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Study on Crack Propagation Rate of 600MPa High Strength Steel for Mn-Ti and Nb-V System

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Abstract. The microstructure of 600MPa Mn-Ti and Nb-V steels for cold stamping axle housing was investigated by means of optical microscope. On the low-frequency fatigue tester MTS-810 with frequency of 10 Hz, the crack propagation rate of two chemical components of the tested steels was tested by three-point bending method. The relationship between the propagation rate da/dN and the amplitude of stress intensity factor ΔK was given. The results showed that the microstructure all of two tested steels were ferrite and pearlite, the grain size of Mn-Ti steel and Nb-V steel was 5.8μm and 3.3μm, respectively. The coefficient C and m in Paris equation of Mn-Ti steel and Nb-V steel were determined as m=2.6298, C=4.13×10⁻¹²mm/cycle and m=2.6799, C=1.30×10⁻¹²mm/cycle respectively, and the threshold value of crack propagation ΔKth was 46.50 MPa·m¹/² and 66.58 MPa·m¹/², respectively.

1. Introduction
With the development of axle manufacturing technology and the need for lightening of cars, the production process of axle housing is shifting from hot stamping to cold stamping [1]. At present, the tensile strength of axle housing steel is above 600MPa in abroad, and the tensile strength is above 500 in China, such as Q345 and 16MnL [2]. Recent GB1589-2016 “Limits of dimensions, axle load and masses for motor vehicles, trailers and combination vehicles” will greatly promote application of high strength axle housing steel above 600MPa.

High bending fatigue strength is needed for axle housing steel, because axle housing withstanding a great impact caused by bumpy road is equivalent to bearing the no symmetric four-point bending fatigue load in a moving vehicle [3]. It is very important to study on the fatigue performance of 600MPa cold stamping axle housing steel. In this work, the fatigue crack propagation rate of 600MPa Mn-Ti and Nb-V steels for cold stamping axle housing was investigated by three-point bending tests with constant amplitude in the article. The curve of fatigue crack propagation rate da/dN and stress intensity factor amplitude ΔK for the experimental material was obtained to provide some reference for the practical application.

2. Experimental procedure and materials
The chemical compositions of the steels used in this study are listed in Table 1. The tensile samples with 12.0 mm in thickness were prepared along the transverse direction. The specimens for optical metallography, which were prepared from the as rolled plates, were mechanically polished and then etched in 4% nitric acid. The three point bending specimen were prepared along the transverse
direction according to GB/T6398-2000, the drawing as shown in figure 1, and tested on a MTS810 250KN low frequency fatigue testing machine at room temperature with stress ratio R=0.1, maximum load 7.2kN, minimum load 0.72kN and the loading frequency 10Hz.

Table 1. Chemical compositions (wt. %) of the experimental steels

| steel | C   | Si   | Mn  | Ti   | V+Nb |
|-------|-----|------|-----|------|------|
| 1#    | 0.07| 0.15 | 1.25| ≤0.15| --   |
| 2#    | 0.06| 0.18 | 1.30| --   | ≤0.15|

Figure 1. Drawings of three-point bend specimens

3. Results and discussion
The cyclic behavior of the steel was strongly related to temperature and hardness. It can even decrease 225HV for the 50HRC sample tested at 600°C. To investigate the role of mechanical loads and thermal aging on the evolution of steel during test, some equivalent tempering tests were carried out, tempering temperature and time are selected corresponding to that of relevant fatigue test.

3.1. Mechanical properties and microstructure
As can be seen in Table 2, the strength of specimen No.1 and No.2 has very little difference, and elongation showed large difference. The yield strength and elongation of No.1 and No.2 is 544MPa and 537MPa, 33.0% and 22.0%, respectively.

The microstructure photos of tested steels as shown in figure 2, the matrix structure of specimen No.1 and No.2 are both ferrite and a little pearlite. According to statistics used by Image-Pro Plus 6.0, the grain size of specimen No.1 and No.2 is 5.8μm and 3.3μm, respectively. Compared with Ti-bearing steel, the ferrite grain is finer in Nb-bearing steel.

Table 2. Mechanical properties of tested steels

| steel | Rel | Rm/MPa | A/% |
|-------|-----|--------|-----|
| 1#    | 544 | 646    | 33.0|
| 2#    | 537 | 635    | 22.0|

Figure 2. Microstructure of tested steels (a) No.1 ; (b)No.2
3.2. Fatigue crack propagation rate

The curve of fatigue crack propagation a-N was made according to the experimental data of the length of ductile crack propagation and the number of cycles N, as shown in figure 3. Under identical experimental conditions, it shows different fatigue crack propagation rate in the steel No.1 and No.2. The length of fatigue crack propagation is longer in steel No.1 than that in steel No.2. When the number of fatigue cycles is 4500 times, the crack length of steel No.1 is 5.8 mm, and steel No.2 is 4.2 mm. It can be seen that steel No.2 hindering propagation of crack was superior to steel No.1.

![Figure 3. The curve of a-N](image)

The slope of the fatigue crack growth curve da/dN is the fatigue crack growth rate, which is the length of fatigue crack growth every one stress cycle and reflects the fatigue property of the steels. Higher fatigue crack growth rate, shorter fatigue life. da/dN is the function of stress intensity factors of cracking tip. The relationship between da/dN and ΔK is an inverse S-curve on the graph [4-5], as shown in figure 4.

The fatigue fracture process is divided into three zones, as shown in figure 4. Zone I is the initial stage of fatigue microcracks propagation, Zone II is the main stage of fatigue crack propagation, which determine fatigue life, Zone III is the stage of fatigue fracture. The Zone I and Zone II are the most important stage of fatigue life estimation for engineering components.

The result of correlation experiments show that a relation between da/dN and ΔK are usually given in Paris formulation [6] in Zone II.

\[
da/dN = C(ΔK)^m\tag{1}
\]

where ΔK is the range of stress intensity factor amplitude, ΔK=Kmax-Kmin, C is constant determined by the experiment, m is the slope of the straight-line portion.
During the test analysis, the fatigue crack propagation rate curve is often plotted with double logarithmic coordinates. The measured curve of crack propagation rate of steel No.1 and No.2 are shown in figure 5. There is an approximately linear relationship between the lg(da/dN) and lg(ΔK) with the stress ratio R=0.1, a maximum load of 7.2kN, a minimum load of 0.72kN and the loading frequency of 10Hz. This illustrates that the crack propagation rate is in the area II in figure 3. Comparing the crack propagation rate curves of the two test steels, the crack propagation rate increases with the increase of the stress intensity factor range ΔK. However, in the case of the same ΔK, the crack propagation rate of the steel No.1 is significantly higher than that of steel No.2.

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**Figure 5.** The measured curve of crack propagation rate

Using the software Origin 8.5, the data in figure 5 are fitted linearly to obtain the fitting curve as shown in figure 6 and fitting equation (2):
\[
\lg(da/dN) = \lg C + m \lg(\Delta K)
\]  
(2)

\(\lg (da / dN) - \lg \Delta K\) curve is obtained by linear fitting

Steel No.1: \(\lg C = -11.38, m = 2.6298, C = 4.13 \times 10^{-12}\) mm·cycle\(^{-1}\)

Steel No.2: \(\lg C = -11.8, m = 2.6799, C = 1.30 \times 10^{-12}\) mm·cycle\(^{-1}\)

Paris equation:

Steel No.1:

\[
\frac{da}{dN} = 4.13 \times 10^{-12}(\Delta K)^{2.6298}
\]  
(3)

Steel No.2:

\[
\frac{da}{dN} = 1.30 \times 10^{-12}(\Delta K)^{2.6799}
\]  
(4)

Figure 6. Crack propagation rate curve

3.3. Fatigue crack propagation threshold \(\Delta K_{th}\)

When the crack propagation rate is 10-7mm/cycle, the stress field strength factor is set as the crack propagation threshold, the crack propagation thresholds \(\Delta K_{th}\) of steel No.1 and steel No.2 are 46.50 MPa·m\(^{1/2}\) and 66.58 MPa·m\(^{1/2}\), respectively. And the \(\Delta K\) values of steel No.1 and No.2 in the first set of data collected in figure 4 are 1035 MPa·m\(^{1/2}\) and 1033 MPa·m\(^{1/2}\), respectively. Note that steel No.1 and No.2 have been in the second stage of crack propagation at the beginning of the three-point bending test given in this paper. This is consistent with the facts. The crack propagation low rate stage, ie the first stage, should be included in the prefabricated crack process. Due to manual intervention, the crack propagation process is stopped when the crack is extended to 0.72 times of specimen width, so the crack propagation stage is not shown in figure 5. The straight line segment in figure 5 is the mid-speed propagation stage of the crack, which is the most valuable for fatigue life estimation.

The influence factors of the crack growth threshold value \(\Delta K_{th}\) have been studied by many scholars at home and abroad, including the microstructure [7], grain orientation [8], grain size [9-11], load ratio R [12-14], loading frequency [15] and temperature [16]. There is no definite conclusion about the influence of grain size on the threshold of fatigue crack growth and the mechanism. In this paper, we study the crack growth threshold \(\Delta K_{th}\) of two kinds of chemical constituent axle housing steels under the same experimental conditions. It can be seen that the microstructures of steel No.1 and No.2 are ferrite and pearlite, but the grain size is more distinct difference. Steel No.1 grain size is 5.8μm, \(\Delta K_{th}\) is 46.50 MPa·m\(^{1/2}\), and steel No.2 grain size is 3.3μm, \(\Delta K_{th}\) is 66.58 MPa·m\(^{1/2}\). It is shown that under the experimental conditions given in this paper, the crack growth threshold increased with the grain size reduced. Although the yield strength and tensile strength of steel No.1 and No.2 are
basically the same, the crack growth threshold value is greatly changed due to the difference of grain size between the two tested steels. Under the same test conditions, the fatigue resistance steel No.2 is superior to that of steel No.1.

4. Conclusions
(1) The crack propagation rate of the two test steels with the stress ratio R=0.1 increased with the increase of the stress intensity range ΔK of the crack tip. However, in the case of the same ΔK, the crack propagation rate of steel No.1 is significantly higher than that of steel No.2.

2) Using the Origin software to fit the crack propagation rate curves of the two test steels, the coefficients in the Paris equation were obtained, steel No.1 m=2.6298, C=4.13×10^{-12} mm/cycle; steel No.2 m=2.6799, C=1.30×10^{-12} mm/cycle.

(3) Under the experimental conditions given in this paper, the crack growth threshold increased with the grain size reduced. Although the yield strength and tensile strength of steel No.1 and No.2 are basically the same, the crack growth threshold value is greatly changed due to the difference of grain size between the two tested steels. Under the same test conditions, the fatigue resistance steel No.2 is superior to that of steel No.1.

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