Investigation on Strain Fatigue Life of Metal Bar with V-shaped Notch in a Radial-forging Cropping Method

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Abstract. To estimate the radial-forging cropping time accurately, it is essential to obtain the strain fatigue life (SFL) of the metal bar with V-shaped notch. According to the radial-forging cropping mechanism, the relation curve between the fatigue strain and the SFL is constructed. Based on it, a new SFL formula of the metal bar with V-shaped notch, which is related to the fracture ductility of material, the fatigue strain critical value and the stress concentration factor of the V-shaped notch, is proposed. The comparison results for the metal bars show that the relative errors between the results obtained by the new SFL formula and the corresponding experimental results are within 10%.

Introduction

The baiting of metal bars is the first process and is widely used in industrial production. Nowadays, the required baiting amount is numerous annually and is still increasing year by year [1]. However, the current cropping processes are plagued with a big shearing force, a poor bar cross-section quality and a long cropping time. Therefore, a new method with the radial-forging cropping which is a promising low-stress blanking process has been proposed [2, 3]. In the cropping process, the machine skillfully utilizes the radial-forging action to make the crack propagate along the prefabricated V-shaped notch for shearing the bar. It is also a fast and energy-saving cropping system because of the stress concentration effect of the V-shaped notch in the bar [4, 5]. However, the radial-forging cropping results show that the cropping time is long and not stable. After repeated analyses, it has been confirmed that the crack SFL of the bar with V-shaped notch is not studied clearly. Therefore, a new SFL formula of the bar with V-shaped notch is proposed and the corresponding experiments are also carried out in this paper.

The Work Principle of the Radial-forging Cropping

The mechanical part of the radial-forging machine mainly consists of five parts (as shown in Figure 1) and the radial displacement adjustment mechanism (not given in Figure 1) [6]. Before the machine works, one end of the bar with V-shaped notch is fixed on the clamping die and the other end is placed at the center of the main shaft as shown in Figure 2. In the plane perpendicular to the axis of the bar, there are seven stationary feeding rollers and four cropping hammers which are homogeneously inlaid in the guide chute of the main shaft and can rotate with the main shaft synchronously. In course of cropping, the load acted on the bar is distributed uniformly along its circumference. When the main shaft rotates one circle, the bar can be uniformly hit 28 times. As the speed of the main shaft is high, up to 3500r/min, the crack at the V-shaped notch tip will propagate uniformly. With the increase of the displacement load acted on the bar, the crack at the V-shaped notch tip grows stably until the bar breaks.
The Strain Fatigue Life for the Metal Bar with V-shaped Notch

Establishment of New Strain Fatigue Life Formula

The initiation time of the V-shaped notch tip crack accounts for about 80% of the cropping time [7], so the SFL of the bar in this paper refers to the crack initiation time. With the data processing method, the SFL curve of the bar is proposed as shown in Figure 3 based on the radial-forging cropping mechanism. This curve meets two constraint conditions: first, the bar will fracture in one-way 1/4-cycle; second, the SFL tends to infinity when the fatigue strain range $\Delta \varepsilon$ is less than the critical value of the fatigue strain $\Delta \varepsilon_c$.

Based on the curve in Figure 3 and data processing results, the expression of the SFL proposed in this paper is given by

$$\Delta \varepsilon_p = A(\varepsilon_f, \Delta \varepsilon_c) N_f^{C(\varepsilon_f, \Delta \varepsilon_c)}.$$  \hspace{1cm} (1)

Where $\varepsilon_f$ is the material fracture ductility and $\Delta \varepsilon_c$ is the critical value of fatigue strain; $\Delta \varepsilon_p$ is the damage strain range, $\Delta \varepsilon_p = \Delta \varepsilon - \Delta \varepsilon_c$; $N_f$ is the SFL; $A(\varepsilon_f, \Delta \varepsilon_c)$ is the fatigue strain strength and $C(\varepsilon_f, \Delta \varepsilon_c)$ is the fatigue strain index. Both the strain fatigue strength and the strain fatigue index are functions of $\varepsilon_f$ and $\Delta \varepsilon_c$.

According to material mechanics, the material fracture ductility is a nominal strain. Under the action of 1/4-cycle cyclic load, when the bar fractures, the fatigue strain range is denoted as $\Delta \varepsilon = 2\varepsilon_f$. 

Therefore, after transformation, Eq. (1) can be written as

\[ N_f = \frac{1}{4} \left( \frac{\Delta \epsilon - \Delta \epsilon_c}{2 \epsilon_f - \Delta \epsilon_c} \right) \]. (2)

Based on Zheng’s formula [8], and neglecting the influence of the fracture ductility, the fatigue strain critical value can be expressed as

\[ \Delta \epsilon_c = \ln\left( \frac{2 \sigma_1}{E} + 1 \right) \]. (3)

Where \( \sigma_1 \) is material’s yield strength and \( E \) is Young’s modulus. After the comparison of the fatigue strain critical value obtained from experiments and Eq. (3), the accuracy of Eq. (3) can be proved extremely high with the biggest relative error of 0.433%.

As the factors influencing the strain fatigue index are \( \epsilon_f \) and \( \Delta \epsilon_c \), the following expression can be obtained by

\[ \log N_f = \log \left( \frac{1}{4} \right) + \frac{1}{C(\Delta \epsilon_c, \epsilon_f)} \log \left( \frac{\Delta \epsilon - \Delta \epsilon_c}{2 \epsilon_f - \Delta \epsilon_c} \right) \]. (4)

In the double logarithmic coordinates, the relationship between \( \log N_f \) and \( \log \left( \frac{\Delta \epsilon - \Delta \epsilon_c}{2 \epsilon_f - \Delta \epsilon_c} \right) \) is linear and the slope \( k \) of the straight line is as following

\[ k = C(\Delta \epsilon_c, \epsilon_f)^{-1} = \frac{\log \left( \frac{\Delta \epsilon - \Delta \epsilon_c}{2 \epsilon_f - \Delta \epsilon_c} \right)}{\log N_f} \]. (5)

By means of the least square method, the strain fatigue index for different materials is calculated by

\[ C(\epsilon_f, \Delta \epsilon_c) = \sum_{i=1}^{N} \left( \log \left( \frac{\Delta \epsilon - \Delta \epsilon_c}{2 \epsilon_f - \Delta \epsilon_c} \right) \right)^2 / \sum_{i=1}^{N} \left( \log 4 N_f \right) \left( \log \left( \frac{\Delta \epsilon - \Delta \epsilon_c}{2 \epsilon_f - \Delta \epsilon_c} \right) \right) \]. (6)

Based on it, by means of the data fitting and the Taylor decomposition method based on above slope values, the expression of the strain fatigue index is obtained by

\[ C(\epsilon_f, \Delta \epsilon_c)^{-1} = -23.4983 \xi^3 - 62.4744 \xi^2 - 28.6587 \xi^1 + 24.1819 \xi + 13.6027 \xi^2 - 1.8482 \xi^3 - 0.0632 \xi - 1.9927 \]. (7)

Where \( \xi = \log(2 \epsilon_f - \Delta \epsilon_c) \).

**Analysis of the Strain Fatigue Life Formula**

According to Eq. (2), there is the same starting point in the double logarithmic coordinates for the SFL formula proposed in this paper, i.e., when \( \Delta \epsilon = 2 \epsilon_f, N_f = 1/4 \), which satisfies the constraint condition of the SFL.

Figure 4. The calculation data and the corresponding experimental data of SFL[3]: (a) Fatigue life curve with 52100; (b) Fatigue life curve with AM350H; (c) Fatigue life curve with 1100Al.
Figure 4 shows that the strain fatigue curves obtained by Eq. (2) are in good agreement with the curves obtained by the existing experimental data in [6], which indicates that the SFL formula proposed in this paper is reasonable.

Calculation of the New Strain Fatigue Life for the Metal Bar with V-shaped Notch

In the state of three-dimensional stress, the plastic deformation at the V-shaped notch tip is very small. Therefore, for the bar with V-shaped notch, Eq. (2) is denoted as the following expression

\[ N_f = \frac{1}{4k_f} \left( \frac{\Delta e - \Delta e_f}{2\varepsilon_f - \Delta e_f} \right)^{\frac{1}{\epsilon - \delta}}. \]  

Where \( k_f \) is the stress concentration factor of the V-shaped notch and its expression is [9]

\[ k_f = 1 + (2\sqrt{\frac{d}{s}} f(d/b) - 1) \times [1 - \left( \frac{\phi}{180} \right)^{1+2\times\frac{d}{s}^\phi}], \]  

\[ f(d/b) = \frac{3}{8} \left[ \frac{1}{2} (1 - \frac{d}{b}) + \frac{3}{16} (1 - \frac{d}{b})^2 + \frac{35}{128} (1 - \frac{d}{b})^3 + \frac{537}{128} (1 - \frac{d}{b})^4 + 0.537(1 - \frac{d}{b})^5. \]  

Where \( b \) is the radius of the bar; as shown in Figure 2; \( d \) is the depth of the V-shaped notch; \( s \) is the radius at the notch bottom and \( \phi \) is the flare angle of the V-shaped notch.

Experimental Results and Discussion

To verify the availability of Eq. (8), the radial-forging cropping experiments for bars are carried out. The bar diameter is 15mm, \( s = 0.1-0.3 \text{ mm}, \) \( d = 0.8-1.2 \text{ mm}, \) \( \phi = 60\degree-90\degree, \) and other parameters are shown in Table 2. By obtaining the fracture ductility, the critical value of fatigue strain and the stress concentration factor of the V-shaped notch, Table 3 shows that the relative errors between the results of the SFL obtained by Eq. (8) and the corresponding experimental results are within 10%, which also further proves that the proposed formula of the SFL is reasonable. Under different control modes, the cross-sections of 45 steel bar and LY8 bars are shown in Figure 5, which show that the smoothness of the bar cross-sections is high and stable.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \sigma_{ij} / \text{MPa} )</th>
<th>( \psi_i / % )</th>
<th>( E / \text{Pa} )</th>
<th>( \varepsilon_f )</th>
<th>( C(e_f, \Delta e_f)^{-1} )</th>
<th>( \Delta e_f )</th>
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<tr>
<td>45</td>
<td>241.8</td>
<td>40</td>
<td>2.06e11</td>
<td>0.51082</td>
<td>-1.99335</td>
<td>0.002236</td>
</tr>
<tr>
<td>40Cr</td>
<td>330.5</td>
<td>45</td>
<td>2.06e11</td>
<td>0.59783</td>
<td>-2.001517</td>
<td>0.003204</td>
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</table>

Figure 5. The cross-sections of 45 steel and LY8 bars under different control modes: (a) 45 steel with step decrement curve; (b) 45 steel with linear decrement curve; (c) 45 steel with convex arc decrement curve; (d) LY8 with step decrement curve; (e) LY8 with linear decrement curve; (f) LY8 with convex arc decrement curve.
Table 3. Calculation results obtained by Eq. (8) and the corresponding experimental results.

<table>
<thead>
<tr>
<th>Material</th>
<th>45</th>
<th>40Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δε</td>
<td>0.003 0.007 0.011 0.015 0.019 0.023 0.003 0.007 0.011 0.015 0.019 0.023</td>
<td></td>
</tr>
<tr>
<td>calculation result/ cycle</td>
<td>1589.4 240 92.5 48.7 30 20.3 2597.8 356.5 134.2 69.8 42.6 28.7</td>
<td></td>
</tr>
<tr>
<td>experimental result/ cycle</td>
<td>1567.3 228.6 94.8 46.2 29.4 21.5 2496.7 364.5 121.6 63.3 41.8 25.9</td>
<td></td>
</tr>
<tr>
<td>relative error</td>
<td>1.40% 4.75% 2.49% 5.13% 2.00% 5.91% 3.89% 2.24% 9.39% 9.31% 1.88% 9.76%</td>
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Summary
Based on the radial-forging cropping mechanism, the relation curve between the fatigue strain and the fatigue life is constructed, which can satisfy two constraint conditions: the material will fracture in one-way 1/4 cycle and the SFL tends to infinity when the fatigue strain range is less than the critical value of fatigue strain. Based on it, a new SFL formula of the metal bar with V-shaped notch is proposed. The comparison results show that the relative errors between the results obtained by the SFL formula proposed in this paper and the corresponding experimental results are within 10%, which proves that the new SFL formula is reasonable. In addition, the experimental results show that the cross-section smoothness of every segment of the bars is very high and stable.

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References