation is selected as the compensation method and strain measurement is used as the measurement method. The hydraulic compensating force \( F_h \) is acted as the concentrated force on the contact center between the bar and bearing, the distance between the action point of force and the center of the strain gage is \( L_1 \), and the distance between the fixture near the end of the V-shaped groove and strain gage is \( L_2 \). Under the rotary bending load of the bearing, the bar would produce a certain deflection, and the bar is equivalent to a cylindrical section. According to the theory of mechanics of materials, the bending moment \( M \) satisfies the following Eq. (3) [29]:

\[
W_z \epsilon E = M = F_h (L_1 + L_2)
\]  

where \( W_z \) is the modulus of bending section \( (\text{mm}^4) \); \( F_h \) is the hydraulic compensation force \( (\text{N}) \); \( \epsilon \) is the value of bar strain measurement; \( E \) is the elastic modulus \( (\text{GPa}) \). The strain of the bar is measured by DHDAS dynamic signal acquisition and analysis system, and the hydraulic compensation force \( F_h \) of bearing to the bar is calculated in Eq. (3). For the clamping force \( F_b \) of the fixture, the bearing kept away from the bar, the fixed fixture retained only No. 1 claw, and the end of the bar is clamped by a moving fixture. The strain gauge is affixed near the contact surface between the fixed fixture and bar, and the bar is pressed by a No. 1 claw driven by a hydraulic cylinder. It is equivalent to the mechanical model of bearing press bar, the strain value is measured by stress–strain gauge, and then the clamping force \( F_b \) of the claw is obtained. Therefore, load conditions are determined during the cropping process.

![Fig. 9 Details of experiment materials](image)

![Fig. 10 Principle diagram of cropping experiment for friction pair](image)
The hydraulic compensation force of bearing is $F_h = 1560$ N, the clamping force of single claw of clamp is $F_b = 10$ kN in the cropping experiment by the above method, and the contact method of friction pair is cambered contact. The fixture-bar friction pair is fixed, and the bearing rotates eccentrically along the bar axis. The radius of rotation $R = 8$ mm, the rational speed is 600 rpm, and the motion time is 10 s. The AE sensor is fixed near the contact zone between the fixture and bar by coupling agent, and the fixture-bar friction pair is worn by rotary bending loading. The continuous AE signal generated by wear is transmitted to the signal analysis system through the preamplifier, and the signal sampling frequency is 3.5 MHz. Before the experiment, the initial contact position between the fixture and bar is marked. #320, #400, and #600 sandpaper are used to polish the contact surface of the fixture first; #800 sandpaper is used to correct the flatness of the surface; 100% pure cotton dipped in alcohol and other cleaning solution are used to wipe the surface carefully, and finally the surface is polished. The surface roughness of polished sample is measured by TIME3202 hand-held surface roughness tester with accuracy of 0.001 μm. In order to ensure the uniformity of the measurement results, each sample surface is measured 6 times to take the average value, and the measured value relative to the standard value allows a certain floating accuracy. The experimental platform is shown in Fig. 12.

After the experiment, the axial sliding distance of the bar is measured, the bar is ultrasonically washed by acetone, then the wear amount of the bar is weighed on the inductive electronic balance of FA1004 with the accuracy of $10^{-4}$ g, and the microstructure of the wear mark on the bar surface is observed by SEM.

### 3 Results and discussion

The overall mass of the bar is different due to the process flow, machining accuracy, internal structure, or a little impurity. In order to ensure the accuracy of the test, the bar mass corresponding to the number is weighed before the test of different fixture-bar wear friction pairs, and the mass loss associated with processing is considered. The average value of each sample is weighed five times. Finally, the bar mass parameters of the fixture contact part under four groups of different contact conditions are obtained. As shown in Table 7, $m_1$ is the original mass of the bar, $m_2$ is the mass of the bar after cropping, $\Delta m_w$ is the mass loss of the bar wear, and $\Delta m_c$ is the mass loss considering the processing.

The relative axial sliding distance of the fixture-bar friction pair during the cropping test is measured. The actual value of the axial sliding distance of the bar is larger than the simulation value due to the factors such as the medium spindle pair of the cropping machine and the rigid vibration of the cropping machine. According to the initial distance $S_0$ of the bar and fixture and the wear mass $\Delta m_w$ of the bar, the average axial sliding distance of the bar is measured, and the average value is calculated by using the Vernier caliper with the accuracy of 0.02 mm. The radial wear degree of the bar after the cropping test is calculated, as shown in Table 8.
Figure 13 shows the histograms of radial wear degree of bars obtained by simulation and experiment under four contact conditions. Overall, the experimental values of radial wear degree of the bar under four contact conditions are greater than the simulation, and the error value is about 6.71–15.61% which is in the appropriate range. The reasons for the comprehensive analysis of the error are as follows: firstly, the average axial sliding distance of the bar increases due to the manufacturing accuracy of the cropping machine itself and the stiffness of the machine in the experiment; secondly, the bar is loaded by the hammerhead in the cropping, resulting in a certain deflection, which changes the contact zone with the fixture and increases the wear amount; finally, because the friction coefficient of the fixture-bar friction pair is always changing in the experiment process, the bar wear obtained by the experiment will be larger than that obtained by the simulation.

In part, the number of auxiliary friction-increasing grooves, opening angle, groove depth, and groove width of the main V-shaped groove is different under the different contact conditions, so the radial wear degree fluctuates greatly. Under the same load and rotational speed, the minimum radial wear degree of the bar under the optimal combination of contact parameters is 0.0469 mm²; the maximum radial wear degree of the bar is 0.1034 mm² under the No. 11 contact condition. Compared with the normal line contact condition, the radial wear degree of the bar is reduced by 34.50% under the optimal combination of contact parameters. The radial wear degree of the bar under the orthogonal group 11 is increased by 44.41% compared with the ordinary line contact.

Figure 14 shows the macro surface morphology of the No. 45 steel bar under four contact conditions. The observation shows that due to the different contact surface parameters of the fixture, the bar surface presents different macro morphologies and there are three areas: the reference plane of the bar sliding relative to the fixture is represented by pink area 1; the wear dent caused by the bar sliding is blue area 2; red area 3 represents the worn peak caused by the bar

### Table 7 The mass result of bar material contact with fixture

| Contact condition     | Mass of bar in contact part of fixture | △m (g) | △m (g) |
|-----------------------|----------------------------------------|--------|--------|
|                       | m1 (g)                                 | m2 (g) | △m (g) |
| Optimal combination   | 54.4406                                | 54.4312| 0.0092 | 0.0002 |
| Orthogonal.11th       | 54.5123                                | 54.4956| 0.0162 | 0.0005 |
| Orthogonal.12th       | 54.6862                                | 54.6751| 0.0107 | 0.0004 |
| Line contact          | 54.5412                                | 54.5266| 0.0143 | 0.0003 |

### Table 8 Radial wear degree of bar under four contact tests

| Contact condition     | Related parameters (S = 25 mm, ρ = 7.89 g/cm³) | △S (μm) | △m (g) | λ (mm²) |
|-----------------------|-----------------------------------------------|---------|--------|--------|
|                       |                                              | S (μm)  | △m (g) | λ (mm²) |
| Optimal combination   | 120                                           | 0.0093  | 0.0469 |
| Orthogonal.11th       | 220                                           | 0.0206  | 0.1034 |
| Orthogonal.12th       | 180                                           | 0.0107  | 0.0538 |
| Line contact          | 300                                           | 0.0143  | 0.0716 |
sliding. Under the No. 11 contact condition of the orthogonal group in Fig. 14(b), the wear degree of the bar surface is the highest, and approximately equidistant wear dents can be observed. Under the optimal combination in Fig. 14(a), the wear degree of the bar surface is the lowest, and the surface wear marks are shallow, which is consistent with the research results in Fig. 13.

In order to further reflect the surface wear of bar slip, a dial indicator is used to measure the wear mark gradient on the bar surface. The three-dimensional contour map of the bar surface is established with the actual contact length $l_0$ of the fixture bar as the $X$-axis, the actual contact width $b_0$ as the $Y$-axis, and the wear mark depth $h_0$ of the bar as the $Z$-axis. Due to the short length of a single bar, the
measurement interval of \( l_0 \) is 3 mm, and the value of \( b_0 \) is taken at equal intervals based on the center angle of the arc contact area of the fixture. In order to ensure the accuracy of the test, the average value is obtained through multiple measurements, and finally, the three-dimensional contour simulation diagram of the bar surface under the different contact conditions is obtained, as shown in Fig. 15. The red area represents the worn peak caused by material transfer or surface manufacturing during bar sliding, and the blue-green area represents the wear dent caused by bar sliding. It can be seen that there are wear marks, pits, and peaks on the bar surface under four contact conditions due to sliding and extrusion, but the gradient of Fig. 15(a) is less than the other three conditions, with a value of 0.8–1.2 mm. By observing Fig. 15(b) and (c), it can be seen that although the wear mark gradient on the bar surface is relatively similar, the change of the wear mark gradient in (b) is more severe than that in (c), which is in line with the evaluation results of radial wear degree on the bar surface. It can be seen from Fig. 14(d) that under the line contact condition: at the beginning, most of the bar surface are wear dents, and the range of wear dents is 0–0.4 mm; there are only a few wear peaks, and the peaks appear at the tail end of the bar, with a maximum value of 0.1 mm. This is because, under the condition of line contact, when the hammerhead applies load to the bar, there will be not only relative sliding but also torsion between fixture and bar, resulting in uneven wear dents on the bar surface. There is a certain deflection of the bar, which will cause the material to accumulate at the end of the bar.

Figure 16 shows the wear surface morphology of the no. 45 steel bar observed by scanning electron microscope at different magnifications under four contact conditions. It can be seen from Fig. 16(a) that there were some narrow and shallow scratches and plowings on the surface of the bar under this state. After the fixture contacts the bar, due to the sliding of the bar relative to the fixture, the rough peak of the fixture is embedded in the bar surface to push and form plowings, and at the same time, abrasive particles are generated, so that the bar surface is abraded and many narrow and shallow scratches are generated. At this time, the oxide layer on the bar surface is not destroyed, and the main occurrence is slight abrasive wear. Figure 16(b) shows the wear surface morphology of the orthogonal group no. 11 amplified by 100 times. At this time, the extrusion of the fixture on the surface of the bar is more serious, and the oxide layer on the surface of the bar is destroyed slightly.
resulting in oxidative wear. The material is partially stacked on both sides, and the wear is more serious. At the same time, due to the poor brittleness of no. 45 steel, under the action of abrasive extrusion, a slight extrusion spalling phenomenon occurred on the surface, and the combined action of abrasive particles and debris generated wide scratches. Moreover, due to the relative motion of the friction pair, the random migration of abrasive particles and debris generated adhesive layers of different sizes. Figure 16(c) shows the morphology of the orthogonal group no. 12 amplified by 200 times. At this time, the surface of the bar is extruded and worn by the fixture. The slight plastic deformation on the surface makes some adhesive nodes break and fall off to form wear debris, and adhesive wear occurs. Under the combined action of debris and abrasive particles, many wide scratches and pits with different depths appear on the surface. With the relative movement of the friction pair, fine abrasive particles and wear debris form a thin layer of mixture are adhered to the worn surface during repeated extrusion, which reduces the wear of the bar surface to some extent. Figure 16(d) shows the surface morphology enlarged by 150 times by linear contact. It can be seen that the extrusion of the fixture on the bar is more serious under this contact. Serious plastic deformation occurs on the surface of the bar, and the material transfers and accumulates to form a new adhesive layer. The oxide layers on the surface of the bar are destroyed to form oxide and solid solution crystallization [30, 31], and new oxide layers are formed during the movement, which hinders the further wear of the bar to some extent.

When only considering the influence of fixture surface contact parameters on the wear characteristics of friction pairs, the radial wear degree of the bar surface changes greatly under the four contact conditions. However, under the actual contact condition, any friction surface is composed of micro peaks and valleys with different shapes, which can be comprehensively expressed as surface roughness. The surface roughness of the friction pair has a significant influence on the friction and wear characteristics under dry friction [32]. Therefore, in order to further explore the influence of fixture surface roughness on the wear characteristics of friction pairs, firstly, three groups of fixtures with the same contact parameters and different roughness are selected for verification test under the same environment. The results of the radial wear degree of the bar and the surface profile of the fixture are shown in Fig. 17.

The blue, red, and pink curves in Fig. 17 reflect the surface profile of the fixture when the roughness $Ra = 0.32, 0.4$, and $0.5 \, \mu m$, respectively. It can be seen that under the same contact parameters and different fixture roughness, the radial wear degree of the bar surface changes greatly, and the radial wear degree of the bar does not decrease with the decrease of fixture roughness. The radial wear degree of bar under $Ra = 0.4 \, \mu m$ is less than one of the bar under $0.32 \, \mu m$. Therefore, it is significant to further study the influence of fixture surface roughness on bar wear characteristics.

Under four different contact conditions, the AE signal data of the fixture-bar friction pair are collected and analyzed, and the AE characteristic parameter curves characterizing the wear characteristics of the friction pair are obtained, as shown in Fig. 18. It is shown that under different contact conditions, the differences of AE characteristic parameters such as amplitude, energy, RMS, and ASL are

![Fig. 16](image1.png)  
**Fig. 16** Wear surface morphology of bar under different contact conditions

![Fig. 17](image2.png)  
**Fig. 17** Effect of fixture roughness on radial wear of bar
obvious; the AE characteristic parameters reach the maximum value under orthogonal group 11 condition. However, under the optimal combination of contact parameters, the value of AE characteristic parameters reaches the minimum. It can be seen from Fig. 13 that the radial wear degree of the bar under the four working conditions is closely related to the AE signal, and the value of AE characteristic parameters increases with the increase of the radial wear degree of the bar. This is because the radial wear degree characterizes the wear depth of the contact zone between the fixture and the bar. The greater the radial wear degree is, the more severe the extrusion effect of the fixture on the bar surface and the wear characteristics are. Therefore, the AE characteristic parameters increase accordingly.

The amplitude in Fig. 18(a) reflects the intensity of extrusion and collision of the surface asperity when the friction pair is worn under the condition of AE monitoring. The energy in Fig. 18(b) reflects the energy released by the random extrusion collision of the surface asperity when the friction pair is worn. Figure 18(c) and (d) show the wear characteristics of the friction pair respectively. It can be seen from Fig. 18 that when the contact condition remains unchanged, the amplitude, energy, RMS, and ASL of AE characteristic parameters increase slightly at first, then decrease to the minimum, and then increase continuously with the change of the surface roughness Ra of the fixture, and the value of AE characteristic parameters is the minimum when Ra = 0.4 μm. Therefore, under the different contact conditions, when the fixture surface roughness Ra = 0.4 μm, the wear characteristics of the friction pair are optimal.

4 Conclusions

1. A new fixture of cambered grooving structure in low-stress precision cropping is proposed, whose contact parameters are depth of V-groove \( h \), the width of V-groove \( b \), fillet radius of V-groove \( r \), angle of friction increasing groove \( \alpha \), and the number of auxiliary friction grooves. The fixture can significantly reduce the axial sliding of the bar and the wear of the bar surface, which can improve the surface quality of the bar.

2. The results indicate that in the contact parameter, the width of V-grooves \( b \) has the greatest influence on the wear quantity, and the number of auxiliary friction grooves has the greatest influence on the axial sliding distance, which can reduce the axial sliding distance of bars and wear at the same time. On this basis, the
optimal contact parameter scheme of the orthogonal test is obtained as A₄B₃C₂D₁E₄, that is, h = 3.0 mm, b = 1.4 mm, r = 0.3 mm, α = 45°, and the number of auxiliary friction grooves is 12.

3. The radial wear degree is further proposed to research the wear state of the bar surface under four contact conditions. The results show that the radial wear degree of the bar reaches the minimum under the optimal contact condition, which is 0.0469 mm². In the orthogonal group No. 11 contact condition, the maximum radial wear degree is 0.1034 mm². Compared with the linear contact condition, the radial wear degree of the bar is reduced by 34.50% under the optimal contact condition.

4. The results based on SEM indicate that under first three contact conditions, the bar mainly has slight sliding, and two-body contact causes the material to fall off, transfer, and form abrasive particles. Then, with multi-body contact, new micro morphological features such as scratch, plowing, plastic deformation, and caking are produced. The wear mechanism of fixture-bar friction pair is micro sliding wear dominated by adhesive wear and abrasive wear.

5. The radial wear degree of the bar is obviously different under different fixture surface profiles. AE technology is used to study this phenomenon. The results show that the amplitude, energy, RMS, and ASL increase with the increase of radial wear degree of bars. Under the same contact condition, when the surface roughness Ra of the fixture is changed, the AE parameters all show a trend of first increasing, then decreasing, and then increasing. When Ra = 0.4 µm, the AE parameters are all the smallest, and the comprehensive wear characteristics of the friction pair are the best.

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