ICF100110OR

SIMULATION OF PROBABILITY DISTRIBUTION OF FATIGUE LIFE OF NOTCHED FRICTION WELDED JOINTS UNDER VARIABLE-AMPLITUDE LOADING

J.H. Yan, X.L.Zeng, K.Zhao and H. Wang

College of Materials Science &Engineering, Northwestern Polytechnical University, Xi'an 710072, China

Abstract Experimental investigation is first carried out on the fatigue property of notched friction welded (FW) joints of mild-carbon steel under constant amplitude loading. The fatigue life of notched specimen of FW joints can be expressed as the function of equivalent stress amplitude $\Delta\sigma_{eqv}$ i.e. $N_i = C[\Delta\sigma_{eqv}^{2/(1+n)} - (\Delta\sigma_{eqv})_{th}^{2/(1+n)}]^{-2}$, where C and $(\Delta\sigma_{eqv})_{th}$ are respectively the fatigue resistant coefficient and the threshold expressed by equivalent stress amplitude below which no crack initiates at the notch root and $N_i \to \infty$, and n is the strain-hardening exponent. C and $(\Delta\sigma_{eqv})_{th}$ are found to follow the log-normal distribution. According to the physical meaning and their probability distribution of fatigue resistant coefficient C and threshold $(\Delta\sigma_{eqv})_{th}$ in the fatigue life expression, a new method is proposed to simulate the fatigue test and the probability distribution of fatigue life of notched FW joints of mild-carbon steel under variable amplitude loading and checked by test results on notched FW joints under a programmed block loading spectrum. It is shown that both the simulated fatigue life and the test result of fatigue life of 45 steel notched friction welded joints under variable amplitude loading follow the log-normal distribution, and the two distributions agree well with each other, which is important and essential for the life estimation and the reliability assessment of FW joints under variable-amplitude loading.

Keywords: probability distribution, simulation, fatigue life, variable amplitude loading, friction welding, Monte Carlo approach

1. Introduction

Since considerable amount of mechanical elements including the friction welded (FW) structures work under cyclic loading of variable amplitude, it's of practical importance in the design and reliability assessment of mechanical elements to investigate experimentally the probability distribution of fatigue life under variable amplitude loading(VAL). Some work has been devoted to the cyclic fatigue of FW joints[1], nevertheless, the fatigue test under VAL is often very difficult, expensive and time consuming, and the probability distribution under VAL is then determined based on the fatigue test under VAL with relatively small sample size. Obviously there exist some limitations in the experimental investigation. In order to guarantee the safety and reliability of mechanical elements in service, it is imperative to develop the simulation model and method for fatigue life under VAL with big sample size.

In the present study, the fatigue tests under constant-amplitude loading (CAL) and analyses on the results are carried out on the notched friction welded joints of 45 carbon steel, which is similar to the AISI 1045 steel and used for half-shaft and cam shaft of car. Then, according to the physical meaning and their probability distribution of fatigue resistant coefficient and threshold in the fatigue life expression[2,3], attempts are made to find an approach for simulating the fatigue life and its probability distribution of 45 steel notched FW joints under VAL, the simulated results are compared with the test results under VAL.

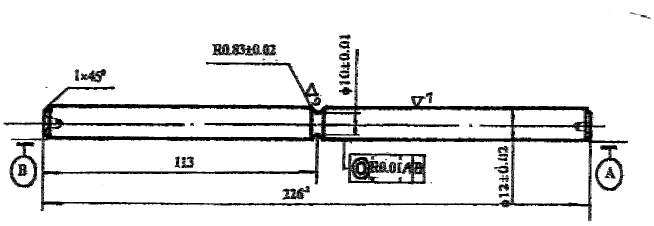
2. Experimental Procedure

Hot rolled bars of 16 mm diameter of 45 carbon steel in normalized condition were taken as the test material. The composition (wt. %) of 45 steel is as follows: 0.51C, 0.22Si, 0.65Mn and balance Fe. The experimentally measured tensile properties of this steel are: ultimate strength $\sigma_b = 703$ MPa, yield strength $\sigma_s = 441$MPa, elongation $\delta_{10} = 15.3\%$, reduction in area ψ=50.7%, and strain-hardening exponent n=0.134.

The friction welding process was performed on C25 type continuous driving friction welding machine. The welding parameters used are: heating pressure 130 MPa, heating time 1.4 sec, forge pressure 270 MPa and forge holding time 4 sec. The fracture of the joint in tension was found at the base metal and the tensile properties are found almost the same as those of the base metal. The as-welded joints were then turned and optically ground into standard fatigue specimen with notch at the welding interface. Consequently, before ground the specimen were corroded to display the welding interface. The stress concentration factor of the notched specimen is determined from ref.[4] to be K_t=2.0 as shown in Figure 1.

The fatigue tests were carried out on the rotating bending fatigue machine. The loading frequency was 50 Hz and the stress ratio was -1. The fatigue life was defined as the number of cycles to failure of the notched FW joints. The fatigue tests under constant-amplitude loading were performed at five cyclic stress levels with 10 specimens for each stress level to obtain five groups of fatigue test data. The fatigue tests under variable-amplitude loading were performed according to the programmed block loading shown in Figure 2.

Figure 1 Sketch of the notched fatigue test specimen of FW joints.



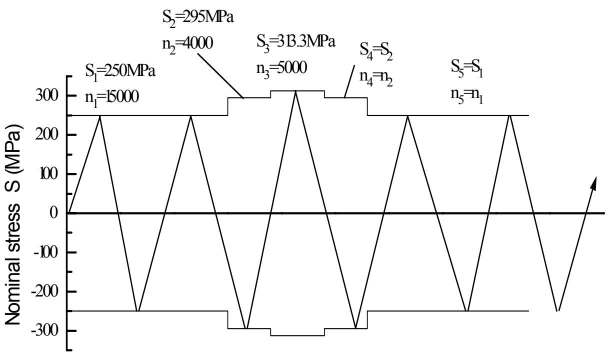


Figure 2 Sketch of the block loading

3. Fatigue Test Results under CAL and Analysis

Expression for Fatigue Life

Theoretical analysis[2] and experimental results[3,5-7] indicate that the fatigue crack initiation (FCI) life of notched specimen of metals and welds can be expressed as the function of equivalent stress amplitude $\Delta\sigma_{eqv}$,

$$N_i = C[\Delta\sigma_{eqv}^{2/(1+n)} - (\Delta\sigma_{eqv})_{th}^{2/(1+n)}]^{-2} \quad (1)$$

where

$$\Delta\sigma_{eqv} = \sqrt{\frac{1}{2(1-R)}} K_t \cdot \Delta S \quad (2)$$

In eqn(2) ΔS, R are the nominal stress range based on the net section and the stress ratio, respectively; K_t is the stress concentration factor. In eqn (1) C and $(\Delta\sigma_{eqv})_{th}$ are, respectively, the FCI resistant coefficient and the threshold expressed by equivalent stress amplitude, and n is the strain-hardening exponent.

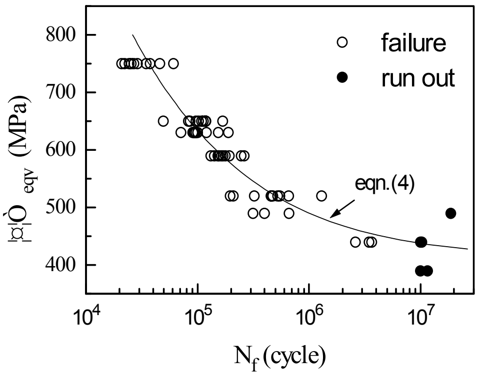


Figure 3 Test and fitting results of fatigue life

The fatigue test results of 45 steel notched FW joints under CAL are shown in Figure 3. As it may be seen from Figure 3, most data for fatigue life are beyond 10^5 cycles. Moreover, multiple cracks initiate surrounding the notch root and coalesce to form a large crack, which was observed on the fracture surface. Therefore, it may be thought that the FCI life occupied the dominant part of the fatigue life. In this case, eqn(1) can be approximately used to fit the test data of fatigue life N_f. Replacing N_i in eqn(1) with N_f and making the logarithmic transformation, eqn(1) becomes

$$\log N_f = \log C - 2\log[\Delta\sigma_{eqv}^{2/(1+n)} - (\Delta\sigma_{eqv})_{th}^{2/(1+n)}] \quad (3)$$

Eqn(3) represents a straight line with a slope of -2 on a logarithmic scale, i.e., $\log N_f$ vs. $\log[\Delta\sigma_{eqv}^{2/(1+n)} - (\Delta\sigma_{eqv})_{th}^{2/(1+n)}]$ scale. By using a trial and error approach to write a computer program for linear regression analysis, whose flow chart is shown in ref.[2], the values of C and $(\Delta\sigma_{eqv})_{th}$ can be obtained with the condition that the slope is within the range of -2±0.002.

By substituting the values of C and $(\Delta\sigma_{eqv})_{th}$ so-obtained back into eqn(1), the expression for fatigue life of 45 steel notched FW joints can be reached :

$$N_f = 2.179\times10^{14}[\Delta\sigma_{eqv}^{1.764} - 411.7^{1.764}]^{-2} \quad (4)$$

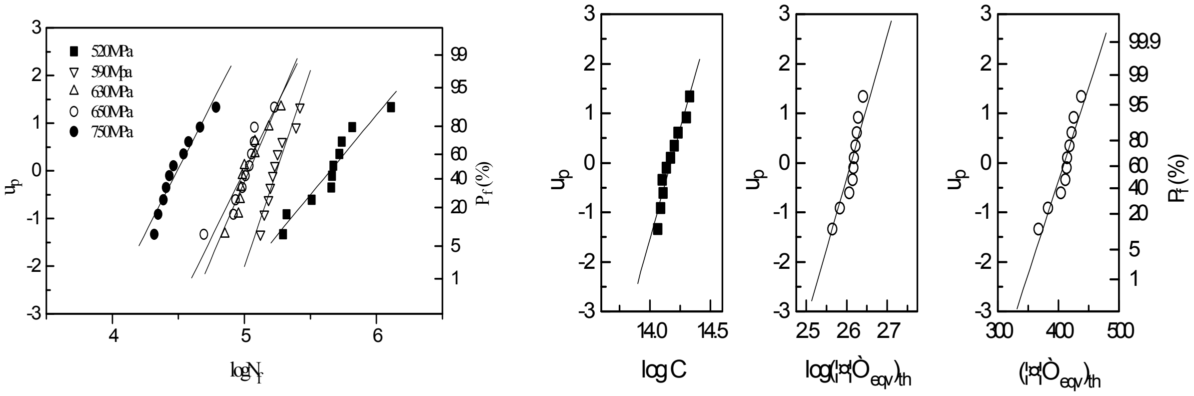
where n= 0.134 for the base material is taken as that for FW joint. Regression analysis gives the value of linear correlation coefficient r=0.9213 much higher than 0.28, the critical value for all data. This means that eqn(1) can be applied to successfully fit the test data of the fatigue life of 45 steel notched FW joints. Figure 3 shows the fatigue life curve drawn according to eqn(4).

Probability distribution of fatigue life, the constants C and $(\Delta\sigma_{eqv})_{th}$

The test data for the fatigue life at each cyclic stress in Figure 3 are respectively plotted on the normal probability paper as shown in Figure 4(a), where the mean rank is taken as the estimated value of the failure probability, P_f of the population[8]. Transforming the failure probability into the standard normal deviate, U_p, a straight line between $\log N_f$ and U_p can be obtained. The values of linear correlation coefficient between $\log N_f$ and U_p at each given equivalent stress amplitude given by regression analysis is much higher than the critical value of linear correlation coefficient given in ref.[8]. It shows that the fatigue life of 45 steel notched FW joints follows the usual log-normal distribution. Further examination by using Sharpiro-Wilk approach[8] leads to the same conclusion.

According to the approach in ref.[3,5], taking each one from the rearranged five groups of test data at five different stress levels in sequence can form 10 sets of fatigue test data. Using eqn(3) to fit so obtained 10 sets of fatigue test data respectively, 10 pairs of C and $(\Delta\sigma_{eqv})_{th}$ values can be obtained, where the values of correlation coefficient are higher than the critical value of the correlation coefficient [8] . It suggest that eqn(1) can be successfully applied to fit the test data of each set of fatigue life of 45 steel FW joints.

The so-obtained values of C and $(\Delta\sigma_{eqv})_{th}$ are rearranged according to the increasing order and plotted on the normal probability paper as shown in Figure 4(b) and (c). The values of the correlation coefficient given by the above-mentioned regression analysis are much higher than the critical value. Further examination by Shapiro-Wilk method shows that C and $(\Delta\sigma_{eqv})_{th}$ of 45 steel notched FW joints follow the log-normal distribution. The logarithmic mean value and standard deviation of C are 14.3405 and 0.0982, and those of $(\Delta\sigma_{eqv})_{th}$ are 2.6120 and 0.0222. It is also found that $(\Delta\sigma_{eqv})_{th}$ follows the normal distribution as well.



(a) (b) (c) (d)

Figure 4 Probability distribution of (a) fatigue life N_f , (b)log C, (c) log $(\Delta\sigma_{eqv})_{th}$ and (d) $(\Delta\sigma_{eqv})_{th}$ of 45 steel notched FW joints on normal probability paper

4. The principle and method for simulating fatigue life test under VAL

Investigations[2,6] show that C and $(\Delta\sigma_{eqv})_{th}$ are material constants determined by the crack forming mechanism and tensile properties and follow certain probability distribution. Analyses on many fatigue test results indicate that C and $(\Delta\sigma_{eqv})_{th}$ follow the log-normal distribution. Therefore, the probability distribution of C and $(\Delta\sigma_{eqv})_{th}$ can be used to represent the probability distribution characteristics of fatigue properties of the material, if only the probability distribution of C and $(\Delta\sigma_{eqv})_{th}$ is known, the corresponding fatigue properties of the material can be settled consequently.

Based on the above consideration and results, and regarding the famous hypothesis of Weibull on the S-N curve of individual [9], the following model for fatigue test procedure can be developed:

1) The distribution of C and $(\Delta\sigma_{eqv})_{th}$ can be used to represent the distribution characteristics of fatigue properties of the material, i.e., for a definite material, its fatigue curves with different survivabilities (P-S-N curves) are determined.
2) Each individual specimen has a corresponding S-N curve, which is one member of the P-S-N curves family, i.e., different fatigue specimen is assumed to be distinguished by different combination of C and $(\Delta\sigma_{eqv})_{th}$.
3) The scatter of the fatigue life results from the difference between the fatigue specimens, i.e., from the random sampling of individual specimen from the population of specimens, or from the random selection of P-S-N curve from the family of P-S-N curves of the material.

It is pointed out that for the notch elements of metals with non-continuous hardening characteristic such as 45 steel and its welds, the so-called overloading effect factor, z.=0, in this case, Miner's rule and the expression for the fatigue life can be directly applied to predict the fatigue life and cumulative fatigue damage of notched elements of metals with non-continuous strain-hardening characteristic under VAL. According to the above model and the research result, the simulation for the fatigue test result under VAL can be carried out following the below procedures to write a computer program:

1) According to the approach in ref.[5,6], determine the probability distribution and its characteristic parameters such as logarithmic mean value and standard deviation of C and $(\Delta\sigma_{eqv})_{th}$ from the results of group fatigue life test under different constant amplitude loading.
2) Adopt Monte Carlo approach to produce 10000 simulating values of C according to the logarithmic mean value and standard deviation of C, then rearrange the so-obtained 10000 C according to the order of increasing value.
3) Adopt Monte Carlo approach to produce 10000 simulating values of $(\Delta\sigma_{eqv})_{th}$ according to the logarithmic mean value and standard deviation of $(\Delta\sigma_{eqv})_{th}$, then rearrange the so-obtained 10000 $(\Delta\sigma_{eqv})_{th}$ according to the order of increasing value.
4) Take each one from the rearranged C and $(\Delta\sigma_{eqv})_{th}$ in sequence to get 10000 pairs of C and $(\Delta\sigma_{eqv})_{th}$ values and constitute the family of 10000 P-S-N curves, which forms the parent specimens.
5) Randomly sample n pairs of C and $(\Delta\sigma_{eqv})_{th}$ from the above obtained 10000 pairs to represent n specimens, then substitute the n pairs of C and $(\Delta\sigma_{eqv})_{th}$ into equation (1) to yield n expressions of S-N curves.
6) Transform the nominal stress spectrum into the equivalent stress amplitude spectrum by substituting the values of K_t, ΔS and R (see Figure 2) into eqn(2).
7) Calculate the fatigue life $N_{f,j}$ (j=1,2,...,5) at each level of $\Delta\sigma_{eqv}$ in the equivalent stress amplitude spectrum by substituting the equivalent stress amplitude into one of the so obtained expressions of S-N curves, which corresponds to a fatigue test specimen.
8) Calculate the cumulative fatigue damage of one load block according to Miner's rule, $D_0=\Sigma n_j/N_{f,j}$, where n_j is the number of cycles at stress level *j* in load spectrum.
9) Obtain the fatigue life expressed by load blocks N_b when the total fatigue damage accumulation reaches 1.0, i.e., $N_b=1.0/D_0$.
10) Repeat step 7) to step 9) to obtain the fatigue life N_b under VAL corresponding to the sampled n specimens.
11) Make statistical analysis on the n fatigue life N_b under VAL to determine the probability distribution and its corresponding characteristics of fatigue life under VAL.

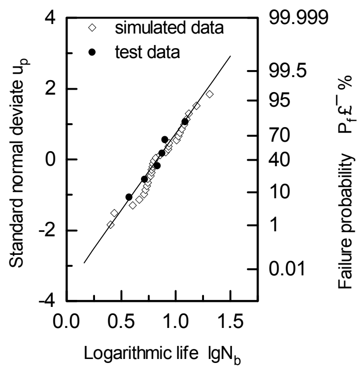


Figure 5 Probability distribution of the simulated and test fatigue life of 45 steel notched FW joints

5. Simulation results of probability distribution of fatigue life under VAL and substantiation

By following the above procedures and considering the logarithmic mean value and standard deviation of C and $(\Delta\sigma_{eqv})_{th}$ obtained in section 3, the simulation of fatigue life of notched 45 steel FW joints under VAL shown in Figure 2 can be carried out. The so-obtained 30 values of N_b are rearranged according to the increasing order and plotted on the normal probability paper as shown in Figure 5. The value of linear correlation coefficient between $\log N_b$ and U_p by regression analysis is 0.9847, much higher than the critical value of linear correlation coefficient [8]. It shows that the fatigue life N_b of 45 steel notched FW joints under VAL follows the usual log-normal distribution[5,6]. Further examination by using Sharpiro-Wilk approach[8] leads to the same conclusion. The logarithmic mean value and standard deviation of N_b are 0.8588 and 0.2061.

The fatigue test results with 6 specimens of 45 steel notched FW joints obtained under the programmed block loads shown in Fig. 2 are also plotted in Figure 5. It can be seen that the fatigue test results under VAL follow the log-normal distribution. The logarithmic mean value and standard deviation of the test N_b are 0.85284 and 0.1745. Further examination by using Shapiro-Wilk method shows that the test results of fatigue life under VAL mentioned above still follow a log-normal distribution.

Further test on the significant difference between the simulated and test lgN_b in Figure 6 by following the approach in ref.[8] suggest that there is no significant difference between the two logarithmic mean fatigue lives, and between the two logarithmic standard deviations under the significance level of 5%. Therefore, the fatigue test results of the notched FW joints under VAL of figure 2 simulated according to the procedures in section 4 come from the same population of the test results, thereby the simulated probability distribution of fatigue life is in good agreement with that of test results of notched 45 carbon steel friction welded joints. Therefore, the probability distribution of fatigue life under VAL can be simulated by the model developed in the paper, which offer the base for fatigue design and reliability assessment of notched elements under VAL.

6. Conclusions

(1) The test results and analysis show that the fatigue life of 45 steel notched FW joints can be expressed as a function of the equivalent stress amplitude as shown by eqn(1), which contains only two fatigue constants C and $(\Delta\sigma_{eqv})_{th}$.

(2) The test results of fatigue life of 45 steel notched FW joints of small size follow the log-normal distribution as usual. In this case, the fatigue resistant coefficient and threshold of 45 steel notched FW joints follow the log-normal distribution, respectively, and the fatigue threshold follows the normal distribution as well.

(3) According to the physical meaning and their probability distribution of fatigue resistant coefficient C and threshold $(\Delta\sigma_{eqv})_{th}$ in the fatigue life expression (1), a new method is proposed to simulate the fatigue test and the probability distribution of fatigue life of notched elements under variable amplitude loading.

(4) The simulated fatigue life of 45 steel notched friction welded joints under variable amplitude loading of figure 2 follow the log-normal distribution, and agree well with the test result of fatigue life.

Acknowledgment—Thanks are given to the Committee of Aeronautical Science Funds for their supports to our work through Document 97H53102.

REFERENCES

[1] Hasegawa, M., Ieda, T. and Taki, N.. Fatigue strength of friction-welded joints with flash in various carbon steels[J]. Welding Int., 1997, 11(12): 950~957.

[2] Zheng Xiulin. A further study on fatigue crack initiation life--Mechanical mode for fatigue crack initiation[J], Int. J. Fatigue, 1986, 8(1):17~21.

[3] Zheng, X. L., Quantitative Fatigue Theory for Metals, Press House of Northwestern Polytechnical University, Xi'an, China, 1994.1

[4] M. Nisida, Stress Concentration Factors, Mositoka Press, in Japanese(1971)

[5] Zheng X.L., Li Z. and Lu B.T.. Prediction of probability distribution of fatigue life of 15MnVN steel notched elements under variable amplitude loading[J]. Int. J.Fatigue, 1996, 18(2):.81~86.

[6] Wei, J. F., On Models For Prediction Probability Distribution of fatigue Life under Variable Amplitude Loading, A Dr. Dissertation , Northwestern Polytechnical University, Xi'an China, 1996.11

[7] Lin C, Zheng XL. Overload Effects on Fatigue Life Prediction of 16Mn butt welds Steels. Transaction of China welding Institue, 1991, 12(4):247~251.

[8] P.Deng, Applications of Statistics in Measurements and Experiments, Press of Chemical Industry, Beijing (in Chinese)(1981)

[9] Weibull W.. Fatigue testing and analysis of results[M]. New York: The Macmillan Company, 1961.