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Development of a remote-controlled fatigue test machine using a laser extensometer for investigation of irradiation effect on fatigue properties

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Abstract

In order to investigate effects of neutron irradiation on fatigue properties of nuclear materials, a remote-controlled high temperature fatigue test machine was developed at the hot laboratory of the Japan Materials Testing Reactor (JMTR) in the Japan Atomic Energy Research Institute (JAERI). A small-sized fatigue specimen having double blades to measure strain with a laser extensometer was designed for this machine. A strain amplitude in fatigue tests of a completely reversed push-pull type using a triangular wave was controlled with an accuracy of ±3% of the total strain range during test. Low cycle fatigue tests of type 304 stainless steel irradiated in JMTR at 823 K up to a fast neutron fluence of 1×10^{25} n/m^2 ($E > 1$ MeV) were performed in total strain ranges of 0.7–1.4% at 823 K using the designed small-sized specimens.

1. Introduction

Low cycle fatigue behavior at elevated temperatures is of considerable interest in the design of many components used in nuclear and non-nuclear power plants [1–5]. Although many studies have been made on fatigue properties of several kinds of fusion reactor materials at elevated temperatures [1–3,6,7], not so many studies have been performed on the effect of neutron irradiation on fatigue properties of these materials [8]. It is very essential for designing of fusion reactors to obtain many low cycle fatigue data for irradiated materials, which are candidates for the structure and component of the fusion reactor.

In this study, a remote-controlled high temperature fatigue test machine has been developed to investigate the effect of neutron irradiation on fatigue properties of the structural materials. The fatigue test machine was installed in the hot laboratory of the Japan Materials Testing Reactor (JMTR) of the Japan Atomic Energy Research Institute (JAERI) and in-cell testing was performed. Furthermore, low cycle fatigue tests of unirradiated and irradiated type 304 stainless steel were conducted by the machine.

2. Remote-controlled high temperature fatigue test machine

A schematic drawing of the remote-controlled high temperature fatigue test machine installed in a hot cell of

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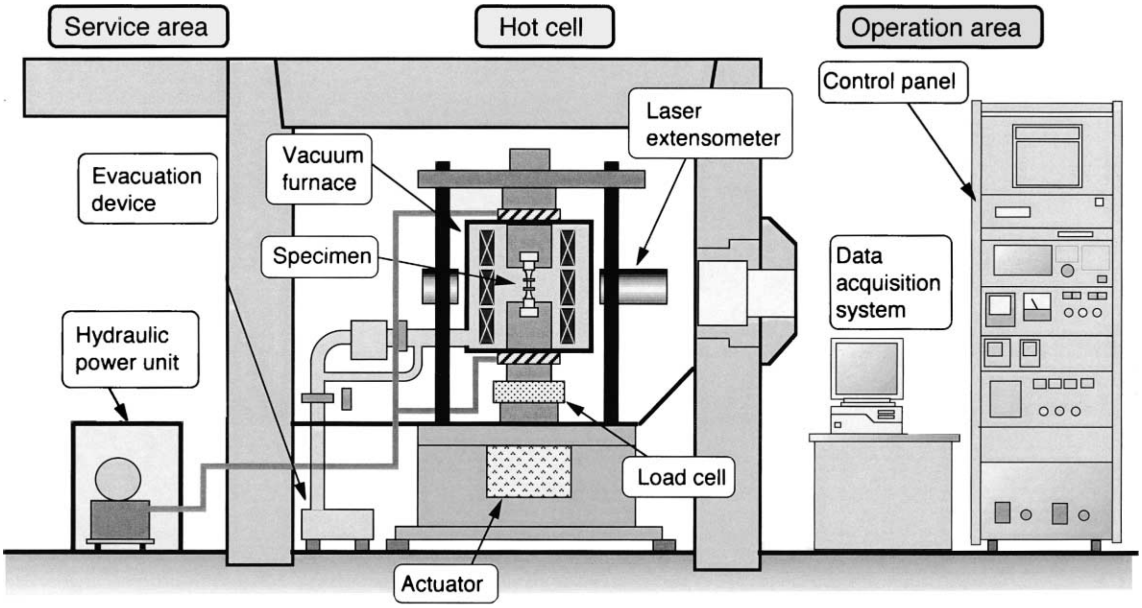

Fig. 1. Schematic drawing of remote-controlled high temperature fatigue test machine.

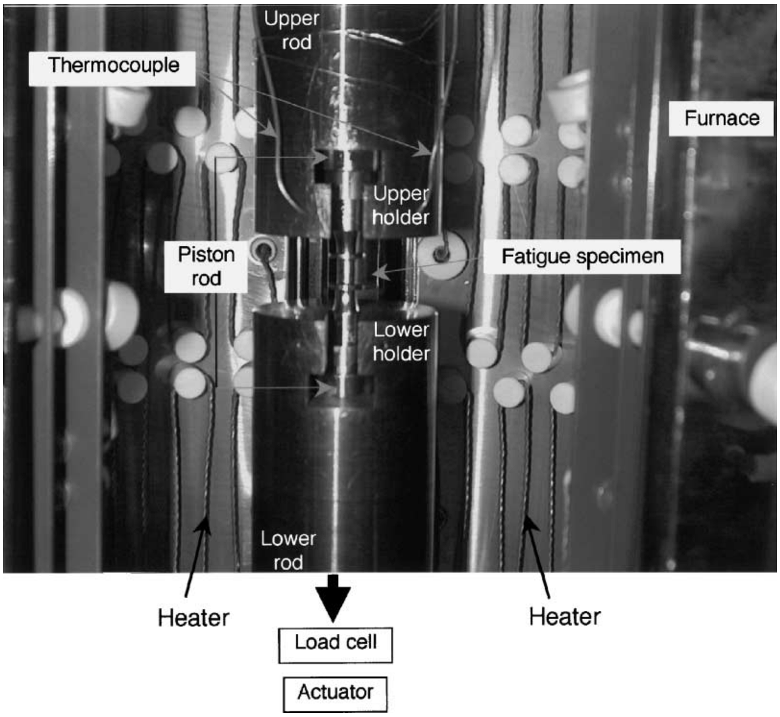

Fig. 2. Photograph of the irradiated fatigue specimen between upper and lower rods.

the hot laboratory in the JMTR is shown in Fig. 1. The machine mainly consists of a load control unit, a vacuum furnace and a laser extensometer. An actuator of the machine is controlled mechanically by a servo-motor. Low cycle fatigue tests can be performed at RT or temperatures ranging from 573 to 1073 K with an accuracy of ±3 K under an axial strain-controlled condition. The strain control is a completely reversed push-pull type using a triangular or a trapezoidal waveform. In the case of the gauge length of 8 mm, the axial strain rate can be changed from 2×10^{-5} to 5×10^{-1}%/s in the fatigue test. The maximum compressive and tensile loads of the actuator during the fatigue test are 10 kN. Furthermore, the maximum stroke of the actuator is 70 mm. The axial strain during the fatigue test is measured by a laser extensometer with an accuracy of ±0.5%. The fatigue test can be carried out in either a vacuum of 10^{-4} Pa or an inert atmosphere.

A photograph of an irradiated fatigue specimen fixed between upper and lower rods is shown in Fig. 2. A holder for the fatigue specimen is attached to both upper and lower rods. A heater in the furnace is made of nickel–chromium alloy. Thermocouples are installed in the upper rod to control and measure test temperatures. The procedures to fix the specimen using both holders by remote manipulation are as follows. The lower rod is moved up in a vertical direction to the position for setting the specimen into holders. After the specimen is set into both upper and lower holders, the lower rod is moved down until quite a little amount of tension load is applied to the specimen. Furthermore, to fix the specimen completely by both holders, a piston rod moved by hydraulic pressure is contacted to the bottom-end of the specimen in both upper and lower holders.

3. Subjects in development of the remote-controlled fatigue test machine

3.1. Utilization of a small-sized fatigue specimen

Utilization of a small-sized fatigue specimen to obtain the fatigue data is one of the subjects in the development of the remote-controlled fatigue test machine. As shown in Fig. 3(a), the small-sized fatigue specimen specially designed for this machine is round bar type having a gauge section of 4 mm in diameter and 6 mm in length, and has double blades at both ends of the gauge section for strain control during test. Especially, the semicircular groove is manufactured in the blades from their outsides to prevent the crack initiation around the blade from the concentrating of the stress during the fatigue test. As a result of the finite element method (FEM) analyses concerning the distribution of the stress in the specimen deformed by tensile and compressive stresses, no stress concentration was confirmed around the blades. The volume of the small-sized specimen is about one-twentieth to that of middle-sized specimens used in previous study [9]. The calorific value of the middle-sized specimen due to the gamma heat during neutron irradiation is larger than that of the small-sized specimen. The design of the small-sized fatigue specimen

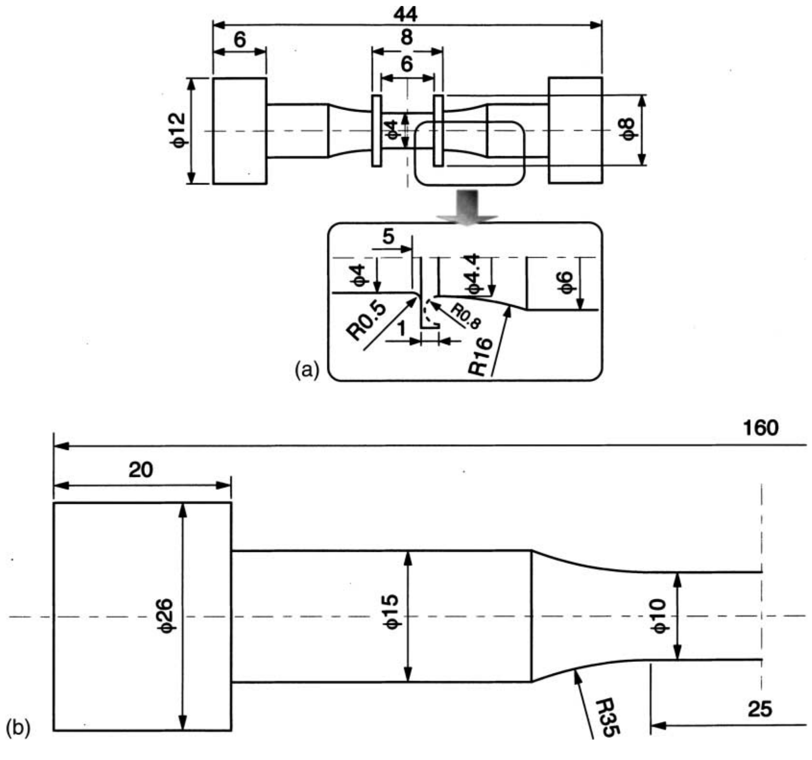

Fig. 3. Shape and dimension of fatigue specimens (unit: mm). (a) Small-sized fatigue specimen designed for the present PIE in our laboratory. (b) Middle-sized fatigue specimen designed in accordance with ASTM E606 for the past PIE in our laboratory.

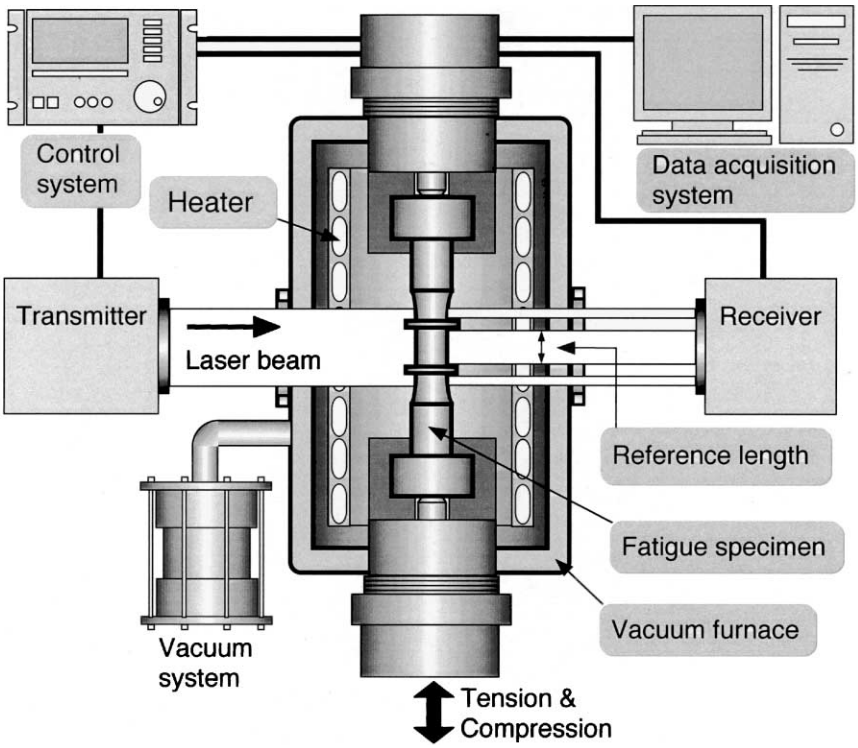

Fig. 4. Schematic drawing of the strain measurement system using a laser extensometer.

is very essential to investigate fatigue properties of materials irradiated at low temperature regions, since it is difficult for the middle-sized specimen to keep the irradiation temperature to be constant at low temperature regions. Furthermore, an irradiation capsule has the limitation of the space to install specimens. The number of specimens to be installed in one irradiation capsule increases with decreasing volume of the specimen. Therefore, fatigue properties can be obtained sufficiently on the irradiated materials by using this machine.

3.2. Utilization of a Laser extensometer

Since the small diameter of the small-sized fatigue specimen is disadvantage to use an extensometer with two rods that are contacted with the specimen, the development of a laser extensometer is needed to measure strain during a fatigue test. A schematic drawing of the strain measurement system with the laser extensometer is shown in Fig. 4. The laser device consisted of a semiconductor type laser transmitter and receiver, which aligned with one another. The laser extensometer has a scanning ranges of 0.5–55 mm in width with an accuracy of ±3 μm. Strain measurement using laser extensometer requires the definition of a reference length. As shown in Fig. 4, the distance, 6 mm, between both blades was determined as the reference length in the small-sized specimen. In particular, the capacity of a scanning frequency of the laser beam was improved from 16 to 480 Hz in order to measure the distance between blades with high resolution. Furthermore, in order to improve the signal–noise ratio in the digital output of voltage from the laser extensometer, the mean value of thirty data

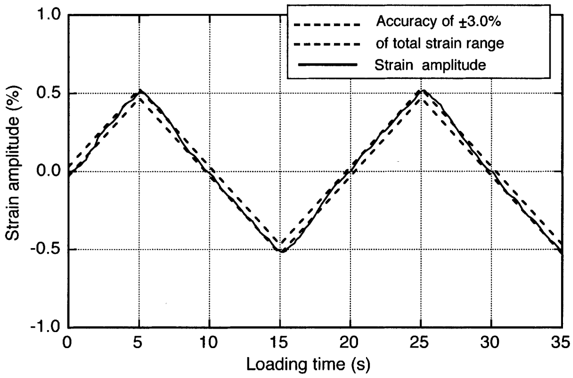

Fig. 5. Strain amplitude of the specimen during fatigue test under the total strain range of 1.0%.

accumulated at intervals of about 0.002 s was calculated by the computer with each time the digital output was obtained during test. By these improvements the strain-controlled fatigue test using the laser extensometer can be conducted with a complete triangular waveform.

Fig. 5 shows a strain amplitude of the actuator during the fatigue test at 823 K in a vacuum under the controlled strain range of 1.0% with an axial strain rate of 0.1%/s. The signal from the actuator is changing in range of ±3.0% against the controlled strain range of 1.0%. Therefore, it is clear that the actuator was controlled by triangular waveform with the controlled strain range of 1.0%.

4. Fatigue test results of irradiated type 304 stainless steel

Low cycle fatigue tests of both unirradiated and irradiated type 304 stainless steel were conducted by the machine. The chemical compositions of the steel are shown in Table 1. The tests were performed at 823 K in a vacuum less than 10^{-4} Pa under an axial strain-controlled condition. The triangular waveform was used in the test. Total strain ranges were controlled at 0.7%, 1.0% and 1.5% with an axial strain rate of 0.1%/s. The number of cycles to failure, the fatigue life, was defined as a point at which the tensile stress decreases to 75% of the maximum stress during cyclic stress testing [10].

The variation in stress amplitude as a function of number of cycles for an irradiated specimen at a total strain range of 0.7% is shown in Fig. 6 as a representative result of fatigue tests by this machine. The stress amplitude increases with increasing the number of cycle in the low-cycle region, and shows the saturated region afterward. The curve showing this variation of the stress amplitude during the strain-controlled fatigue test is called the fatigue hardening curve [11]. This behavior, which was previously caused in this material [12], was also observed in the results of other fatigue tests for both unirradiated and irradiated specimens.

Fatigue life data of unirradiated and irradiated type 304 stainless steel are shown in Fig. 7 as the number of cycles to failure, N_f, versus the total strain range, $\Delta\varepsilon t$. The reduction of about 50% in the fatigue life of the irradiated specimens was observed compared with that of the unirradiated specimens.

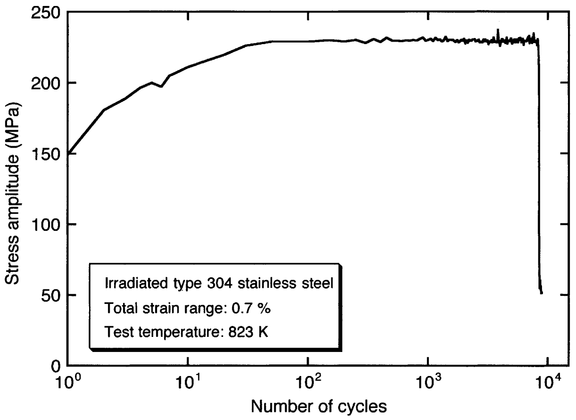

Fig. 6. Cyclic stress response curve of the irradiated specimen during fatigue test under the total strain range of 0.7% at 823 K.

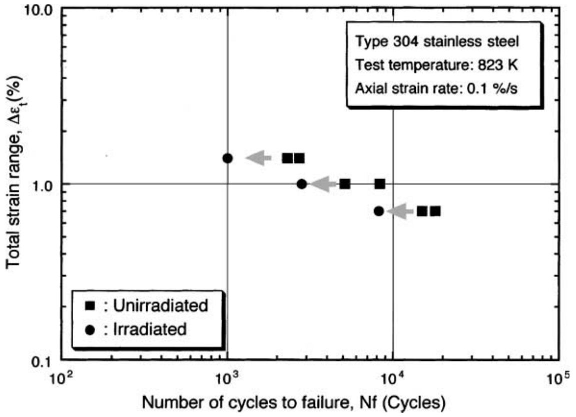

Fig. 7. Fatigue life data of unirradiated and irradiated specimens made of type 304 stainless steel.

On the basis of the experimental results by this fatigue test machine, Ioka et al. [8,13] investigated the effect of the neutron irradiation on fatigue properties of the irradiated type 304 stainless steel in detail.

5. Summary

In order to investigate the effect of the neutron irradiation on fatigue properties of structural materials for fusion and fission reactors, a remote-controlled high temperature fatigue test machine was developed in the hot laboratory of JMTR in JAERI. Low cycle fatigue tests of irradiated type 304 stainless steel were performed by the machine.

Table 1
Chemical composition of material used in this test (wt%)

C	Si	Mn	P	S	Cu	Ni	Cr	Nb	V	N	Co	B	Fe
0.0047	0.54	0.78	0.024	0.003	0.09	9.08	18.52	0.02	0.08	0.034	0.05	0.0002	Balance

1. A small-sized fatigue specimen having double blades at both ends of the gauge section for the strain measurement during test was used in this machine.
2. A developed laser extensometer can control a strain amplitude in fatigue tests of a completely reversed push-pull type using a triangular wave with an accuracy of ±3% of the total strain range during test.
3. It was found that neutron irradiation caused a significant reduction in the low cycle fatigue life of type 304 stainless steel by using this fatigue test machine.

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