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Fatigue strength assessment of SUS316 by small bulge fatigue (SBF) test

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Abstract: A new fatigue test apparatus with a small disk-type specimen (8 mm in diameter) was developed in the authors' group. This testing technique was termed "Small Bulge Fatigue (SBF) test". Unlike the small punch (SP) test, a hydraulic bulging method was adopted for avoiding problems attributable to the contact or the friction between ball and specimen. A cyclic oil pressure could be alternatively applied to both specimen surfaces at the frequency of 10 Hz. The specimen thickness of central region (gauge area) was relatively reduced to avoid cracking at the edge of specimen, and the characteristic small disk-type specimen with flat and concave surfaces was proposed considering machinability and handleability. Austenitic stainless steel SUS316 was subjected to the preliminary test using this newly developed testing technique. The obtained results indicated that this SBF test had a potential for fatigue strength assessment.

Keywords: small sample testing technique; small punch test; fatigue; hydraulic bulging method

1. Introduction

The unplanned outage in fossil power plants is caused by various types of damage or materials degradation such as a fatigue, creep, erosion/corrosion, oxidation, wear, etc. [1-4]. The low cycle fatigue is the most critical issue in high temperature components. As can be clearly seen in Figure 1, the fatigue damage causes almost one third of the outages in the industrial boiler, gas turbine and industrial steam turbine, respectively. In the case of commercial boiler, sixty percent is attributable to this fatigue damage. Therefore, it is very important to evaluate the change in fatigue property of in-service components with higher accuracy for maintaining their integrity for a long period of time and preventing their premature failure.

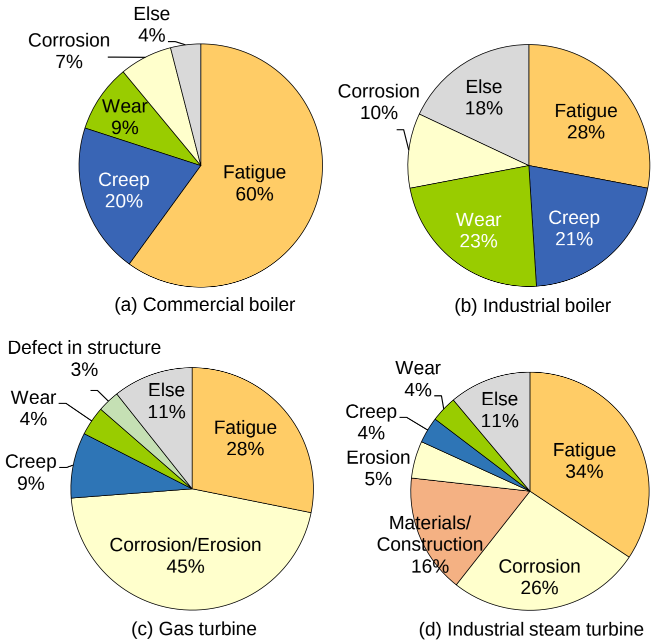

Figure 1. Causes of unplanned outage in fossil power plants.

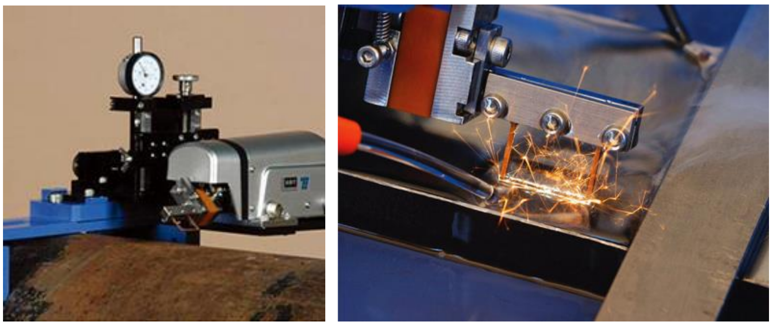

Figure 2. On-site electric discharge sampling equipment with copying mechanism.

In the late 1970s and early 1980s, the small punch (SP) testing technique using a miniaturized disk-type specimen was developed for determining post-irradiation mechanical properties. This technique has been widely used for evaluating various material properties, such as tensile property, ductile-brittle transition behavior, fracture toughness, hydrogen embrittlement, and stress corrosion cracking. It has also been successfully employed in evaluating high temperature creep property. This SP creep test is expected as a strong tool for assessing the heat-to-heat variation of in-service USC boiler pipings, because it requires only a small amount of sample [5]. This can minimize the damage caused by removing the sample from the components. In recent years, a novel on-site electric discharge sampling equipment with copying mechanism has been also developed for this purpose (Figure 2 [6]). This equipment is capable of taking a small plate-type sample as thin as 1 mm from the component's surface.

If the SP testing technique was made applicable to fatigue strength assessment also, almost all material strength tests could be conducted using the same or similar small disk-type specimen. This would be very beneficial from practical and engineering viewpoints. Under those things as background, the authors' group have developed a new fatigue testing technique with a small disk-type specimen, namely, "Small Bulge Fatigue (SBF) Test" [7]. In this SBF test, a hydraulic bulging method is adopted for avoiding several problems attributable to the contact or the friction between ball and specimen. Some results obtained from the preliminary tests using austenitic stainless steel SUS316 are briefly reported in this paper.

2. Testing Vessel and Specimen Developed for SBF Test

Figure 3 shows the testing vessel, which has been newly manufactured for the SBF test. The vessel is connected to the existing hydraulic servo-type material testing machine. As illustrated in Figure 4, the vessel consists of two hydraulic chambers, and the pressure gauge is connected to each chamber. A connector for drawing a lead wire of strain gauge is attached to one of the chambers (chamber 1), and a space for setting dummy strain gauge is also prepared in that chamber. A quartz glass window is installed in the other chamber (chamber 2) for the measurement of displacement with a laser sensor and the direct observation of specimen surface with a borescope. A small disk-type specimen is placed between those two chambers using gaskets and clamping screws, and a cyclic oil pressure is alternatively applied to both chambers.

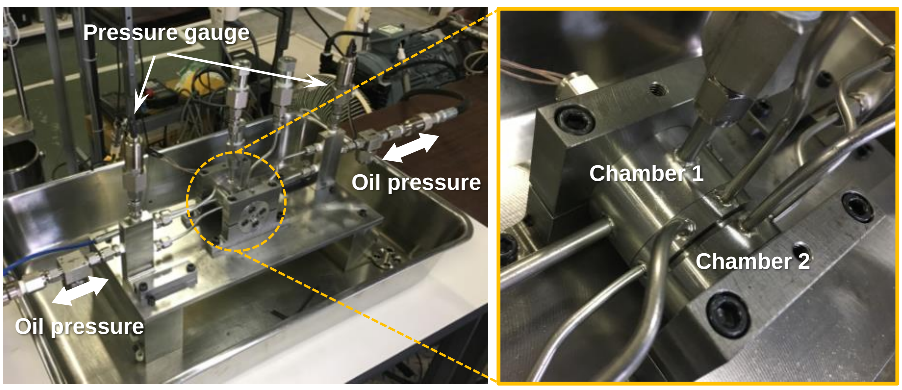

Figure 3. Testing vessel newly manufactured for SBF test.

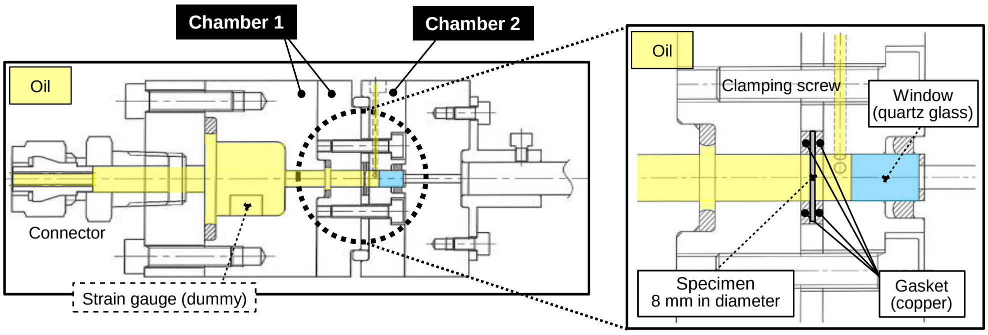

Figure 4. Testing vessel consisting of two hydraulic chambers.

It was revealed from the finite element analysis (FEA) that the equivalent strain was concentrated at the edge of unclamped area when the conventional SP specimen (8 mm in diameter, 0.5 mm in thickness) was subjected to the test, as shown in Figure 5. Therefore, the thickness of central region was relatively reduced for avoiding the fracture at around edge of unclamped area. Finally, as shown in Figure 6, the shape and dimension of small disk-type specimen with flat and concave surfaces were determined as follows; diameter of gauge area: 1.6 mm, thickness of gauge area: 0.15 mm, length of clamped area: 2 mm, thickness of clamped area: 0.4 mm, radius of fillet: 3 mm. This SBF specimen was placed in the testing vessel so that the concave side faced the quartz glass window.

3. SBF Test Results of SUS316

The material used in this study was austenitic stainless steel SUS316. The chemical composition is given in Table 1. The on-off pressure-controlled tests were conducted at room temperature and under several different

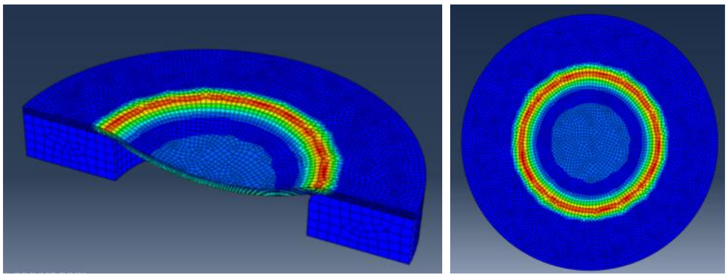

Figure 5. Strain distribution of SP test specimen subjected to SBF tests.

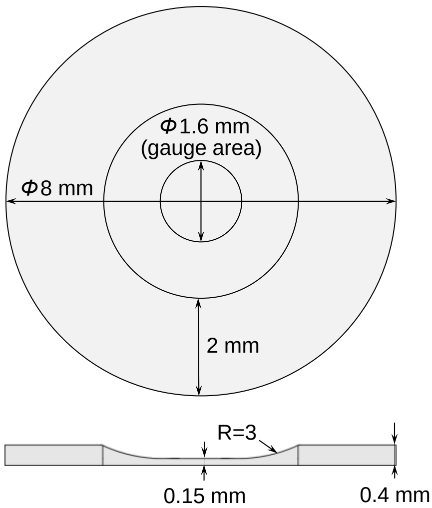

Figure 6. Small disk-type specimen with flat and concave surfaces for SBF test.

Table 1. Chemical composition of SUS316 (mass%).

Fe	C	Si	Mn	P	S	Ni	Cr	Mo
Bal.	0.05	0.41	0.84	0.026	<0.001	10.20	16.10	2.11

Table 2. Maximum pressure, equivalent strain, strain range and fatigue life [7].

Pressure, MPa	$\pm\varepsilon$, %	$\Delta\varepsilon$, %	N_f, cycles
10.5	0.26	0.52	21100
	-0.26		
12.0	0.36	0.75	46100
	-0.39		
12.5	0.42	0.90	7600
	-0.48		
13.2	0.52	1.20	3500
	-0.67		
13.5	0.58	1.37	6300
	-0.79		

maximum pressure levels (10.5, 12.0, 12.5, 13.2, 13.5 MPa) using the above-mentioned testing vessel and specimen. The oil pressure was alternatively applied to the flat and concave sides at the frequency of 5 or 10 Hz. The FEA was carried out for determining the strain on specimen surface. As a result, it was revealed that the strain state was a complete equi-biaxial ($\varepsilon_r/\varepsilon_\theta$=1) at the center of specimen, and the strain ratio deceased with increasing distance from the center. The equivalent strain and strain range on the specimen center of flat side are summarized in Table 2.

Figure 7 shows the change in oil pressure in two hydraulic chambers at the maximum pressure of 13.5 MPa and the frequency of 5 Hz. It can be clearly seen that the pressure is alternatively applied to the concave and flat sides. But, the pressure wave shape is slightly different between them. This difference is likely to result from the different shape of specimen surface. It has been also confirmed that the oil pressure could be successfully applied to both chambers even when the frequency was increased up to 10 Hz.

The SBF test was periodically interrupted to investigate the initiation and propagation behaviors of surface crack. Figure 8 shows examples of surface cracks observed on the specimen tested at the maximum pressure of 12.5 MPa. Some small cracks were initiated at around the center of gauge area on the flat side after 2000 cycle. But, there was no crack on the concave side at that time. When the number of cycles was 3000, the cracks of flat side were longer and some cracks pierced through the specimen into the concave side. The oil pressure of chambers was abruptly decreased and the test was automatically stopped, when the number of cycles reached 7600. The SEM

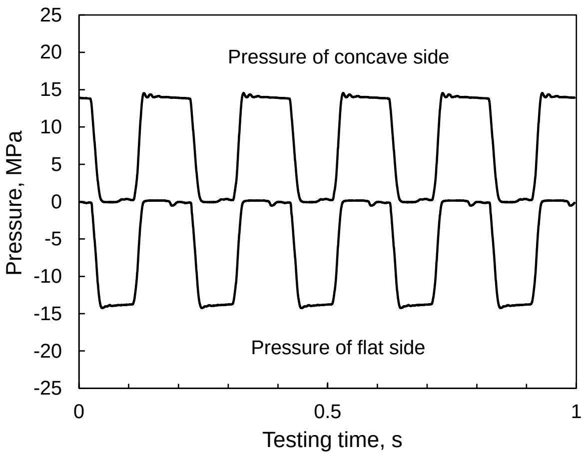

Figure 7. Changes in oil pressure in two hydraulic chambers during SBF test.

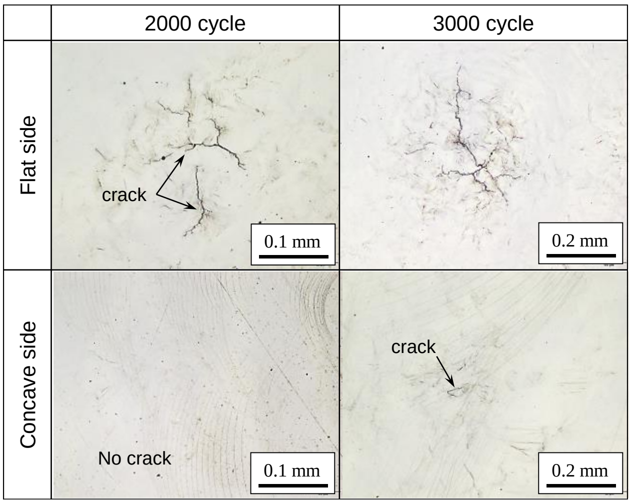

Figure 8. Examples of surface cracks observed on specimen tested at 12.5 MPa.

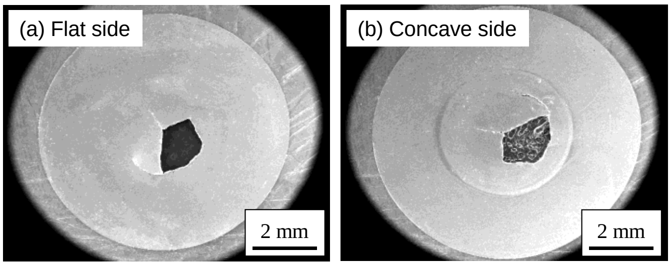

Figure 9. SEM micrographs of SBF specimen fractured at 12.5 MPa.

observation revealed that a part of gauge area was broken and dropped out after that number of cycles (Figure 9). The specimen always had a chip in the gauge area (1.6 mm in diameter, 0.15 mm in thickness) after the sudden drop in oil pressure, irrespective of test conditions.

The fatigue test results obtained in this preliminary study is given in Figure 10, where the fatigue life is plotted against the equivalent strain range determined by FEA. In this paper, the fatigue life is defined as the number of cycles to the drop in pressure due to fracture. The fatigue lives measured at five different maximum pressures are given in Table 2, along with the equivalent strain range. The fatigue life as a whole has a tendency to increase with decreasing strain range, although some scattering results can be seen. This result may indicate that the present SBF test has a potential for fatigue property assessment. In the presentation, the correlation between the results of the

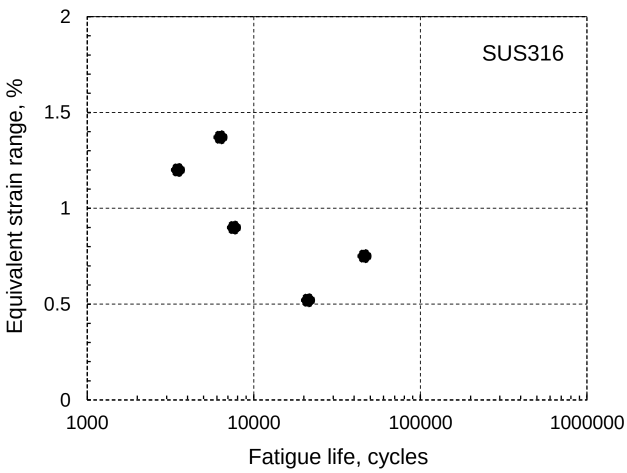

Figure 10. Fatigue life plotted as a function of equivalent strain range.

SBF test and the conventional uniaxial and plate bending fatigue tests will be introduced in addition to the results of strain and displacement measurements.

4. Summary

A new fatigue test apparatus with a small disk-type specimen was newly developed in the authors' group. This testing technique was termed "Small Bulge Fatigue (SBF) test". A cyclic oil pressure could be alternatively applied to both specimen surfaces at the frequency of 10 Hz by adopting hydraulic bulging method. The shape and dimension of small disk-type specimen with flat and concave surfaces were finally determined as follows; diameter of gauge area: 1.6 mm, thickness of gauge area: 0.15 mm, length of clamped area: 2 mm, thickness of clamped area: 0.4 mm, radius of fillet: 3 mm. Austenitic stainless steel SUS316 was subjected to the preliminary test using this newly developed testing technique. As a result, the initial cracking occurred at around the center of gauge area on the flat side, and the specimen always had a chip in the gauge area after the sudden drop in oil pressure irrespective of test conditions. In addition, the fatigue life as a whole had a tendency to increase with decreasing strain range, although some scattering results could be seen.

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