Study on the influence of tube surface notch on crack initiation during blanking

R F Zhao, X D Xiao*, L Guo, W C Gao, and Y W Liu

School of Mechanical and Instrument Engineering, Xi’an University of Technology, 5 South Jinhua Road, Xi’an Shaanxi 710048, China

*E-mail: xiaoxd@xaut.edu.cn

Abstract. In the process of precision tube separation, according to the prefabricated notches on the outer surface of the tube, the notch effects of different types of notches are studied, and the influence of the stress field at the root of the annular V-shaped notch is analyzed. It is determined that the notch angle, notch depth and the radius of the bottom angle of the notch root are the three main parameters that affect the stress field at the root of the notch, and the mathematical expression of the V-notch parameters suitable for tube separation is derived. The design of tube precision separation notch is put forward, and four different notches are numerically simulated. It is concluded that 45° asymmetric V-shaped notch and annular V-shaped notch facing the cutting end are the two notches which are more suitable for the blanking method in this paper. An experimental study is carried out on the crack propagation caused by the notch, and the experimental results are consistent with the numerical simulation results.

1. Introduction

Because of the hollow structure of the pipe, it is easy to deform when suffer from radial impact and compression. Saw blade or grinding wheel is widely used to cut off the pipe. The disadvantages of this method are more metal consumption, loud noise and longer burrs[1-5]. Shear machining is an economical method of feeding. It has no waste loss and with high production efficiency. It is suitable for mass production of metal rods. However, the raw materials produced by ordinary shearing method are less accurate, it cannot meet the requirements of tube precision forming[6-8]. Nowadays, the new methods for the development of various precise blanking materials are developed. But there is little research references on the tube blanking, only a few such as cutting with core rods[9,10]. And this method can makes the pipe section collapse, tear and other unavoidable defects, therefore, we need to further explore and perfect the new material process and material mechanism.

The ring gap types of pipe surface are one of major factors affecting fatigue fracture. The stress concentration effects are significantly different produced by different notch shapes[11,12]. Therefore, the appropriate gap type can reduce the external force during the fatigue fracture of the pipe, also reduce energy consumption. So, the study of the gaps design and the stress concentration effect of the pipe material are important problems in the research of the precision blanking for metal bars.

2. Analysis of stress field at the root of V-notch on the tube surface

V-shaped notch is the most common ring notch type, the maximum stress strain concentration area is in the root of V-shaped notch[13]. Whether the tip of the V-shaped notch root can initiation or expand related to the stress field here. Therefore, when the stress field near the tip of the V-shaped notch root is calculated, it can be helpful to analyze which parameters are related to the stress concentration of the
root of V-shaped notch. The stress field of the plane elliptical notch is studied in reference [14]. This article is based on this, combined with the stress concentration effect of V-shaped notch, the stress field distribution near the tip of V-shaped notch is analyzed. Firstly, the coordinate system at the center of the ellipse is set up, as shown in Figure 1.

From the theory of elasticity, when it is stretched in the vicinity of the elliptic gap, the relationship between the stress components is shown as [14]:

\[
\sigma_x + \sigma_y = \frac{\sigma_m}{(1+m)\Re} \left( \frac{\xi}{\sqrt{x^2-c^2}} - 1 \right)
\]

\[
\sigma_y - \sigma_x + 2\sigma_{xy} = \frac{\sigma_m}{2m} (1+m) \left\{ \frac{1}{\sqrt{(\epsilon^2-c^2)^2}} \left[ 2(1+m^2)c \xi \xi^* - c^2 \xi^2 \right] + 0.5\sigma(1+m^2) \right\}
\]

Where, \( \sigma_x \), \( \sigma_y \) and \( \sigma_{xy} \) are respectively the XYZ direction stress near the root of V-shaped notch.

\[
m = \frac{a-b}{a+b}
\]

\[
L = 0.5(a+b)
\]

\[
\xi = c + r e^{i\theta}
\]

Where, \( a \) is the length of the long half axis of the ellipse, \( b \) is the length of the short half axis of the ellipse, \( 2c \) is the focal length of the ellipse, \( \rho \) is the radius of curvature of the elliptical tip, \( r \) and \( \theta \) is polar coordinates.

In order to make the semi-major axis of the ellipse tip closer to ring V-shaped notch tip shape of crack, assume that \((a \gg \rho, \ a \gg r, \ a \gg b)\), The stress intensity factor of the tip of the plane elliptical notch can be approximatively expressed as: \( K_I = \sigma \sqrt{\pi a} \). Derived:

\[
\sigma_x = \frac{K_I}{2\pi r} \left[ \cos \frac{\theta}{2} \left( 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) - \frac{\rho}{2r} \cos \frac{3\theta}{2} \right]
\]

Similarly:

\[
\sigma_y = \frac{K_I}{2\pi r} \left[ \cos \frac{\theta}{2} \left( 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) + \frac{\rho}{2r} \cos \frac{3\theta}{2} \right]
\]

\[
\tau_{xy} = \frac{K_I}{2\pi r} \left[ \cos \frac{\theta}{2} \sin \frac{\theta}{2} \cos \frac{3\theta}{2} - \frac{\rho}{2r} \sin \frac{3\theta}{2} \right]
\]

In plane strain condition, ring V-shaped notch root area is in the three to stress state. According to
the generalized hooker law $\varepsilon_z = 0$, the stress field distribution in the tip area of the tubular V-shaped notch can be obtained:

\[
\begin{align*}
\sigma_x &= \frac{K_i}{\sqrt{2\pi r}} \left[ \cos \frac{\theta}{2}(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2}) - \frac{\rho}{2r} \cos \frac{3\theta}{2} \right], \\
\sigma_y &= \frac{K_i}{\sqrt{2\pi r}} \left[ \cos \frac{\theta}{2}(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2}) + \frac{\rho}{2r} \cos \frac{3\theta}{2} \right], \\
\tau_{xy} &= \frac{K_i}{\sqrt{2\pi r}} \left[ \cos \frac{\theta}{2} \sin \frac{\sin \frac{3\theta}{2}}{2} - \frac{\rho}{2r} \sin \frac{3\theta}{2} \right], \\
\sigma_z &= \nu(\sigma_x + \sigma_y) = 2\nu \frac{K_i}{\sqrt{2\pi r}} \cos \frac{\theta}{2}, \\
\tau_{xz} &= 0, \\
\tau_{yz} &= 0.
\end{align*}
\]

The stress component of the root of the tubular V-shaped notch is related to the stress intensity factor $K_i$ can be seen by the formula (9), namely it is related to the depth of the notch $h$, and can also be get it is related to the radius of the channel $\rho$ too.

In the process of blanking, a ring V-shaped notch is used, the maximum tensile stress of the V-shaped notch root under the plane strain state is given by the theory of sliding line field:

\[
\sigma_{ymax} = 2k \left( 1 + \frac{\pi}{2} - \frac{\alpha}{2} \right)
\]

(10)

Where, $\alpha$ is opening angle of the notch, its unit is the radian; $k$ is shear yield strength. According to Von-Mises type:

\[
2k = \frac{2\sqrt{3}}{3} \sigma_s
\]

(11)

Where, $\sigma_s$ is yield strength. So formula (10) should be rewritten as:

\[
\sigma_{ymax} = \frac{2\sqrt{3}}{3} \sigma_s \left( 1 + \frac{\pi}{2} - \frac{\alpha}{2} \right)
\]

(12)

According to the Tresca sentence type, $2k = \sigma_s$, the formula (12) should be written as

\[
\sigma_{ymax} = \sigma_s \left( 1 + \frac{\pi}{2} - \frac{\alpha}{2} \right).
\]

Can be seen from the above formula, as long as the angle of the gap $\alpha$ is changed, the maximum stress $\sigma_{ymax}$ of the root of the V-shaped notch can be changed. That is the size of the opening angle $a$ of the V-shaped notch will affect the stress concentration of the V-shaped notch.

3. Notch design of tube and its finite element simulation

3.1. Notch design and the finite element model established

In order to compare the effect of different forms of notches, we set up the mathematical model firstly, as shown in Figure.2, the maximum stress of the notch root for several different forms of notch specimen model is analyzed and calculated under the same conditions using the software ABAQUS. In the case
of the same constraint and external load $F$, the gap which can produce the maximum stress is the most favorable gap in the fracture. The notch out of the circular tube should be better designed into a uniform annular notch. Therefore, the notch form mentioned in the next part of this paper is prefabricated uniform annular notch. Four common notch sample models are designed in this paper, including the V-shaped notch sample, the ring U-shaped notch sample and the blanking direction 45° asymmetric V-shaped notch and the blanking opposite direction 45° asymmetric V-shaped notch. The geometry dimensions of the four notch sample models are the same. Outer diameter is $\phi 20\text{mm}$, wall thickness of steel tube is 3mm, fixed end length is 20mm, the length of the billet is 50mm, the depth of the notch is 1mm, the corner radius of the opening angle is 0.1mm. The difference between models is limited to the gap forms.

![Figure 2](image.png)

**Figure 2.** Model schematic diagram of pipe notch analysis.

### 3.2 Numerical simulation analysis

Using ABAQUS for analysis and calculation, Firstly, based on the mathematical model of Figure 2, finite element model is established for different gap forms, and SUS304 is used for model materials, and then, the model is meshed. The same grid parameters are set for the four notch tube loading model to ensure the reliability of the analysis results. In addition, the load conditions of the four notch tube loading model are set the same. The 6 DOF of the tube are limited at the fixed end, and the same load is applied at the blanking end. Due to the singularity of the root stress of the notch tube loading model, a smaller number on the load is selected. If a large load is applied to the model, the maximum stress will be greater than the strength limit of the material, that will not be convenient for comparison. In order to see the difference of the stress of the various models at the root of the notch, the lateral force of 350N in the end of each model is applied.

Firstly, the test samples of V-shaped notch tubes are analyzed. Ring V-shaped notch opening angle is 90°, the notch deep is 1mm, the corner radius of the notch is 0.1mm, Hex unit grid is selected, linear reduction of integral unit calculation. Mises stress results of V-shaped notch under loading is shown in Figure 3. It is easy to see that the maximum stress appears at the V-shaped notch with a value of 142.9MPa. Secondly, The blanking direction 45° asymmetric V-shaped notch is analyzed. Annular V-notch opening angle is 90°, the notch deep is 1mm, the corner radius of the notch is 0.1mm, Hex unit grid is selected, linear reduction of integral unit calculation. Mises stress results of the blanking direction 45° asymmetric V-shaped notch under loading is shown in Figure 4. It is easy to see that the maximum stress appears at the gap of 45°, and its value is 149.9 MPa.
Figure 3. Stress cloud diagram of V-notch of tube.

And then, the blanking opposite direction 45° asymmetric V-shaped notch is analyzed. Parameter setting is the same as the above. Mises stress results of the blanking opposite direction 45° asymmetric V-shaped notch under loading is shown in Figure 5. It is easy to see that the maximum stress is in the direction of reverse 45°, and its value is 133.4MPa. In the end, the ring U-shaped notch is analyzed too. Parameter setting is the same as the above. Mises stress results of the ring U-shaped notch under loading is shown in Figure 6. It is easy to see that the maximum stress is at the U-shaped gap, and its value is 129.1MPa.

Figure 5. Stress cloud diagram of 45° notch on the back of the tube in the direction of the end of the material.

Figure 6. Stress cloud diagram of U-notch of tube.

We can see from the above analysis, the maximum stress in the stress concentration of the blanking direction 45° asymmetric V-shaped notch is the largest of the four. This conclusion is similar to the conclusion of references [15]. The maximum stress of the V-shaped notch is smaller, the maximum stress values of the remaining two gaps from large to small are opposite direction 45° asymmetric V-shaped notch and the ring U-shaped notch. The two notched forms, namely the blanking direction 45° asymmetric V-shaped notch and V-shaped notch are the two most outstanding forms of stress concentration, while the symmetric V-shaped gap is more suitable for industrial practical materials.

4. Experimental verification

In order to further verify the simulation results, four different notches are compared. The same material and the same type of tube are taken for experiment. SUS304 stainless steel is chose as the test material, before the experiment. The tubes will be prepared to work out the desired shape of the notches in a lathe, and the length of the feeding which is 50mm per section is consistent with the length of the simulation. Three samples are prepared for each notch, There are 12 samples and is divided into four groups: the V-shaped notch sample, the ring U-shaped notch sample, the blanking direction 45° asymmetric V-shaped notch sample and the blanking opposite direction 45° asymmetric V-shaped notch sample. The outer diameter of the tube is 20mm and the wall thickness is 3mm. In order to avoid the influence of the base
angle radius in the test, the base angle radius of each notch is toke 0.1 mm.

Verification tests are performed on Low-cycle eccentric rotary fatigue feeding machine, which is blanking the metal round tubes. The eccentric high-speed rotary precision feeding machine is shown in Figure 7. The main mechanism consists of three parts: transmission mechanism, radial load feeding mechanism and pipe fixing device. The control part includes the loading frequency control system and the sound detection of the blanking.

Figure 7. The eccentric high-speed rotary precision feeding machine.

Using constant frequency loading method, the loading frequency is 4.5 Hz and the loading time is 10s. When the load is finished, 10mm for a section is chose and then be cut, a separate section of the gap is partially cut by line cutting, then we will do the metallographic experiment. The microscopic images of four samples is shown as Figure 8. Through tessellation, grinding samples and microscopically observation and pictures is got.
Figure 8. Tube gap metallographic images: (a) V-shaped notch sample; (b) U-shaped notch sample; (c) The blanking direction 45° asymmetric V-shaped notch sample; (d) The blanking opposite direction 45° asymmetric V-shaped notch sample.

We can see that the crack of the blanking direction 45° asymmetric V-notch is the longest in the Figure 8. The order of the others are the V-shaped notch pipe, the blanking opposite direction 45° asymmetric V-shaped notch, and the ring U-shaped notch specimen is in the state of the initiation crack. This means that the blanking direction 45° asymmetric V-shaped notch is the most prone to crack in the same load case. and the V-shaped notch is similar with it. So, The two types of notches are suitable for the blanking method. This result is consistent with the results obtained from the finite element analysis. However, considering that end of the tube is generally 45° chamfering in industry, the symmetrical V-notch pipe is more suitable for the gap form in industrial production.

5. Conclusions

1) Above all, the parameter analysis of the root stress field of the V-shaped notch pipe is analyzed, the distribution of the stress field of the root of V-notch pipe is obtained, the three main geometric parameters that influence the stress concentration of the root of V-notch pipe are also obtained: the depth of the notch $h$, the radius of the channel $\rho$ and the angle of the gap $\alpha$.

2) Aim at the characteristics of blanking for the metal round tubes, four kinds of annular notch are designed. They are respectively the V-shaped notch sample, the ring U-shaped notch sample and the blanking direction 45° asymmetric V-shaped notch and the blanking opposite direction 45° asymmetric V-shaped notch. A numerical simulation of the root stress field of the four notch samples were carried out under the same loading condition with the finite element software ABAQUS. It is pointed out that the V-shaped notch sample and the blanking direction 45° asymmetric V-shaped notch have greater stress concentration effect.

3) The effect of ring V-shaped notch is tested, the different length of crack propagation in each notch in the same test condition is verified. There are two types of notches which are the blanking direction 45° asymmetric V-shaped notch and ring type U-shaped notch specimen are suitable for the blanking method. However, considering that the tube end of industry is generally 45° chamfering, the symmetrical V-notch pipe is more suitable for the gap form in industrial production.

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