Study on Fatigue Limit Test of TCS Stainless Steel

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Abstract. Material fatigue limit plays a vital role in the fatigue life of railway vehicle parts. According to the fatigue test method, the fatigue performance of TCS stainless steel used in railway rolling stock was studied in this paper. The corresponding fatigue limit calculation methods of lifting method and group method were given, and the P-S-N curve of TCS stainless steel under test conditions and fatigue limit under different survival rates were obtained. The results showed that the fatigue limit of TCS stainless steel was 176.43 MPa under 50% survival rate, 163.21 MPa under 90% survival rate, and 152.44 MPa under 99% survival rate. The results of this paper provide basic data for the application of TCS stainless steel in railway rolling stock.

1. Introduction

The fatigue limit of stainless steel material plays a vital role in the fatigue life of railway vehicle parts. Due to the discreteness of fatigue test data, the relationship between fatigue life and stress level is not a one-to-one single value relationship, but is closely related to survival rate P. A large number of fatigue tests show that the material fatigue limit obeys normal distribution or logarithmic normal distribution when the life is constant. When the stress is constant, the fatigue life obeys logarithmic normal distribution or Weibull distribution.

Before metal materials are used, fatigue limit test should be carried out. Teimourimanesh [1] studied the influence of the stress range lower than the fatigue limit on the fatigue life of materials. Generally, the up-down method is used to test the fatigue limit of materials. Holst [2] proposed the fatigue limit test method based on Bayesian test, which can shorten the time of obtaining the fatigue limit.

Y. Song [3] carried out theoretical and experimental research on fatigue life evaluation of aluminum alloy body of EMU, and proposed three loading test schemes including constant amplitude loading, variable amplitude loading, and random loading. T. Ma [4] studied the fatigue performance of the surface reinforced layer of the axle of high-speed EMU, obtained the fatigue limit of S38C axle steel under the specified confidence and reliability, and drew the P-S-N curve. Q. Wang [5] gave the probabilistic fatigue durability strength of rim and spoke of D1 steel wheel and probability S-N curve containing the ultra-long life. Y. Zhang [6] carried out a study on the fatigue performance and reliability of axle steel with ultra-long life, and proposed two fatigue limit reliability evaluation methods. M. Li [7] analyzed the dynamic stress of dangerous section of EMU axle under random excitation and different line conditions, and carried out axle damage calculation and life evaluation under the impact condition of flat scar of wheels.

J. Zhou [8] studied the rapid prediction of fatigue limit of 20Cr2Ni4A gear steel based on infrared thermal imaging method, and revealed the change rule of damage index of materials during fatigue cyclic loading. S. Guo [9] investigated the method of rapid determination of fatigue limit of metal materials based on temperature distribution characteristics, and obtained the evolution law of heat
dissipation rate of AZ31B magnesium alloy under high cycle fatigue load. D. Fu [10] conducted MT transmission fatigue design and test research based on load spectrum, and obtained S-N curve of gear material. W. Xu et al. [11] carried out an experimental study on the fatigue performance of titanium alloy film disk material based on vibration, and provided the fatigue limit of this material sample.

These studies mainly focus on specific materials. One stainless steel co., LTD produced TCS stainless steel material used for railway vehicles under the condition of a certain technology. In order to confirm the fatigue performance of this TCS stainless steel, this paper intends to conduct indoor fatigue test research, which can obtain P-S-N curve of the TCS stainless steel under test conditions and fatigue limit under different survival rates, so as to provide basic data for the application of the TCS stainless steel.

2. Test Method and Sample

2.1. Test Equipment and Loading Conditions
The experiment was completed by Zwick high frequency fatigue testing machine as shown in figure 1. The data collection system is IMC CRONOS Compact data collection system.

Symmetrical cyclic loading was adopted with a loading frequency of 117±1Hz. The temperature of the experiment was 20~25 ℃, and the air humidity was 50%~60%.

![Figure 1. Sample measurement equipment](image)

2.2. Experimental Sample
According to test requirements and GB/T3075-2008, the shape and size of specimen was designed as figure 2.

![Figure 2. The shape and size of sample (unit: mm)](image)

3. P-S-N Curve Determination Method
P-S-N curve refers to the S-N curve under a given survival rate P and a given confidence. The survival rate represents the failure probability of the sample after a certain number of cycles N under a certain stress level S, and the confidence reflects the credible degree of the event itself.
When measuring P-S-N curve, the combination of group method and up-down method is generally adopted. The low stress level point of the curve (fatigue limit) was determined by up-down method, and the higher stress level of other 3~4 grades was determined by group method. The number of samples required by the up-down method and the number of samples required by the group method at each stress level depends on the dispersion degree of the test data and the required survival rate and confidence. After statistical analysis, the fatigue limit or safety life of the material under a certain survival rate and confidence can be obtained. The fatigue life and safety life of the materials under the specified survival rate and confidence are drawn on the coordinate paper, and the P-S-N curve with confidence can be obtained by fitting each data point with the curve.

3.1. Up-down Method

The fatigue limit distribution under the specified life cycle $10^7$ is measured by the up-down method of small sample. Generally, the stress level of 3~5 grades is taken, and the stress increment is usually chosen as 3%~5% of the predicted fatigue limit. The number of effective samples is no less than 13. A large number of studies show that the fatigue limit obeys normal distribution. It is assumed that $n$ is the total number of pairs of effective samples, $m$ is the stress level of order, $n_i$ is the number of pairs between the stress of order $i$ and $i+1$, and $\sigma_i$ the mean value of the stress of order $i$ and $i+1$. Then the mean value of the fatigue limit $\bar{\sigma}$ and its standard deviation $s$ are defined respectively as follow

$$\bar{\sigma}_i = \frac{1}{n} \sum n_i \sigma_i \quad (1)$$

$$s = \sqrt{\frac{\sum n_i (\sigma_i - \bar{\sigma}_i)^2}{n-1}} \quad (2)$$

After the minimum paired number and distribution test, the fatigue limit $\sigma_{1-p}$ when confidence $\gamma$ and survival rate $P$ are specified can be obtained from equation (3).

$$\sigma_{1-p} = \bar{\sigma}_i + u_p \hat{s} \quad (3)$$

3.2. Group Method

When the group method is used, the stress level of 3~4 is generally taken. When testing a group of samples under a certain stress level, less samples can be taken when the data dispersion is small, while more samples are needed when the data dispersion is large.

Firstly, the measured fatigue life $N_i$ at this stress level is written in sequence, and the mathematical expectation of the failure rate of the i-th sample is

$$\hat{\rho}_i = 1 - \frac{1}{n+1} \quad (4)$$

The mean, standard deviation and coefficient of variation of logarithmic fatigue life at this stress level can be determined by equation (5) - (7) respectively.

Mean:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad (5)$$

Standard deviation:
Coefficient of variation:

\[ C_v = \frac{s}{\bar{x}} \times 100\% \]  \hspace{1cm} (7)

It is generally assumed that the fatigue life of the sample obeys lognormal distribution and can be tested on lognormal probability coordinate paper.

Under a certain stress level, the minimum number of samples required for a given confidence can be determined by equation (8).

\[ \frac{\delta}{t_r \sqrt{\frac{1}{n} + u_p^2 (\hat{k}^2 - 1) - \delta u_p \hat{k}}} \geq \frac{s}{\bar{x}} \]  \hspace{1cm} (8)

In equation (8), \( \delta \) denotes the relative error limit, \( n \) denotes the minimum number of samples required, \( \hat{k} \) denotes the standard deviation correction coefficient, \( t_r \) denotes the distribution value and is related to confidence \( \gamma \) and number of samples \( n \), is the standard normal deviation related to survival rate. In general, \( \delta \) takes as 5%, and \( \hat{k}, t_r, u_p \) can be obtained by referring to the table of fatigue reliability data. Safety logarithmic fatigue life or safety fatigue strength with specified confidence \( \gamma \) and survival rate \( P \) can be calculated according to equation (9).

\[ \hat{x}_p = \hat{u} + u_p \hat{k}s \]  \hspace{1cm} (9)

When the number of samples cannot meet the criterion of equation (8), the unilateral tolerance coefficient \( k \) should be used to give the safe fatigue life with confidence \( \gamma \). The function of the unilateral tolerance coefficient \( k \) is to substitute the \( u_p \) in equation (8).

\[ k = \frac{u_p - u}{\sqrt{\frac{1}{n} \left[ 1 - \frac{u^2}{2(n-1)} \right] + \frac{u_p^2}{2(n-1)}}} \]  \hspace{1cm} (10)

In equation (10), \( u \) is the standard normal deviation related to confidence, which can be obtained by referring to relevant literatures.

### 3.3. P-S-N Curve Plot

Power function is used to express P-S-N curve equation:

\[ \sigma^m N = C \]  \hspace{1cm} (11)

Where, are material constants. The logarithm of both sides of this equation is taken, then we get

\[ m \lg \sigma + \lg N = \lg C \]  \hspace{1cm} (12)

The P-S-N curve is a straight line on the log-log coordinate.

By using the least square method, linear fitting was carried out for the logarithmic safety fatigue life and logarithmic safety fatigue strength under specified reliability and different stress levels.
4. Material Fatigue Performance

4.1. Mechanical Properties of Test Base Material
Table 1 shows the mechanical properties of the tested materials.

| Material Properties          | Value     |
|------------------------------|-----------|
| Tensile strength (MPa)       | ≥350      |
| Yield strength (MPa)         | ≥480      |
| Elongation (%)               | ≥20       |
| Cold bend 180° D=2d Surface | perfect   |
| Impact power Akv(J) (Half sample) | ≥34 (-40°C) |

4.2. Single-point Test and Data Processing
When the stress of the material is less than 170MPa, no fracture occurs under $1 \times 10^7$ cycle load. When the stress of the material is 180MPa and the number of cycles is $2.54 \times 10^6$, the material fractures. The fitted line is shown in figure 3. The estimated fatigue limit is 170MPa.

![Figure 3. Fitted line of single point method](image)

4.3. Up-down Method Test and Data Processing
It is known that the fatigue limit of the material is about 170MPa. During the test, 190MPa was selected as the stress level for the first specimen test, and the stress level difference should be 10MPa. The fatigue up-down diagram is shown in figure 4. In figure 4, × represents fracture and ○ represents unfractured. The data included 7 pairs, which were used to calculate the fatigue limit, standard deviation and coefficient of variation of the specimen.

$$
\bar{\sigma} = \frac{1}{n} \sum_{i=1}^{n} \sigma_i = 176.43\text{MPa}
$$

$$
s = \sqrt{\frac{\sum_{i=1}^{n} (\sigma_i - \bar{\sigma})^2}{n-1}} = 9.90
$$

$$
\nu = \frac{s}{\bar{\sigma}} = \frac{2.76}{71.57} = 0.0561
$$

Table 2 shows the related coefficients in the process of fatigue test data processing and analysis. It can be seen that when the confidence is 90%, the value of T distribution is relatively stable.
The value of $k$ can be obtained by looking up Table 2, and when the specified life is $10^7$, the conditional fatigue limit is obtained. When confidence is 95% and survival rate is 50%, $\sigma_{-1p} = 176.34$ MPa. When confidence is 95% and survival rate is 90%, $\sigma_{-1p} = 163.21$ MPa. When confidence is 95% and survival rate is 99%, $\sigma_{-1p} = 152.44$ MPa.

Table 2. Mechanical properties of the tested materials

|                | n  | 6   | 7   | 8   | 9   | 10  | 12  |
|----------------|----|-----|-----|-----|-----|-----|-----|
| Suspicious value test $| \left( x_i - \bar{x}_j \right) / s_u $ | 1.730 | 1.800 | 1.860 | 1.910 | 1.960 | 2.040 |
| Coefficient of variation $\nu$ tolerance value | 0.132 | 0.139 | 0.144 | 0.150 | 0.154 | 0.162 |
| Correlation coefficient $r_{\text{min}}$ | 0.811 | 0.754 | 0.707 | 0.666 | 0.632 | 0.576 |
| Standard deviation correction factor $k$ | 1.051 | 1.042 | 1.036 | 1.031 | 1.028 | 1.023 |
| When $r=90\%$, $p=90\%$, unilateral tolerance coefficient $k$ | -2.379 | -2.244 | -2.145 | -2.071 | -2.012 | -1.925 |
| When $r=90\%$, $p=99\%$, unilateral tolerance coefficient $k$ | -4.408 | -3.822 | -3.658 | -3.537 | -3.442 | -3.301 |
| When confidence is at 90\%, the value of T distribution | 1.943 | 1.895 | 1.860 | 1.833 | 1.812 | 1.782 |

4.4. Group Method Test and Data Processing

We arrange the fatigue life in descending order and take the corresponding list of logarithms to calculate the corresponding survival rate. Three stress levels of 180MPa, 195MPa and 205MPa were selected for group test. The data are shown in Table 3. The mean value, standard deviation and coefficient of variation of the group method data were calculated respectively and listed in Table 4.
Table 3. Mechanical properties of the tested materials

| Stress level σ (MPa) | Number i | Fatigue life $N_i$ (times) | Logarithmic fatigue life $\log N_i$ | Survival rate $P_i$ |
|----------------------|----------|----------------------------|------------------------------------|--------------------|
| 205                  | 1        | 409596                     | 5.612355                           | 0.875              |
|                      | 2        | 369790                     | 5.567955                           | 0.750              |
|                      | 3        | 350203                     | 5.544319                           | 0.625              |
|                      | 4        | 340308                     | 5.531872                           | 0.500              |
|                      | 5        | 315138                     | 5.498500                           | 0.375              |
|                      | 6        | 307565                     | 5.487936                           | 0.250              |
|                      | 7        | 278050                     | 5.444122                           | 0.125              |
|                      | 1        | 654878                     | 5.816160                           | 0.875              |
|                      | 2        | 602486                     | 5.779946                           | 0.750              |
|                      | 3        | 585411                     | 5.767460                           | 0.625              |
| 195                  | 4        | 584614                     | 5.766869                           | 0.500              |
|                      | 5        | 582456                     | 5.765263                           | 0.375              |
|                      | 6        | 504567                     | 5.702918                           | 0.250              |
|                      | 7        | 479596                     | 5.680875                           | 0.125              |
|                      | 1        | 2116902                    | 6.325701                           | 0.875              |
|                      | 2        | 2137565                    | 6.329919                           | 0.750              |
|                      | 3        | 2233302                    | 6.348947                           | 0.625              |
| 180                  | 4        | 2335792                    | 6.368434                           | 0.500              |
|                      | 5        | 2335835                    | 6.368442                           | 0.375              |
|                      | 6        | 2589640                    | 6.413239                           | 0.250              |
|                      | 7        | 2597533                    | 6.414628                           | 0.125              |

Table 4. Data processing results of group method

| Stress level σ (MPa) | Mean $\bar{x}$ | Standard deviation $s$ | Coefficient of vibration $v$ |
|----------------------|----------------|------------------------|-------------------------------|
| 205                  | 5.5267         | 0.0514                 | 0.0093                        |
| 195                  | 5.7542         | 0.0430                 | 0.0075                        |
| 190                  | 6.3670         | 0.0334                 | 0.0052                        |

The P-S-N curve equation and P-S-N curve (figure 5) can be obtained by using the stress value and logarithmic safety life obtained by group method and up-down method mentioned above.

Figure 5. P-S-N curve
5. Conclusions
According to the fatigue test method, the fatigue performance of TCS stainless steel for railway vehicles was studied, and the P-S-N curve and fatigue limit of TCS stainless steel under the test condition were obtained. The results showed that the fatigue limit of TCS stainless steel was 176.43 MPa under 50% survival rate, 163.21 MPa under 90% survival rate, and 152.44 MPa under 99% survival rate. This data provided basic data for TCS stainless steel applications.

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7. References
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