Article

Influence Rule of Annular Notch Geometric Parameter on the Tubing Surface: A Case Study

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Abstract: In regards to the problem of tubing precision separation, the high-efficiency precision separation method for tubing under eccentric wheel high-speed rotational bending fatigue loading is proposed, which aims to promote the initiation of fatigue cracks at the root of the annular V-notch on the tubing surface. Research on the stress concentration effect of the annular notch on the tubing surface is carried out. The design of the notch takes into account the characteristics of tubing precision separation. The numerical simulation calculation includes four kinds of notches, namely, annular V-notch, annular U-notch, asymmetric V-notch towards the blanking end direction 45°, and asymmetric V-notch away from the blanking end direction 45°. The crack propagation lengths produced by each notch under the same experimental conditions are investigated experimentally. According to the findings, the annular V-notch is suitable for this separation method. By analyzing the theoretical stress concentration factor of the annular V-notch on the tubing surface, three main parameters affecting the annular V-notch root stress field are determined, namely, notch angle, notch depth, and notch root base angle radius. Through calculation and analysis, the influence law of tubing annular V-notch angle, notch depth, and notch root base angle radius on the stress concentration effect is obtained. Based on the process characteristics of tubing precision separation, the ideal tubing annular V-notch geometric parameter is presented within a reasonable value range. For the validation experiment of tubing precision separation, 45# steel, 304 stainless steel, and T2Y copper tube are selected, respectively. Finally, a great tubing precision separation effect is achieved, which verifies the reasonable selection of the tubing surface annular V-notch geometric parameter.

Keywords: tube; precision separation; stress concentration; v-notch; crack initiation

1. Introduction

Due to the hollow structure, the tube is easily deformed due to radial impact and compression. In China, saw blades or grinding wheel blades are commonly used to cut tubing. This method has disadvantages such as high metal consumption, high noise, and long burrs [1–5]. In contrast, shear processing is a more economical blanking method, with no scrap loss and high production efficiency, which is suitable for mass production of metal bars. However, the roughness of the tubing produced by the ordinary shearing method is relatively low so that it cannot meet the precision requirements [6–8]. At present, there are many kinds of precision cutting methods. However, there is a lack of cutting research on tubing; there are only studies such as shearing with core bar [9,10]. In addition, this cutting method will cause inevitable defects such as collapse and tear of the tubing section. Therefore, it is necessary to further explore and improve the new tubing cutting technology and cutting mechanism.
The tubing precision separation, high-efficiency precision separation method for tubing under eccentric wheel high-speed rotational bending fatigue loading, proposed to adapt to this development trend and requirements, can solve the problems of material waste, low efficiency, and poor section quality of existing tubing separation methods, which provides an effective way to realize the high efficiency and precision of the tubing separation. First, the surface of the tubing is artificially prefabricated with an annular groove, which applies cyclic bending fatigue loads in the radial direction of the tubing by rotating a specially designed eccentric wheel at high speed. Under the stress concentration effect of the annular groove and the dynamic load of bending fatigue, the root of the tubing annular groove quickly initiates microcracks. In addition, the macroscopic cracks continuously propagate towards the center of the tubing in the specified direction and velocity in the section of the tubing annular groove. Ultimately, efficient and precisely controlled separation of tubing is achieved. The principle is shown in Figure 1. The annular notch on the tubing surface is a major factor affecting fatigue fracture. The stress concentration effect produced by different notch shapes is obviously different [11,12].

![Figure 1. Principle of tubing high-efficiency precision separation of eccentric wheel high-speed rotational bending fatigue loading: (a) schematic diagram of circumferential rotational bending fatigue loading of eccentric wheel; (b) schematic diagram of tubing high-efficiency precision separation.](image)

2. Tubing Notch Design and Finite Element Simulation Analysis

2.1. Notch Design and Finite Element Model Establishment

To compare the effects of different forms of notches on the tubing fatigue fracture, based on the ABAQUS software (2021HF5 (6.21-6), ABAQUS Inc., Palo Alto, CA, USA), the maximum stress of the notch root of several different forms of notch specimen models under the same conditions is calculated and analyzed to study the stress concentration effect. The notch that can generate the maximum stress under the same restraint and external load F loading is regarded as the most favorable form of notch for fracture. The schematic diagram of the tubing loading finite element model is shown in Figure 2. Design for the circular tubing notch should be based on the uniform annular notch. Therefore, the notch forms mentioned later in this article are prefabricated uniform annular notches on the tubing circumference. In this article, there are four common notch specimen models, including annular V-notch, annular U-notch, asymmetric V-notch towards the blanking end direction 45°, and asymmetric V-notch away from the blanking end direction 45°. The geometry of the outline is the same for the four notch specimen models. The outer diameter of the steel tube is φ 20 mm, the wall thickness is 3 mm, and the length of the fixed end is 20 mm. The blanking end has a blanking length of 50 mm and a notch depth h of 1 mm. The base angle radius of flare angle ρ is 0.1 mm. In general, the difference between the models is only in the notch form [13,14].
2.2. Analysis of Numerical Simulation Calculations

For the analysis and calculation based on the ABAQUS software, modeling is carried out according to the mathematical model of Figure 2 for different forms of notch SUS 304 stainless steel tubing. Then, the model is meshed. The four notch tubing loading models set the same grid parameters to ensure the reliability of the analysis results. Moreover, the simulation object is 304 stainless steel, with elastic modulus of $2.1 \times 10^5$ MPa, Poisson’s ratio of 0.3, and density of 7850 kg/m$^3$, as shown in Table 1. The failure criterion adopts the maximum principal stress criterion. The four notch tubing loading models are also set to the same loading conditions. All six degrees of freedom of the tubing at the fixed end are restricted, and the blanking end is subjected to the same load. For the applied load, a relatively small value is chosen because of the singularity of the root stress in the notch tubing loaded model. If a large load is applied to the model, the calculated maximum stress at the root of each notch tubing loaded model will be greater than the strength limit of the material, which is not convenient for comparison. In order to distinguish the notch root stress of each model more clearly, a lateral force of 350 N is applied to the end of each model.

Table 1. Chemical composition and physical properties of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>C Content (%)</th>
<th>Cr Content (%)</th>
<th>Si Content (%)</th>
<th>Mn Content (%)</th>
<th>Melting Point (°C)</th>
<th>Yield Stress (MPa)</th>
<th>Mass Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>304 stainless steel</td>
<td>0.07</td>
<td>18.53</td>
<td>0.74</td>
<td>1.50</td>
<td>1400</td>
<td>270</td>
<td>7850</td>
</tr>
</tbody>
</table>

First, the V-notch tubing specimen is analyzed. The flare angle of the annular V-notch $\alpha$ is 90°, the notch depth $h$ is 1 mm, and the notch root base angle radius $\rho$ is 0.1 mm. The element grid selects Hex elements, which are calculated using linear reduced-integration elements. Figure 3 shows the Mises stress results of tubing with V-notch after loading. According to Figure 3, it can be seen that the maximum stress occurs at the V-notch with a value of 158.9 MPa. Next, analysis of the asymmetric V-notch specimen towards the blanking end direction 45° is performed. The notch depth $h$ is 1 mm, and the notch root base angle radius $\rho$ is 0.1 mm. The element grid selects Hex elements, which are calculated with linear reduced-integration elements. Figure 4 shows the Mises stress results of the
tubing with asymmetric V-notch towards the blanking end direction 45° after loading. According to Figure 4, it can be seen that the maximum stress occurs at 45° notch in the forward direction, and its value is 48.5 MPa.

Figure 3. Mises stress moiré diagram of V-notch tubing.

Then, analysis of the asymmetric V-notch specimen away from the blanking end direction 45° is performed. The notch depth $h$ is 1 mm, and the notch root base angle radius $\rho$ is 0.1 mm. The element grid selects Hex elements, which are calculated using linear reduced-integration elements. Figure 5 shows the Mises stress results after loading for tubing with the asymmetric V-notch away from the blanking end direction 45°. According to Figure 5, it can be seen that the maximum stress is at the notch in the reverse 45° direction, and its value is 53.5 MPa. Finally, the analysis of the U-notch specimen is carried out. The notch depth $h$ is 1 mm, and the notch root base angle radius $\rho$ is 0.1 mm. The element grid selects Hex elements, which are calculated with linear reduced-integration elements. Figure 6 shows the Mises stress results of tubing with U-notch after loading. According to Figure 6, it can be seen that the maximum stress is at the U-notch with a value of 43.4 MPa.
The structures of the four specimens are shown in Figure 7.

It can be seen from the above analysis that the maximum stress at the maximum stress concentration of the V-notch tubing is the largest among the four kinds of notches, which is similar to the conclusion in Ref. [15]. Furthermore, the maximum stress of the asymmetric V-notch towards the blanking end direction $45^\circ$ is slightly smaller. Therefore, V-notch is the most prominent form of the stress concentration.

To further validate the simulation results, a comparison of fatigue initiation crack with four different notches is performed. The tubing is the same material and type to ensure accuracy. Among them, the materials of the specimen are all SUS 304 stainless steel. Notches of the desired shape are prepared in advance on a lathe prior to the experiment. The blanking length is consistent with the simulated length, and each section is $50$ mm. Three specimens are prepared for each notch tubing, with a total of 12 specimens. There are four groups, namely V-notch specimen, U-notch specimen, asymmetric V-notch specimen towards the blanking end direction $45^\circ$, and asymmetric V-notch specimen away from the blanking end direction $45^\circ$. The outer diameter of the tubing is $20$ mm and the wall thickness is $3$ mm. To avoid the effect of notch base angle radius, each notch base angle radius $\rho$ is set to $0.1$ mm. The structures of the four specimens are shown in Figure 7.
The V-notch specimen, U-notch specimen, asymmetric V-notch specimen towards the blanking end direction 45°, and asymmetric V-notch specimen away from the blanking end direction 45° are studied separately. Within a short period of time of loading, the tubing does not fracture but already initiates microcracks or just promotes the growth of small cracks. In this case, the crack length for each notch can be visually compared. Under the same loading conditions, the longest notch form of the crack is the most favorable for the initiation and propagation of the tubing crack. The simulation results are verified, which can provide a reference for the subsequent selection of the tubing notch.

Validation experiments are performed on the precision separation testing machine of metal tubes. The constant frequency loading method is adopted. The loading frequency is 4.5 Hz, and the loading time is 10 s. After the loading is completed, the notch portion of the tubing is half-cut to a length of 10 mm by wire cutting. Then, the cut specimens are subjected to metallographic experiments. Figure 8 is a microscopic picture of four kinds of specimens, namely annular V-notch, annular U-notch, asymmetric V-notch towards the blanking end direction 45°, and asymmetric V-notch away from the blanking end direction 45°. First, the resin mounting method is used to mount specimens. Then, the specimens are polished to 1800# with metallographic sandpaper. Moreover, manual pressure is used to polish specimens on the metallographic polishing machine. Finally, Neophot-21 metallographic microscope is used to observe and photograph the metallographic specimens.
From Figure 8, it can be seen that the order of the cracks is asymmetric V-notch specimen towards the blanking end direction 45°, annular V-notch specimen, asymmetric V-notch specimen away from the blanking end direction 45°, and U-notch specimen. Under the same loading conditions, the asymmetric V-notch specimen towards the blanking end direction 45° is most prone to cracks, followed by the annular V-notch specimen. Therefore, asymmetric V-notch towards the blanking end direction 45° and annular V-notch are suitable for the blanking method herein. This result is consistent with the analysis by ABAQUS software.

3. Stress Concentration Factor of Annular V-Notch on Tubing Surface

The V-notch induces elastic stress, stress-strain concentration, and triaxial stress that constrain plastic deformation. Therefore, the material is more prone to overall yielding, which effectively increases the brittle fracture tendency effect. The stress concentration at the bottom tip of the V-notch is directly related to the crack initiation direction, propagation tendency, and total life of the V-notch root crack. The cutting sections obtained by different tubing V-notch geometric parameters are different. Therefore, it is necessary to study the influence of the stress concentration at the tip of the tubing V-notch on the low-cycle fatigue precision blanking of thick-walled tubing. For a certain tubing with outer diameter of D and inner diameter of d, the geometric characterization parameters of V-notch are shown in Figure 9, including three geometric parameters of notch depth h, notch root base angle radius ρ, and shape flare angle α. The length of tubing precision separation is L1.
where \( \sigma_x \), \( \sigma_y \), and \( \sigma_z \) are the triaxial stress state near the root of tube V-notch respectively; \( v \) is the Poisson’s ratio; \( \tau_{xz} \) is the shear stress perpendicular to \( x \) axis on the plane \( xz \); \( \tau_{yz} \) is the shear stress perpendicular to \( y \) axis on the plane \( yz \); \( r \) and \( \theta \) are Polar coordinates; \( \rho \) is the groove bottom curvature radius; \( K_1 \) is the stress intensity factor.

When the tubing surface is smooth, the nominal stress at the corresponding tip point is \( \sigma \). When the tubing is prefabricated with annular V-notch, the maximum peak stress of the tubing at the V-notch tip is \( \sigma_{max} \). Under bending load, the theoretical stress concentration factor of the V-notch tip is as follows [19]:

\[
k_1 = \sigma_{max} / \sigma
\]

When the tubing with V-notch is subjected to radial loading, it is mainly subjected to bending loads. The force on principle diagram is shown in Figure 10. Among them, \( M \) is the bending moment of the tubing. In Equation \( (1) \), \( K_1 \) is the stress intensity factor at the crack tip when the profile flare angle is 0°. In order to describe the stress intensity factor at the tip of the tubing V-notch more accurately, Equation \( (1) \) \( K_1 \) is modified [20] as follows:

\[
k_1 = \sigma \sqrt{\pi h f_1}
\]
where $f_1$ is the coefficient, which can be found in Ref. [21]. It can be seen from Ref. [22] that 
\[
\sigma = \frac{4MR_f}{\pi(R_1^4 - R_2^4)}.
\]

\[\sigma_f = \frac{\sqrt{h}}{\rho} f_1 \cos \frac{\theta}{2} (1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} + \cos \frac{3\theta}{2}) \]

When $\theta = 0^\circ$
\[
\sigma_f = 2 \sqrt{\frac{h}{\rho}} f_1 = k_0 \sigma
\]

Therefore, when the shape flare angle is 0°, the theoretical stress concentration factor of the tip notch is:
\[
k_0 = 2 \sqrt{\frac{h}{\rho}} f_1
\]

When the shape flare angle of V-notch is $\alpha$, the relationship between its theoretical stress concentration factors $k_f$ and $k_0$ is [23–25]:
\[
k_f = 1 + (k_0 - 1) \times [1 - (\frac{\alpha}{180})^{1+2.4\sqrt{\rho/h}}]
\]

Equation (6) is substituted into Equation (7). When the shape flare angle of V-notch is $\alpha$, the corresponding theoretical stress concentration factor is:
\[
K_f = 1 + (2 \sqrt{\frac{h}{\rho}} f_1 - 1) \times [1 - (\frac{\alpha}{180})^{1+2.4\sqrt{\rho/h}}]
\]

According to the theoretical stress concentration factor expression, it can be clearly seen that V-notch depth $h$, V-notch root base angle radius $\rho$, and V-notch shape flare angle $\alpha$ are the three main factors affecting the notch’s stress concentration effect [26].

4. Influence Law of Annular V-Notch Key Geometric Parameter

ABAQUS software is used for the analytical calculations and the model is meshed. Element mesh Select Hex elements use linear reduced integration elements for calculations. For the main body of tubing, the element size of the finite element model is 1 mm. The V-groove area is separately divided by the quantitative method. The total number of
elements for the tubing finite element model is 18,354. The 3D mesh model of tubing V-notch is shown in Figure 11. The notch flare angle, notch depth, and notch root base angle radius will be studied in detail below.

Figure 11. Three-dimensional mesh model of tubing V-notch.

4.1. Influence of Tubing Annular V-Notch Flare Angle

According to the finite element model shown in Figure 2 and the theoretical stress concentration factor relational Equation (8), the #45 steel tube specimen is analyzed. Figure 12 shows the influence of the V-notch shape on the flare angle when the outer diameter of the tubing is 20 mm, the inner diameter is 14 mm, the notch root base angle radius is 0.1 mm, and $30^\circ \leq \alpha \leq 120^\circ$.

Figure 12. Effect of V-notch flare angle $\alpha$ on $k_t$. 

According to Figure 12, with a certain notch depth, the larger the notch flare angle $\alpha$, the smaller the impact on the theoretical stress concentration factor $k_t$. The smaller
According to Figure 12, with a certain notch depth, the larger the notch flare angle $\alpha$, the smaller the impact on the theoretical stress concentration factor $k_t$. The smaller the notch flare angle, the better the stress concentration effect of fracture. When the flare angle is the same, the deeper the notch depth, the greater the influence of the stress concentration effect. At that time, it should be noted that the corners that are too small are prone to sharpening and chipping. In traditional tubing separation methods, the separated blank ends usually require secondary machining, namely, turning a $45^\circ$ chamfer. Through the blanking method proposed in this paper, the tubing blank does not need to be processed twice. Based on the above reasons, the V-notch angle of tubing in this paper is preferably $90^\circ$, so as to save the turning and chamfering process after blanking.

4.2. Influence of Tubing Annular V-Notch Depth

Figure 13 shows the influence law of the theoretical stress concentration factor at the tip of tubing V-notch when the tubing diameter is 20 mm, the inner diameter is 12 mm, the notch flare angle is $90^\circ$, and the notch depth ranges from 0.3 mm to 1.7 mm.

![Figure 13. Effect of V-notch depth $h$ on $k_t$.](image)

It can be seen from Figure 13 that with a certain V-notch shape flare angle, the theoretical stress concentration factor will increase first and then decrease with the increase of notch depth. When $h = 0.5$ mm, the theoretical stress concentration factor $k_t$ reaches the maximum. In addition, reducing the same amount of $\rho$ has different effects on the theoretical stress concentration factor. When the $\rho$ is smaller, the theoretical stress concentration factor has a larger variation range.

With the increase of notch depth, the stress concentration factor first increases and then decreases, which is due to the decrease of the ligament area of tubing. In shrimp with the same bending moment, the axial tensile stress generated on the root tip surface of annular V-notch decreases rapidly with decreasing ligament radius, resulting in a rapid decrease in stress concentration factor. For tubing with a defined wall thickness, the depth of the annular V-notch should not be too large. The notch depth that is too deep will cause waste in the turning process. Considering the processing technology and economy, the depth $h$ of annular V-notch is preferably less than 3 mm for the tube with wall thickness below 15 mm.
4.3. Influence of Tubing Annular V-Notch Root Base Angle Radius

Figure 14 shows the influence law of the theoretical stress concentration factor at the tip of tubing V-notch when the tubing diameter is 20 mm, the inner diameter is 14 mm, the notch flare angle is 90°, and the notch root base angle radius ranges from 0.05 mm to 1.3 mm. The tubing notch depth \( h \) is 0.5 mm, 0.8 mm, 1.3 mm, and 1.6 mm, respectively. According to Figure 14, the corresponding stress concentration factor \( k_t \) gradually decreases with the increase of notch root base angle radius. The base angle radius is an important factor in the parameters of the tubing annular V-notch.

![Figure 14: Effect of V-notch root base angle radius \( \rho \) on \( k_t \).](image)

In theoretical studies, the smaller the notch root base angle radius, the better. When the radius tends to 0, the theoretical stress concentration factor increases rapidly. In view of the limitations of machining tools in actual industrial production, there is a minimum critical radius at the tool tip itself when machining round holes or rounding corners. When it is less than this minimum value, the life of the tool can be greatly reduced, which then directly affects the processing efficiency. Considering the economy and processing efficiency, the notch root base angle radius is preferably 0.1 mm–0.5 mm.

5. Determination of Tubing Annular V-Notch Geometric Parameter

With the steel tube with outer diameter of 48 mm and inner diameter of 26 mm as analysis object, the finite element software ABAQUS is used for the simulation analysis. In the setup, the length of the fixed restraint end is 20 mm, and the length of the blanking end is 50 mm. Moreover, the displacement load of 0.05 mm is added to the tubing blanking end. When \( \rho = 0.1 \) mm, \( h = 1.0 \) mm, and \( \alpha = 90^\circ \), the bending stress distribution along the axial direction at \( z = 1.5 \) mm on the upper surface at different sections in the axial direction is used for analysis.

According to Figure 15, the farther from the blanking end V-notch, the lower the bending tensile stress at the upper edge, since the corresponding reduction in the moment arm reduces the bending moment. The stress value is the largest at the cross-section \( (x = 5 \text{ mm}) \) where the V-notch is located, which further indicates that the most likely place for the tube to initiate cracks is at the V-notch.
In order to study the relationship between the V-notch root radius $\rho$ and the resulting corresponding stress $\sigma$, $\alpha = 90^\circ$, $\rho = 0.1 \sim 1.0$ mm, and $h = 0.55 \sim 5.0$ mm are set for numerical calculation. In order to ensure universality, when $h = 0.5$ mm and $h = 2.75$ mm, the value of $\rho$ is set as $0.1 \sim 1.0$ mm. The numerical calculation results are shown in Figure 16.

According to Figure 16, as the notch root base angle radius increases, the corresponding stress gradually decreases. When $0.1 \leq \rho \leq 0.3$, the stress change is the largest. When $\rho$ is greater than $0.3$ mm, the change of stress is slow, and shows a gradually decreasing trend. When $h = 2.75$ mm, the corresponding stress is greater than the corresponding stress when $h = 0.5$ mm.

In order to study the relationship between the notch depth $h$ and the resulting corresponding stress $\sigma$, $\alpha = 90^\circ$, $\rho = 0.05 \sim 1.0$ mm, and $h = 0.55 \sim 5.0$ mm are set for numerical calculation. When $h = 2.75$ mm, the value of $\rho$ is set as $0.1 \sim 1.0$ mm. The numerical calculation results are shown in Figure 16.

![Figure 15](image1.png)  
**Figure 15.** Stress distribution along the axial direction at $z = 1.5$ mm on the upper surface of the tubing.

![Figure 16](image2.png)  
**Figure 16.** Relationship between $\rho$ and $\sigma$. 

When $h = 0.5$ mm and $h = 2.75$ mm, the value of $\rho$ is set as $0.1 \sim 1.0$ mm. The numerical calculation results are shown in Figure 16.
calculation. When \( \rho = 0.4 \) mm and \( \rho = 1.0 \) mm, the corresponding V-notch bottom depth \( h \) is taken as 0.35–5.0 mm. The calculated maximum stress results are shown in Figure 17.

From Figure 17, as the notch depth increases, the corresponding stress also increases gradually. When \( 0.5 \leq h \leq 2 \), the stress increases rapidly. When \( h > 2 \) mm, the increasing trend of stress becomes slower. The corresponding stress at \( \rho = 0.4 \) mm is greater than the stress at \( \rho = 1.0 \) mm. Under the same notch depth, the smaller the notch root base angle radius, the greater the stress.

According to the influence of the tubular geometric parameter on the stress concentration factor and a large number of calculation simulations, the processing technology, economy, and processing efficiency are considered. When the outer diameter \( D \), the wall thickness \( H \) of the tubing, and the length of the blanking material \( L \) are determined, the reasonable value range of the annular V-notch geometric parameter of the tubing surface with the outer diameter less than 50 mm and the wall thickness between 3 and 20 mm is \( 0.025 \leq r / h \leq 0.1 \), \( h / H = 0.2 \), \( \alpha = 90^\circ \), and \( L / D > 1.25 \).

### 6. Tubing High-Efficiency Precision Separation Experiment

The experimental device was developed by the research group based on the proposed precision separation method under eccentric wheel high-speed rotational bending fatigue loading. Its main mechanism consists of a transmission mechanism, radial loading and unloading mechanism, and tubing fixing device. The control part includes the loading frequency control system and blanking sound detection. As shown in Figure 18, the precision separation method under eccentric wheel high-speed rotational bending fatigue loading comprehensively utilizes the rapid initiation of microcracks and the controllable crack propagation technology. First, the tubing surface is artificially prefabricated with annular notches. Through the high-speed rotation of the designed eccentric wheel, the periodic cyclic bending fatigue load is applied to the tubing radial direction. The blanking die will load the tubing radially during the rotation with the eccentric wheel. Each revolution is a loading cycle. Under the stress concentration effect of annular notch and the dynamic load of bending fatigue, microcracks rapidly develop at the root of the annular notch. In addition, the macrocracks continuously expand to the tubing center according to the specified direction and growth rate in the section of the annular notch. Ultimately, efficient, precise, and controllable separation of tubing is achieved. In simple terms, the tubing with prefabricated notches applies periodic radial load by adjusting the loading frequency of
the motor, which causes microcracks at the root of the annular notch and promotes crack propagation until the tube breaks and separates.

![Diagram of tubing loading device and tubing fixing device.](image)

**Figure 18.** Diagram of tubing loading device and tubing fixing device.

Table 2 shows the chemical composition and physical properties of materials of 45# steel and T2Y copper tube, and the chemical composition and physical properties of materials of 304 stainless steel have been shown in Table 1. Table 3 shows the material, type, and annular V-notch geometric parameter of the tubing used. Through experimental research and verification, the V-notch geometric parameter used for precision separation of tubing sections was selected. Figure 19 is the actual picture of the tube separation blank, including (a) 45# steel tube precision separation specimen, (b) 304 stainless steel tube precision separation specimen, (c) T2Y copper tube precision separation specimen, and (d) 304 stainless steel with ruler.

**Table 2.** Chemical composition and physical properties of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si Content (%)</th>
<th>Ni Content (%)</th>
<th>Cr Content (%)</th>
<th>Cu Content (%)</th>
<th>Elastic Modulus (MPa)</th>
<th>Yield Stress (MPa)</th>
<th>Mass Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45# steel tube</td>
<td>0.35</td>
<td>0.30</td>
<td>0.25</td>
<td>0.25</td>
<td>2.1 × 10⁵</td>
<td>335</td>
<td>7850</td>
</tr>
<tr>
<td>T2Y copper tube</td>
<td>/</td>
<td>0.005</td>
<td>99.95</td>
<td>/</td>
<td>1.37 × 10⁵</td>
<td>80</td>
<td>8900</td>
</tr>
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</table>

**Table 3.** Specifications of experimental tubing and its surface V-notch geometric parameter.

<table>
<thead>
<tr>
<th>Material</th>
<th>D</th>
<th>d</th>
<th>L1</th>
<th>α</th>
<th>ρ</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td>45# steel</td>
<td>φ20 mm</td>
<td>φ14 mm</td>
<td>50 mm</td>
<td>90°</td>
<td>0.2 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>304 stainless steel</td>
<td>φ20 mm</td>
<td>φ14 mm</td>
<td>50 mm</td>
<td>90°</td>
<td>0.2 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>T2Y copper tube</td>
<td>φ20 mm</td>
<td>φ14 mm</td>
<td>50 mm</td>
<td>90°</td>
<td>0.2 mm</td>
<td>0.5 mm</td>
</tr>
</tbody>
</table>
The notch depth \( h \) of the annular V-notch is preferably less than 3 mm. As the notch root base angle radius \( \rho \) increases, the theoretical stress concentration factor first increases and then decreases. The suitable range of notch root base angle radius \( \rho \) according to the geometric parameter. The notch not only provides a good stress concentration effect for tubing crack initiation, but also creates conditions for subsequent stable expansion, which is conducive to the rapid initiation and smooth expansion of cracks. To a large extent, tubing precision separation time is shortened and efficiency is improved. Furthermore, this results in a good profile of blank.

7. Conclusions

(1) According to the characteristics of the proposed precise separation technology of metal round tubing, annular V-notch, annular U-notch, asymmetric V-notch towards the blanking end direction 45°, and asymmetric V-notch away from the blanking end direction 45° are designed. Through numerical simulation calculation, the relevant experimental research is conducted on the crack propagation length of each kind of notch under the same experimental conditions. Through comprehensive analysis, it can be determined that the annular V-notch is the most suitable notch for this separation method. After analyzing the relationship between the crack initiation at the root tip of the V-notch and the stress field, as well as the stress state of the tubing under radial bending loading, the theoretical stress concentration factor expression of the annular V-notch is established:

\[
K_I = 1 + (2 \left( \sqrt[3]{h} f_1 - 1 \right) \left( 1 - \left( \frac{\alpha}{180} \right)^{1.24 \sqrt{\rho/h}} \right))
\]  

(9)

(2) Through the analysis of the influence of the three main geometric parameters of notch flare angle \( \alpha \), notch root base angle radius \( \rho \), and notch depth \( h \) of the V-notch on tubing surface on the theoretical stress concentration factor, the influence rule is obtained. The smaller the notch flare angle \( \alpha \), the greater the stress concentration effect of fracture. Therefore, the recommended flare angle for the tubing V-notch is \( 90^\circ \). With the increase of notch depth \( h \), the theoretical stress concentration factor first increases and then decreases. The notch depth \( h \) of the annular V-notch is preferably less than 3 mm. As the notch root base angle radius increases, the theoretical stress concentration factor decreases continuously. The suitable range of notch root base angle radius is 0.1 mm–0.5 mm. According to the influence law of the three main parameters, further research on the relationship between the geometric parameters of the annular V-notch and its value range is carried out.
It is determined that the ideal value range of tubing annular V-notch geometric parameter is as follows: 0.025 < \( r/h < 0.1 \), \( h/H = 0.2 \), \( \alpha = 90^\circ \), and \( L/D > 1.25 \).

(3) In the eccentric wheel high-speed rotational bending fatigue loading experiment, the tube materials are 45# steel tube, 304 stainless steel tube, and T2Y copper tube, respectively. The outer diameter of the tubing is 20 mm, the wall thickness is 3 mm, the flare angle \( \alpha \) of the surface V-notch is 90°, the root base angle radius \( \rho \) is 0.2 mm, and the depth \( h \) is 0.5 mm. A great precision separation effect is obtained, which verifies the rationality of annular V-notch geometric parameters on the tubing surface. The follow-up research will combine the characteristics of the annular notch on the tubing surface to study the crack initiation and propagation process during the precise separation process of the eccentric wheel high-speed rotating bending fatigue loading. Through the numerical simulation and experimental study on tubing separation, the tubing fatigue fracture separation mechanism and the crack propagation law will be further revealed.

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**References**

1. Liu, Y.; Ikeda, S.; Liu, Y.; Kang, L.; Ge, H. Experimental Investigation of Fracture Performances of SBHS500, SM570 and SM490 Steel Specimens with Notches. *Metals* 2022, 12, 672. [CrossRef]
2. Chmelko, V.; Harakal, M.; Zlabek, P.; Margetin, M.; Durka, R. Simulation of Stress Concentrations in Notches. *Metals* 2022, 12, 43. [CrossRef]