Research on hydraulic compensation and variable loading arm for a new-type low-stress cropping system

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Abstract

Aiming at that the instability of the loading force in the low-stress cropping causes the poor quality of the bar cross-section, a precision cropping system with hydraulic compensation and variable loading arm is proposed. The working principle of the cropping method is introduced. The stability of the loading force acting on the bar during the blanking process is analyzed, a method for evaluating the stability of the loading force is proposed and on this basis the fixed speed of the main shaft is determined to be 1000r/min. The research results show that the stability of the loading force is improved by applying the reasonable hydraulic compensation force. With the help of stress concentration coefficient and stress intensity factor, the required critical loading force before and after the crack initiation at the V-shaped notch tip is obtained and it is determined that the best loading arm after crack initiation is 24.7mm. Based on it, the abrupt change problem of the critical loading force before and after the crack initiation is further solved. The experimental results also show that the high quality cross-section can be obtained by the proposed cropping method.

Keywords: Low-stress cropping, Hydraulic compensation, Loading arm, Instability, Crack initiation

1. Introduction

In machinery manufacturing industry, the precision cropping of bars is usually the first step in metal forming process, which is widely used in the preparation procedure such as die forging, cold extrusion, metal chain pin, bolts, rolling bearing roller and auto parts production (Wang, 2015). At present, there are mainly three kinds of traditional cropping methods in industrial production: sawing, lathe cutting and shearing blanking (Zhao et al., 2015). Fig. 1 shows the operational principle of three traditional cropping methods. The sawing principle is that the high-speed rotating circular saw blade or grinding wheel moves in a radial way to cut off the bar that is fixed at one end (see Fig. 1(a)). The method of sawing will produce more material loss and the poor surface quality of section. Fig. 1(b) shows that the cutting off of the bar is completed by the radial movement of the lathe tool during the rotation of the bar. The material loss is still existed in the lathe cutting process, but the section quality of the lathe cutting is better than that of the sawing. In Fig. 1(c), the movable tool moves in the radial direction of the bar driven by the press machine, and the bar is cut off from the gap between the fixed tool and the movable tool. There is little material loss in the entire shearing blanking process. However, the accuracy of the section is poor, and the power consumption of the press machine is also large.
It can be found that these cropping methods have many disadvantages to some degree, for instance, low utilization of material, unsatisfactory section quality, low repeatability of cropping length and low quality of blank part (Yan, 2012). Therefore, it is necessary to develop the precision cropping method with high precision, high efficiency, little waste of materials and low energy consumption. Low-stress cropping method is a promising method based on crack technology (Chen et al., 1991)(Chen et al., 1992). The blanking process of this cropping method, which makes full use of the notch effect and bending effect, is as follows. Firstly, many circumferential V-shaped notches with equal spacing are prefabricated artificially on the surface of the bar. Then a certain external force is applied at one end of the bar. Finally, the bars are dynamically separated in the form of low-stress brittle fracture and the blanks with no geometric distortion, vertical flat fracture and chamfering are obtained. Many scholars have studied the new precision low-stress cropping method. Kim et al (Kim J D et al., 2013)(Wang J P et al., 2015) studied the influence of the shape of the mold in the precision cropping on the quality of the cropping section, and obtained a higher quality cropping section. Sutasn et al (Thipprakmas S et al., 2010) used numerical simulation to analyze the material flow and stress state, and revealed the influence of V-ring head on the section quality of the part, and it was found that increase of hydrostatic pressure can smooth the cropping section of the bar. Choi et al (Chio B H., 2011)(Chio B H., 2013) studied the effect of shape of the notch, eccentricity and inclination on the fatigue life of the bar crack in polyethylene. However, these scholars mainly study the microscopic damage of materials during the cropping process from the material point of the view, while neglecting the research on the mechanism of low stress cropping.

Hua et al. (Hua et al., 2004)(Zhang et al., 2007) studied the influence of the geometric parameters of V-shaped notch on the crack initiation in precision cropping, and the reasonable values of the geometric parameters of V-shaped notch were determined. Zhao et al. (Hua et al., 2006)(Zhao et al., 2007) proposed a low-stress cropping method with the variable-frequency vibration based on fatigue fracture mechanism and studied the method for heat stress prefabricating ideal crack at the bottom of V-shaped notch. Tang et al. (Tang et al., 2010) proposed a new-type precision cropping system with controllable multiple pneumatic cylinders and radial impact, as well as built the calculating formula of the maximum load and the initial frequency. Zhang et al. (Zhang et al., 2015) proposed a precision cropping system with high-speed and centrifugal action and analyzed the influence of the geometric parameters of the V-shaped notch on the cropping time. The above studies all reflect the advantages of low-stress cropping to a certain extent. However, these cropping methods also have some limitations in the study of the relationship between the external force acting on the bar and the crack initiation and the crack propagation at the tip of the V-shaped notch, which mainly embodies that the external load required for critical crack expansion will significantly reduce after the tip of V-shaped notch is cracked. At present, the force exerted on the bar in these low-stress cropping methods is difficult to be controlled steadily, which results in poor section quality of the bar. Therefore, a new-type low-stress cropping system based on hydraulic compensation and variable loading arm is proposed in this paper, and its advantages are as follows. Through the hydraulic compensation system, the loading force acting on the bar can be easily controlled. In addition, the loading arm of the bar can be real-time adjusted in the process of blanking, which makes the loading force transit transiently and smoothly to the crack expansion loading curve after the tip of V-shaped notch is cracked. On this basis, the steady crack propagation can be carried out. In this paper, the influence of centrifugal force and hydraulic force on the loading force acting on the bar is studied, and the
optimum speed of the main shaft is determined. By analyzing the loading force before and after the crack initiation at the V-shaped notch tip, the optimum loading arm is obtained, which lays a theoretical foundation for the efficient and smooth operation of the cropping machine.

2. Necessity analysis for hydraulic compensation

![Fig. 2 Schematic diagram of a traditional low-stress cropping system with high-speed and centrifugal action](image)

Fig. 2 shows the schematic diagram of a traditional low-stress cropping system with high-speed and centrifugal action. The traditional low-stress cropping system consists of five parts, which are as follows: main shaft, slider, spring, ball bearing and clamp. The centrifugal force is produced by eccentric slider during the rotation of main shaft. The combined force of the centrifugal force and spring force on the clamped bar through the ball bearing. During the main shaft rotates at high speed, the loading force \( F \) on the bar is a fast alternating force. Under the action of the alternating force, the slider moves along the sliding surface. Thus, a crack on the V-shaped notch of the bar is produced, gradually extend to break the bar.

At the initial state, the eccentricity of the slider is \( R_0 \), and its mass is \( M \). The centrifugal force \( F_1 \) produced by the rotation of the main shaft is expressed as

\[
F_1 = M \omega^2 R = M(R_0 + a + y) \omega^2
\]

where \( \omega \) is the angular velocity of the main shaft, \( a \) is crack depth of V-shaped notch, \( y \) is the deflection of the bar and it is shown as follows:

\[
y = \frac{FL_2^3}{3EI}
\]

where \( F \) is the loading force applied on the bar, \( L_2 \) is the horizontal distance of the loading force point from the tip of the V-shape (the loading arm) and the V-shaped notch tip, \( E \) is the elasticity modulus of bar material, \( I \) is the area moment of inertia of the bar.

The compression force of spring \( (F') \) is expressed as

\[
F' = k(H_0 + a + y)
\]

where \( k \) is the spring stiffness, \( H_0 \) is initial compression length of spring.

Thus, the loading force \( F \) applied on the bar is as follows.

\[
F = F_1 + F' = \frac{3EI[M(R_0 + a)\omega^2 - k(H_0 + a)]}{3EI - M\omega^2 + kL_2^3}
\]

The loading force \( (F) \) on the bar is controlled only by the main shaft speed (see Eq. (4)). In order to achieve the required loading force for cracking, the high rotation speed should be adopted. But the high speed will cause the instability of loading force, and then cause the poor quality of the bar cross-section. If a controllable hydraulic force is used instead of the compression force of spring, the hydraulic force is another controllable factor for the loading force except the main shaft speed. Based on the above analysis, the simplified loading model of a new-type cropping machine is shown in Fig. 3. \( F_2 \) is the hydraulic force provided by hydraulic cylinder. Thus, the loading force on the bar...
is derived as:

$$F = F_1 + F_2 = M(R_0 + a + y)\omega^2 + F_2 = \frac{3EI}{3EI - M\omega^2 L_2^3} \left[ M(R_0 + a)\omega^2 + F_2 \right]$$

(5)

Fig. 3 The simplified loading model of the new-type cropping machine

It can make the bar start cracking at lower speed through the hydraulic compensation for centrifugal force. This solves the problem that the instability of loading force caused by the high speed. Therefore, a new-type low-stress cropping system based on hydraulic compensation is proposed (see Fig. 4). The overall structure of the new-type low-stress cropping system based on hydraulic compensation is shown in Fig 4(a). Fig. 4(b) shows the structural scheme of the new-type low-stress cropping system. When cropping, the system controls the hydraulic chucks 1 and 2 to fix the bar. The converter motor drives the main shaft and slider to rotate through the belt-wheel transmission system. Due to the existence of eccentric distance between the main shaft and slider, the centrifugal force is generated when the slider rotates. The controllable horizontal force provided by the hydraulic cylinder 1 is transmitted to the double thrust mechanism through the thrust bearing. The horizontal hydraulic force is converted into the radial force acting on the slider through the linkage mechanism. The magnitude of the hydraulic force is adjusted by controlling the opening pressure of the proportional overflow valve. Therefore, under the action of hydraulic force compensation, the bar can obtain a larger loading force at a lower speed.

In addition, the movable clamping mechanism can dynamically adjust the loading arm $L_2$ as shown in Fig. 4(b). Before the bar is cracked, the loading force can be changed by controlling the centrifugal force and the hydraulic force. Once there is a crack at the tip of the V-shaped notch, the control system will control the lead screw to feed the movable clamping mechanism and the loading arm $L_2$ will be adjusted in a very short time, which makes the loading force transit smoothly from the crack initiation stage to the crack expansion stage. Thus the loading force and the loading position of the bar can be changed by jointly controlling the centrifugal force, the hydraulic force and the loading arm, thereby changing the stress state at the tip of V-shaped notch. After the bar is cropped, the lead screw is reset, hydraulic chuck 1 is opened and hydraulic chuck 2 is still clamped, then the hydraulic cylinder 2 pushes the remaining bar into the hole of the slider to prepare for the next cropping.

(a)

1. Belt-wheel; 2. Hydraulic cylinder 1; 3. Thrust bearing; 4. Double thrust mechanism; 5. Main shaft; 6. Linkage mechanism; 7. Slider; 8. Bar; 9. Hydraulic chuck 1; 10. Hydraulic chuck 2; 11. Hydraulic cylinder 2; 12. Movable clamping mechanism; 13. Lead screw; 14. Converter motor

(b)

Fig. 4 Schematic diagram of low-stress cropping machine based on hydraulic compensation and variable loading arm: (a) Three dimensional structure diagram of the new-type low-stress cropping system, (b) Structural scheme of the new-type low-stress cropping system
3. Dynamic simulation and stability analysis of the cropping machine

3.1 Dynamic simulation and result analysis based on ADAMS software

In order to study the motion characteristics of the cropping machine, the dynamic simulation of the cropping process is carried out by ADAMS software, and on this basis, the relationships among the centrifugal force, the hydraulic force and the loading force are obtained. In order to facilitate the study of the cropping process, the hydraulic compensation mechanism of the cropping machine in Fig. 4 is simplified to a certain extent, with only the main motion structure of the mechanism retained, and the simulation model and its mechanism diagram are shown in Fig. 5.

![Simulation model and mechanism diagram](image)

![Simulation model and mechanism diagram](image)

Fig. 5 Simulation model of main motion structure of the hydraulic compensation mechanism: (a) Simulation model, (b) Mechanism diagram

| Num | t(s) | n(rpm) | Hydraulic force provided by hydraulic cylinder (N) | Hydraulic force acted on the bar(N) | Loading force (N) |
|-----|------|--------|---------------------------------------------------|-------------------------------------|------------------|
|     |      |        |                                                   | Peak value                          | Valley value     | Mean value      |
| 1   | 5    | 500    | 0                                                 | 0                                   | 126.29           | 0               | 63.13           |
| 2   | 5    | 1000   | 0                                                 | 0                                   | 353.96           | 166.15          | 277.48          |
| 3   | 5    | 1500   | 0                                                 | 0                                   | 803.18           | 364.77          | 534.26          |
| 4   | 5    | 2000   | 0                                                 | 0                                   | 1480.02          | 546.20          | 1068.52         |
| 5   | 5    | 3000   | 0                                                 | 0                                   | 3161.02          | 1607.90         | 2464.42         |
| 6   | 5    | 4000   | 0                                                 | 0                                   | 5699.61          | 2863.35         | 4380.19         |
| 7   | 5    | 0      | 500                                               | 788.89                              | 826.37           | 765.76          | 788.89          |
| 8   | 5    | 500    | 500                                               | 788.89                              | 941.26           | 476.94          | 749.92          |
| 9   | 5    | 1000   | 500                                               | 788.89                              | 1140.63          | 862.81          | 980.07          |
| 10  | 5    | 1500   | 500                                               | 788.89                              | 1790.36          | 1042.83         | 1155.53         |
| 11  | 5    | 2000   | 500                                               | 788.89                              | 2263.82          | 1376.08         | 1519.9          |
| 12  | 5    | 3000   | 500                                               | 788.89                              | 4292.82          | 2242.23         | 3224.7          |
| 13  | 5    | 4000   | 500                                               | 788.89                              | 6555.34          | 3329.5          | 5444.66         |
| 14  | 5    | 0      | 1000                                              | 1575.43                             | 1527.57          | 1681.48         | 1575.43         |
| 15  | 5    | 500    | 1000                                              | 1575.43                             | 1787.70          | 1062.22         | 1445.32         |
| 16  | 5    | 1000   | 1000                                              | 1575.43                             | 1887.59          | 1676.92         | 1676.98         |

Table 1 Simulation parameters and experimental results

During the simulation, the bar is taken as a rigid body. Under the action of hydraulic force with 0-1000N (interval 500N) and the main shaft speed with 0-4000rpm (interval 500rpm), the simulation parameters and simulation results are shown in Table 1 using the single variable method. From Table 1, under the action of the same hydraulic force, with the increase of the main shaft speed, the loading force on the bar is also increased, which has a linear relationship with the square of the main shaft speed. At the same time, there is a linear relationship between the loading force and the hydraulic force at the same main shaft speed.
3.2 Stability evaluation and result analysis of the loading force

During the cropping, the stability of the loading force directly affects the quality of the cropping section, because the change of the loading force directly affects the propagation path of the crack on the section of the V-shaped notch. Therefore, the fluctuation factor is proposed to quantitatively analyze the influence of the centrifugal force and the hydraulic force on the loading force as shown in Eq. (6).

$$\eta = \frac{|F - \bar{F}|}{\bar{F}}$$

(6)

where $\eta$ is a fluctuation factor, $F$ is the loading force and $\bar{F}$ is the mean value of the loading force.

When the hydraulic force is 0N, 250N, 500N and the speed of main shaft is 1500rpm, the loading force and its fluctuation factor is shown in Fig. 6. As shown in Fig. 6, the loading force on the bar only provided by the centrifugal force without the hydraulic force is about half of the loading force both provided by the centrifugal force and having the hydraulic force of 500N. The loading force required for the bar with the diameter of 15mm and notch depth of 1mm is about 1200N when the tip of bar V-shaped notch is cracked. From Table 1, to achieve such a force, the main shaft speed needs to reach between 2000-3000rpm under the action of no hydraulic force. However, the mean value of the loading force on the bar reaches 1155.53N when the main shaft speed is 1500rpm and the hydraulic force is 500N. Most importantly, the fluctuation factor of the loading force having the hydraulic force of 500N is half of one of the loading force without the hydraulic force. It can be concluded from Fig.6 and Table 1 that the loading force can be greatly increased and its fluctuation factor is also reduced after the hydraulic compensation is added, which shows that the stability of the loading force on the bar has been improved.

![Fig. 6 The loading force and its fluctuation factor under the different hydraulic force](image1)

![Fig. 7 The loading force and its fluctuation factor under the different rotating speed of main shaft](image2)

When the hydraulic force is constant 500N, the relationships between the loading force and its fluctuation factor and the main shaft speed are shown in Fig. 7 respectively. As shown in Fig. 7, as the speed increases, the loading force decreases first and then increases, but the mean value of fluctuation factor of the loading force on the bar shows an upward trend. It shows that the fluctuation of the loading force on the bar will also increase with the increase of the main shaft speed, even if it has the function of hydraulic compensation. Therefore, the main shaft speed selected is
neither too small nor too large. Based on it, it is necessary to discuss the influence of the hydraulic force between 500N and 1100N, as well as the main shaft speed between 0 and 1600rpm on the fluctuation factor of the loading force. Thus, the appropriate main shaft speed can be determined to improve the stability of the loading force on the bar.

3.3 Determination of the fixed speed of the main shaft

According to the theory of fatigue life (Zheng et al., 1994), the crack initiation velocity and the crack expansion velocity are related to the loading force and the cycles of the loading force. The more the cycles are, the higher the cracking speed is. Therefore, when determining the speed of the main shaft, apart from considering the fluctuation factor of the loading force on the bar, the cycles of the loading force should be taken into account. The simulation results of relationship between the loading force and the hydraulic force under the different speed of main shaft are obtained in Fig. 8.

![Fig. 8 The loading force and its fluctuation factor: (a) Relation of the loading force and the hydraulic force, (b) Relation between the fluctuation factor and the rotational speed](image)

As shown in Fig. 8(a), within 1000rpm of the main shaft speed, the mean value of the loading force on the bar increases linearly with the uniform increase of the hydraulic force. However, while the main shaft speed is over 1000rpm, the increase of the mean value of the loading force on the bar fluctuates. In addition, under the same hydraulic force, when the main shaft speed is within 400rpm, the influence of the speed on the loading force is very small. When the main shaft speed is over 400rpm, the loading force gradually increases with the increase of the main shaft speed. In particular, the loading force increases dramatically when the main shaft speed is over 1000rpm. Therefore, under the condition of ensuring the sufficient number of cycles of the loading force, the speed that has less influence on the loading force should be determined. As shown in Fig. 8(b), the fluctuation factor is about 0.0482 when the speed is 1000rpm. While the speed reaches 1200rpm, the fluctuation factor is about 0.079, which increases by 63.9%. Considering the influence of the speed on the loading force and the cycle number of the loading force, the main shaft speed is fixed to 1000rpm.

4. Mechanical analysis of the cropping machine

Under the condition of the fixed main shaft speed of 1000rpm, to keep the tip of V-shaped notch being constantly at the state of critical crack initiation and crack expansion, the hydraulic force on the bar should be changed with the change of the loading force, which is the critical loading force before and after the crack initiation. Therefore, it is necessary to calculate the critical loading force before and after the crack initiation.

4.1 Calculation of the critical loading force before and after the crack initiation

Fig. 9 shows the schematic diagram of the structure of V-shaped notch. In Fig. 9, $D$ is the diameter of the bar, $h$ is the radius of the root of V-shaped notch, $d$ is notch depth of V-shaped notch, $\phi$ is the angle of V-shaped notch, $s$ is bottom corner radius of V-shaped notch.
Before the tip of the V-shaped notch is cracked, the stress concentration effect of V-shaped notch is mainly used to promote the crack initiation. Therefore, the formula for calculating the critical loading force at the stage of crack initiation by the method of stress concentration coefficient is expressed as

\[ F_{c1} = \frac{\pi (b - d)^3 \sigma_b}{4L_2 k_i} \]  \hspace{1cm} (7)

where \( \sigma_b \) is ultimate strength of bar material, \( b \) is the bar radius, \( k_i \) is the stress concentration factor of V-shaped notch, and its calculation formula (Huang et al., 1992) is as follows:

\[ k_i = 1 + \left\{ \frac{f(d/b)}{2} - 1 \right\} \left[ 1 - \left( \frac{180}{\phi} \right)^{1.24 d/b} \right] \]  \hspace{1cm} (8)

where \( f(d/b) \) is a shape coefficient, and its expression is

\[ f(d/b) = \frac{3}{8} (1 - \frac{d}{b}) + \frac{3}{8} (1 - \frac{d}{b})^2 + \frac{5}{16} (1 - \frac{d}{b})^3 + \frac{35}{128} (1 - \frac{d}{b})^4 + 0.537 (1 - \frac{d}{b})^5 \]  \hspace{1cm} (9)

After the crack initiation, the initial crack of V-shaped notch tip, whose length is about 0.2mm (Zheng et al., 1994), is regarded as a circular crack. Thus, with the help of stress intensity factor in fracture mechanics, the formula of the critical loading force at the stage of crack propagation is determined as

\[ F_{c2} = \frac{\sqrt{\pi} (b - d - a)^3 K_c}{4L_2 \sqrt{d} f(d/b)} \]  \hspace{1cm} (10)

where \( K_c \) is the fracture toughness of materials.

4.2 Mutation analysis of the critical loading force before and after the crack initiation

From Eqs. (7) and (10), it can be seen that the theoretical critical loading force \( F_{c1} \) required for the crack initiation and the theoretical critical loading force \( F_{c2} \) required for the crack propagation under different crack depths are shown in Fig. 10. When \( b=7.5 \text{mm}, \ d=1 \text{mm}, \ L_2=40 \text{mm}, \ s=0.2 \text{mm}, \ F_{c1} \) is about 1216.9N, and \( F_{c2} (a=0.2 \text{mm}) \) is about 859.6N. It is obvious that there is a step between the critical loading force before and after the crack initiation (the dotted line) in Fig. 10. The critical loading force decreases obviously after cracking. In this case, because of the effect of system inertia, at this time the actual loading force is difficult to quickly transit to the crack propagation loading curve(②), which results in the unstable trajectory of crack propagation and poor quality of the cropping section.
Fig. 10 Relation diagram of the critical loading force under the different $L_2$

However, according to the Eq. (7), it can adjust the loading arm $L_2$ to make the loading force smoothly transit from the crack initiation loading curve to the crack propagation loading curve. To calculate the appropriate loading arm $L_2$, and based on the balance between the torque $M_1$ before the adjustment of $L_2$ and the torque $M_2$ after the adjustment of $L_2$, it can be obtained

$$M_2 = F_{c1} \times \bar{L}_2 = F_{c2} \times L_2 = M_1$$  \hspace{1cm} (11)

Substituting Eqs. (7) and (10) into the Eq. (11), the formula for calculating the load arm $\bar{L}_2$ after adjustment is expressed as

$$L_2 = \frac{(b-d-a)^3 K L_2 k}{\sqrt{\pi d f(b-d)\sigma_0}}$$  \hspace{1cm} (12)

For the bar with V-shaped notch, when $b=7.5\, \text{mm}$, $d=1\, \text{mm}$, $L_2=40\, \text{mm}$, $s=0.2\, \text{mm}$, $a=0.2\, \text{mm}$, the most suitable loading arm $L_2$ is 24.7mm by calculation. Therefore, once the crack of V-shaped notch tip is detected, the loading arm will quickly drop from the original 40mm to 24.7mm, which helps to make the loading force curve smoothly transit from the crack initiation stage to the crack growth stage. By changing $L_2$, the theoretical critical loading force required after the crack initiation is increased, which can be smoothly linked to the loading force required before the crack initiation. Based on it, the whole curve of the loading force including the crack initiation and the crack propagation are obtained in Fig. 10 (③).

5. Experiment results and analysis
5.1 Evaluation method of the cropping section quality

In order to effectively evaluate the section quality for the cropping proposed in this paper, an evaluation method is proposed as shown in Fig. 11. There are three characteristic parameters: the eccentricity $z$ of final rupture region comparative to the center of the bar cross-section, which represents the evenness of crack propagation on the section in circumferential direction. The cross-section roughness $h_1$ (the maximum height difference on bar cross-section) and the area $S$ of final rupture region (the diameter is $d_i$ in Fig. 11), which represent the crack propagation trajectory. When these parameters are measured, firstly it needs to take the main view and top view of the blank section as shown in Fig. 11. Then, the crack propagation zone and the final rupture region are drawn, and based on it, the required values of evaluation parameters are obtained.
5.2 Analysis of the cropping experiment results

For the 45 steel bar with the diameter of 15mm, the bottom corner radius of 0.2mm and the notch depth of 1mm, which is commonly used in engineering practice, the cropping results under different experimental conditions are shown in Table 2. The experimental values of the eccentricity $z$, cross-section roughness $h_1$ and area $S$ of final rupture region in Table 2 are obtained by measurement and calculation. The two critical loading forces ($F_{c1}$ and $F_{c2}$) are obtained by substituting the experimental conditions into Eqs. (7) and (10), respectively. $\Delta F$ is the difference between $F_{c1}$ and $F_{c2}$. It can be found that $F_{c1}$ is constant under all experimental conditions. This is because $F_{c1}$ is determined by the structural dimensions and material properties of the bar based on Eq. (7). But $F_{c2}$ can be changed by adjusting the loading arm (see Eq. (10)).

| Experimental conditions                                      | Eccentricity $z$/mm | Cross-section roughness $h_1$/mm | Area $S$ of final rupture region/mm$^2$ | $F_{c1}$/N | $F_{c2}$/N | $\Delta F$/N |
|-------------------------------------------------------------|---------------------|----------------------------------|----------------------------------------|------------|------------|--------------|
| 1 Without hydraulic compensation and no adjusting the loading arm | 0.673               | 1.13                             | 73.16                                  | 1216.9     | 859.6      | 357.3        |
| 2 Without hydraulic compensation and adjusting the loading arm | 0.427               | 0.73                             | 43.30                                  | 1216.9     | 1158.6     | 58.3         |
| 3 With hydraulic compensation and no adjusting the loading arm | 0.586               | 0.97                             | 58.18                                  | 1216.9     | 850.5      | 366.4        |
| 4 With hydraulic compensation and adjusting the loading arm   | 0.384               | 0.64                             | 35.45                                  | 1216.9     | 1177.4     | 39.5         |

In order to better analyze the experimental data, the following five cases are compared based on Table 2, and the specific results are shown in Fig. 12. By comparing case 1 with case 2, it is found that the adjusting loading arm can significantly improve the section quality in the process of cropping, with or without hydraulic compensation. The eccentricity $z$, the cross-section roughness $h_1$, and area $S$ of final rupture region decreased by about 35%, 35%, and 40% respectively. This is because the adjusting the arm can significantly reduce the mutation ($\Delta F$) of critical loading forces required before and after the crack initiation (from Table 2, $\Delta F$ reduced about 85%). The smaller $\Delta F$ allows the crack to expand slowly and uniformly, thus improving the cropping section quality. Based on the comparison between case 3 and case 4, it is found that hydraulic compensation can improve the section quality regardless of whether there is adjustment of loading arm (the eccentricity, the cross-section roughness and area of final rupture region decreased by about 11%, 13%, 19% respectively). This is because hydraulic compensation can reduce the cracking speed, make the cropping system work relatively stable, and then improve the cropping section quality. As shown in case 5 in Fig. 12, it can also be found that under the combined action of hydraulic compensation and adjusting loading arm, the eccentricity, the cross-section roughness and area of final rupture region decreased by 43%, 44% and 52%, respectively. This further proves that the quality of the section is greatly improved when the hydraulic compensation and the variable loading arm are used in the low-stress cropping system.
6. Discussion

Fig. 13 shows the relationship between the loading force and notch depth of V-shaped notch before and after the crack initiation. As shown in Fig. 13, the critical loading force at the stage of crack initiation ($F_{c1}$) and the critical loading force at the stage of crack propagation ($F_{c2}$) decrease with increasing the notch depth of V-shaped notch. And as the notch depth is close to the bar radius, the two critical loading forces tend to 0. It can also be found that the critical loading force at the stage of crack initiation is always greater than the critical loading force at the stage of crack propagation. Only when the notch depth is the bar radius (7.5mm), the two critical loading forces are equal ($F_{c1}=F_{c2}$). However, the notch depth ($d$) can not reach the bar radius in actual working conditions. Therefore, it is impossible to eliminate the difference between the two critical loading forces by adjusting the notch depth. Based on the above analysis, the hydraulic compensation and variable loading arm are effective means to improve the stability of loading force.

7. Conclusions

The following conclusions can be drawn according to the above analysis:

1) A new-type low-stress cropping method based on the hydraulic compensation and the variable loading arm is proposed, and the cropping method can quickly adjust the loading arm of the bar. At the same time, with the help of hydraulic compensation, the problem of the mutation of the loading force before and after the crack initiation is solved and the stability of the loading force is improved in a certain extent.
2) The fluctuation factor for evaluating the stability of the loading force in the blanking process is proposed. The fluctuation factor of the loading force having the hydraulic force of 500N is half of one of the loading force without the hydraulic force. The main shaft speed is fixed to 1000rpm, which is also beneficial to the improvement of stability of the loading force.

3) The formula for calculating the critical loading force before and after crack initiation is given, and the whole curve of the loading force including the crack initiation stage and the crack propagation stage are obtained. The most suitable loading arm \( L_2 \) in theory after cracking is determined as 24.7mm.

4) For the low-stress cropping method, this paper proposes a new evaluation method on bar cross-section quality, which mainly includes the cross-section roughness, the area and the eccentricity of final rupture region. The cropping experimental results show that the quality of the cropping section is greatly improved based on the hydraulic compensation and the variable loading arm.

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