Cyclic Stress-Strain Curve for Low Cycle Fatigue Design and Development of Small Specimen Technology

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Abstract. A blanket system in DEMO requires a low cycle fatigue design because higher inner pressure will act on a structural wall. An importance of cyclic stress-strain curve is investigated and necessity reason for a precise deformation measurement is discussed. Since a small specimen technique is necessary to investigate neutron irradiation effect, it is desired to establish a test procedure to obtain the stress-strain curve with small specimens. To do this, a new test procedure with nanometer scale resolution was developed and some data were obtained.

1. Introduction

A prototype fusion reactor, which is called DEMO, will perform Deuterium (D) - Tritium (T) experiments and generate a lot of 14 MeV neutrons. It is expected that the total amount of neutrons would be ten times or hundred times larger than ITER. To change the kinetic energy of 14 MeV neutrons to the thermal energy, a blanket system will be installed. The nuclear heat in the blanket will be taken out by a coolant which will be heat-exchanged by the secondary loop. The blanket is a kind of a heat generator and a key component for the neutron shielding at the same time. By using lithium or lithium oxide as the coolant, tritium breeding will be performed. Also, by putting beryllium in the blanket, neutron will be multiplied. As the heat generation in the blanket is huge, the very rapid coolant circulation must be established. To realize the fast flowing, the pressurized coolant will be put in the blanket and it would cause the blanket swollen. Some local stresses in the blanket will exceed the yield stress and the high stress will be repeated during the reactor operation. Since the repeated stress level would be high, the low cycle fatigue design would be required.

The low cycle fatigue design needs the fatigue life data which is a fatigue life diagram between a strain range and a fatigue life. A round bar specimen with a certain length of a parallel part is used for the low cycle fatigue test because the stress and strain conditions are uniform in the parallel part. However, an hour glass specimen is also used for the fatigue test. This specimen has a narrow cross section and stress concentration occurs at the minimum cross section. Since the fracture occurs around at the minimum cross section area and a buckling is avoided, the hour glass specimen is preferred in both low cycle and high cycle fatigue tests. However, it is known that the fatigue data of the hour glass specimen does not meet with the data of the round bar specimen. The consideration on this issue will be carried out later.
To investigate the effect of neutron irradiation on the fatigue resistance, a small specimen technique has been developed, for the small specimen reduces the activated waste. To realize the same performance as the standard specimen in the small specimen technique, the high resolution measurement with nanometer scale accuracy of the deformation must be achieved. Therefore, a new test device for the small specimen has been designed and assembled using a laser displacement gage system.

In this study, the low cycle fatigue behavior will be presented and the cyclic stress-strain curve will be discussed. The importance of the precise deformation measurement will be emphasized. Then a new test device with laser displacement gages will be introduced which has been developed to investigate the fatigue life of the small specimen and some data obtained with the new test system will be shown.

2. Low Cycle Fatigue Behavior and Cyclic Stress-Strain Curve

During the fatigue process in the low cycle fatigue, the stress-strain hysteresis curves change gradually. Figure 1 shows typical stress-strain hysteresis curves of low activation ferritic/martensitic steel, JLF-1 [1]. The fatigue test was carried out at room temperature and non-irradiated standard size specimens with 8 mm diameter and 18 mm parallel part length were used. The deformation of the gage length was measured by displacement gage with strain gages attached. Since the maximum and the minimum strains were controlled, the peak stresses at positive and negative loads were changeable. In the case of Fig. 1, the maximum and the minimum strains of +/- 1.1% were controlled and total strain range (\(\Delta \varepsilon_t\)) was kept to be 2.2%. It is clear that the peak stress increased at the initial stage and decreased after that gradually. The changes in the peak stresses during the fatigue in the different specimens are shown in Fig. 2. The cyclic hardening is observed in the region of less than 10 cycles and cyclic softening occurs gradually. It is not easy to determine the representative stress-strain hysteresis curve in each test condition but the hysteresis curve at about half of the fatigue life is taken up as the representative in this study. As it is seen in Fig. 2, the peak stresses already dropped at the half of fatigue life.

The representative stress-strain hysteresis curves are collected in Fig. 3 together with the static stress-strain curve which was obtained under monotonic loading. By connecting the peak stresses at each hysteresis curve, another stress-strain curve was obtained. This curve is

![FIG. 1. Stress-strain hysteresis curves of JLF-1 under axial strain controlled low cycle fatigue.](image-url)
FIG. 2. Change in peak stresses during fatigue process.

FIG. 3. Collection of representative hysteresis curves and cyclic stress-strain curve.

FIG. 4. Comparison of strain hardening process on representative hysteresis curves.
designated as the cyclic stress-strain curve which presents the cyclic stress-strain properties of the material under a certain environment. The cyclic stress-strain relation will be applicable to FEM analysis where the reversible yield stress must be determined. In between the elastic line on the static stress-strain curve and the cyclic stress-strain curve, there is a space. This region is for high cycle fatigue area and there is no clear idea how to connect. Therefore, one may connect a point of a half of yield stress and the cyclic stress-strain curve with a smooth curve to make one cyclic stress-strain curve.

The representative curves were shifted to the negative strain side and fit each elastic line to the elastic line of hysteresis curve under $\Delta \varepsilon$ is 3.0% as shown in Fig. 4. It is noted that all representative curves show almost same cyclic yield stress and hardening properties, and the hysteresis curve of 3.0% of $\Delta \varepsilon$ will be adopted as a master hysteresis curve of the material under this condition. From these results, the following design process will be recognized. As shown in Fig. 5, when the cyclic stress-strain curve and the master hysteresis curve are given, a certain stress-strain hysteresis curve will be able to be predicted based on a given design strain. Since the hysteresis curve at a certain design point is predicted by this process, the low cycle fatigue life will be calculated by Manson-Coffin’s law or Miner’s rule.

3. A New Fatigue Test Device for Small Specimen

A small specimen is preferable to investigate the low cycle fatigue properties of blanket structural material, because the reduction of the activated material is able to be achieved. When the same fatigue design process is supposed even in the case of the small specimens are adopted, a precise deformation measurement must be established to ensure the adequate accuracy for discussion on the low cycle fatigue behavior. Since a new laser displacement gage system which has nanometer resolution came on the market recently, a new fatigue test device with an axial strain control was fabricated for a small round bar specimen.

To measure the deformation of the gage length precisely, a clip-on type displacement gage with strain gages is commonly used for the standard specimen that has the gage length of about 10 mm. One micrometer must be resolved to perform the accuracy of 0.0001 strain in case of 10 mm gage length. When the gage length is 1 mm for the small specimen, 100 nanometers must be resolved and 10 nanometers accuracy must be achieved to keep the accuracy of 0.0001 strain.

![FIG. 5. Prediction process of stress-strain hysteresis curve form design strain.](image-url)
To achieve such high accuracy on the small round bar specimen, a laser displacement gage system with one nanometer resolution was installed in a new fatigue test device to measure the axial deformation, and a Piezo actuator was adopted as a driving source to control the deformation of the gage length. The block diagram of the new test system is shown in Fig. 6 [2]. Two sets of laser displacement gage were used to measure the distance from the fixed point to reflecting plates (0.2 mm thick and polished) independently as shown in Fig. 7. The two reflecting plates were fixed on the support beam (0.2 mm thick) which was pulled by a spring to be attached on the small specimen. The distance between two reflecting plates was adopted as a gage length. The deformation of the gage length was calculated (subtracting distance B from distance A) and the signal was feed backed to the Piezo controller (0-150 µm in capacity) to control the deformation of the gage length. The specimen was fixed by pushing the both ends of the specimen with rods, and the device was put on the stiff desk and covered with an acryl case to avoid the fluctuation [2].

The control wave was sine wave, the frequency was 0.25 Hz (0.03 Hz was adopted when the data was recorded.), strain ratio was -1, and the sampling rate for record was 10 Hz. The test portion of the specimen is 1.1 mm diameter and the 2.0 mm long round bar which is almost same size as S. Nogami et al reported [3]. The test material was JLF-1 [1].
4. Test Results and Discussion

To determine the gage length, the specimen surface was investigated with microscope after the test. As the support beam was pulled to vertical direction to the loading axis and was attached on the small specimen as shown in Fig. 7, the traces of the edges of the support beam were found on the specimen surface as shown in Fig. 8 (Specimen #12). The gage length was determined by measuring the distance between the edge traces. In case of Fig. 8, the distance (gage length) was 500 μm and the crack was observed outside of the gage length (Type C).

The stress-strain hysteresis curves of Specimen #6 are shown in Fig. 9. At the initial stage of the fatigue, the peak stresses are high and the plastic strain component is small. The changes in peak stresses and strains at zero stress of specimen #6 during fatigue are shown in Fig. 10. The peak stresses become smaller within around 100 cycles after the test started and the strains at zero stress become larger. Such rapid changes were not observed in the tests with the standard specimen [1]. Also, the hysteresis curve does not show the elastic line. Although there is no clear evidence to explain these behaviors, it is considered that the small specimen would be twisted and bended when the specimen was chucked to the test frame. If the specimen would be twisted and bended, multi-axial stress condition was generated in the parallel part resulting in increase of apparent yield stress. Under the alternative axial plastic deformation, the torsion and bending component would be released and the axial plastic strain component would be increased. The relaxation might occur within about 100 cycles after the test started. The contact points of the support beam edges on the specimen might be movable in the case that the initial twisted or bending deformation was large. This may influence the hysteresis curves which did not show the clear elastic line. When the fatigue life is discussed, the strain range at half of fatigue life will be useful as representative, because the period that the rapid change in strains occurred is rather shorter than the stable period.

FIG. 8. Tested surface of specimen #12. Nf; 2,808 cycles. Δε; 1.55%.

FIG. 9. Hysteresis curves of small specimen #6. Nf; 5,065 cycles. Δε; 1.18%.
The fatigue life diagram between the total strain range and the fatigue life is shown in Fig. 11 [1,5]. In the figure, there are four set of the JLF-1 fatigue life data, i.e., the data sets of the standard and small round bar specimens and the data sets of the standard and small hourglass specimens. In case of the hourglass specimen, the axial strain ($\varepsilon_z$) was converted from the radial strain ($\varepsilon_r$) using a conversion equation in ASTM E606 Appendix X2 [6] as follows:

$$\varepsilon_z = \frac{\sigma_z}{E} (1 - \nu_e) - 2\varepsilon_r \quad (1)$$

where $\sigma_z$, $E$, and $\nu_e$ are the axial stress, Young’s modulus, and elastic Poisson’s ratio.

Equation (1) consists of two terms. The first is elastic component and the second is perfect plastic component. When the elastic strain is negligible, i.e., when fully plastic deformation occurs, the volume does not change. In this case, Poisson’s ratio is 0.5 and equation (1) becomes $\varepsilon_z = -2\varepsilon_r$. Since the elastic strain component is not negligible, equation (1) will give larger $\varepsilon_z$ than the real axial strain. When the strain is small, the first term becomes dominant, but it is smaller than the real one because the stress concentration is not considered. Also, the strain distribution on the minimum cross section is not taken into account. So, as mentioned before, the hourglass specimen data does not meet with the round bar specimen data, and small hourglass data does not meet with the standard hourglass data.

In case of the round bar specimens, the small specimen data is plotted on the result of the

FIG. 10. Change in peak stresses and strains of specimen #6. $N_f$: 5,065 cycles. $\Delta\varepsilon_t$: 1.18%.

FIG. 11. Example of hysteresis curves on small specimen. $N_f$: 5,065 cycles. $\Delta\varepsilon_t$: 1.18%. 
standard specimen. Although the effects of grain size and homogeneity are considered, it must be noted that the axial controlled low cycle fatigue data of the small round bar specimen would give the same results of the standard round bar specimen. The same results have been obtained by S. Nogami et al. using other ferritic/martensitic steel, F82H [4].

From the results, the importance of the precise deformation measurement in the axial direction is recognized and it is anticipated the deformation mode at the initial stage of the fatigue must be analyzed clearly.

5. Summary

In this paper, the importance of the hysteresis curve and the cyclic stress-strain curve was discussed showing the low cycle fatigue data of JLF-1 at room temperature. The cyclic stress-strain curve is useful for the FEM analysis to characterize the cyclic yielding behavior of the structural material.

To discuss the hysteresis curve and the cyclic stress-strain curve, the deformation measurement with nanometer scale accuracy must be established and the trial assembly of the new fatigue test device for the small round bar specimen was conducted using the laser displacement gage with one nanometer resolution.

The very low noise and high accuracy test system was constructed and demonstrated. The clear hysteresis curves were obtained. However, it is considered that some issues on the chucking procedure will still remain and the further efforts must be done to improve the test system more precisely.

The low cycle fatigue property is one of the important material properties and indispensable to perform the fatigue design of the blanket. The clear database is anticipated.

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References


