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Mean stress effect on fatigue strength of stainless steel

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ABSTRACT

Influence of mean stress on fatigue life and fatigue limit was investigated for Type 316 stainless steel. The results for prestrained specimens revealed that fatigue life was almost the same in the same strain range regardless of stress amplitude, maximum peak stress and mean strain. The fatigue life was shortened when applying the mean stress for the same strain range, whereas it was increased for the same stress amplitude. It was shown that the reduction in fatigue life was brought about by the change in the effective strain range, which was caused by the increase in minimum peak stress and the ratcheting strain. The fatigue life could be predicted conservatively even if the mean strain was applied by assuming the effective strain range to be equal to the total strain range (by assuming the crack mouth to be never closed). It was concluded that the mean stress correction was not necessary for the load-controlled cyclic loading and for the region where the ratcheting strain was constrained.

1. Introduction

In fatigue damage assessments for designs of nuclear power plant components, influence of mean stress on fatigue strength of stainless steels is considered in the design fatigue curve, which represents allowable cycles for design [1,2]. The detrimental effect on the fatigue limit and fatigue life caused by the mean stress is taken into account according to the modified Goodman diagram. On the other hand, some experimental results [3,4] showed that the mean stress brought about a beneficial effect on the number of cycles to specimen failure (hereafter, fatigue life) of stainless steels under the same stress amplitude.

It has been shown that the fatigue life of stainless steels correlates better with the strain range than with the stress amplitude even in the high-cycle regime [5,6], and the design fatigue curve has been determined using fatigue lives obtained by strain-controlled fatigue tests [7]. Since the mean stress raises the maximum stress and induces additional plastic strain, the fatigue life may be extended due to the reduced strain range for a given stress amplitude. Therefore, changes in the fatigue life due to the mean stress should be compared for the same strain range. The mean stress effect under the strain-controlled condition is important from a practical viewpoint. For example, the effect of a residual stress is focused on in an assessment of fatigue damage caused by the thermal fatigue [8]. The mean stress is also caused by an inhomogeneous temperature distribution in a pipe downstream from a tee junction at which fluids of different temperature flow in [9,10].

Stainless steels exhibit considerable cyclic softening and hardening under cyclic loading. This makes it difficult to investigate the mean stress effect for a given strain range because the strain range is altered significantly during load-controlled fatigue tests. In order to overcome this problem, Vincent et al. [11] performed strain-controlled fatigue tests under a constant mean stress. They successfully controlled both the strain range and mean stress to the objective values by adjusting the mean strain. Their testing technique allowed the mean stress effect to be investigated for the constant strain range and the results revealed that the mean stress shortened the fatigue life under the same strain range. It should be noted that, however, the mean strain might affect the fatigue strength. Furthermore, the mean strain cannot be large in actual components due to geometrical constraints. In order to simulate the mean stress in components, fatigue tests should be conducted for a constant strain range without any significant change in the mean strain.

This study was aimed at investigating the effect of the mean stress on the fatigue strength of a stainless steel. First, prestrained specimens were subjected to the strain-controlled fatigue tests in order to clarify the influence of the maximum peak stress, stress amplitude and mean strain. Since the mean stress raised the maximum stress and stress amplitude under the same strain, the use of prestrained specimens allowed investigation of the influence of these changes as well as the mean strain induced by the prestraining. Second, fatigue lives of the stainless steel were investigated

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under load-controlled fatigue tests with mean stress using the prestrained and non-prestrained specimens. By using the prestrained specimens, it was possible to suppress the cyclic hardening and softening during the fatigue tests and to keep an almost constant strain range for a given mean stress. Then, the reason for the change in the fatigue life due to the mean stress was discussed. Particularly, the contribution of the increasing mean strain observed during the fatigue tests was focused on. Finally, discussions were made for whether the mean stress effect should be taken into account for the fatigue damage assessment in component designs.

2. Test procedure

2.1. Material

The material used for the fatigue tests was solution heat-treated Type 316 austenitic stainless steel provided in a bar shape. Its chemical composition (in mass%) was: C, 0.06; Si, 0.50; Mn, 1.30; P, 0.031; S, 0.027; Ni, 10.18; Cr, 16.94; Mo, 2.02 and balance Fe. Prestrained and non-prestrained specimens were prepared for fatigue tests. In order to induce prestraining, specimens for tensile tests were machined and they were subjected to tensile plastic deformation to a nominal plastic strain of 20% or 40%. Then, round-bar fatigue test specimens, whose geometry is shown in Fig. 1, were machined from the deformed tensile specimens so that the loading axis was the same as that of the tensile specimens. The surface of the specimens was polished using up to 3 μm diamond paste. Since the loading axis of the fatigue tests was the same as that of tensile loading for prestraining, the fatigue tests using the prestrained specimens could be regarded as the tests with the mean strain, of which the magnitude was the same as the degree of the plastic strain. Although the surface roughness was increased by inducing the plastic strain, it had no influence on the fatigue tests because the surface was machined and polished when preparing the fatigue test specimens.

The prestrained specimens of nominal plastic strain of 20% and 40% are respectively referred to as CW20 and CW40, while CW0 denotes those without the prestraining. The mechanical properties and the stress–strain curves of CW0, CW20 and CW40 obtained by tensile tests are shown in Table 1 and Fig. 2, respectively.

2.2. Procedure of fatigue tests

Pull–push fully-reversed strain-controlled fatigue tests were conducted for the prestrained specimens. Strain range was controlled to be 1.0% for CW20 and 0.6% or 0.8% for CW40 under the strain rate of 0.4%/s. The fatigue life was defined as the instant when the maximum peak load became less than 14 kN (178 MPa). Tests using the non-prestrained specimens made from the same material have been conducted in a previous study [12], for which the fatigue life was defined as the instant when the elongation measured by the extensometer exceeded 1.0 mm or when complete separation of the specimen occurred. These data are quoted to compare the change in fatigue life due to prestraining.

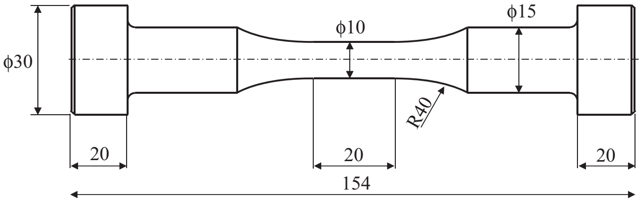

Fig. 1. Geometry of fatigue test specimen (unit: mm).

The mean stress effect was investigated by load-controlled fatigue tests. The applied mean stress was 50 MPa or 100 MPa whereas the stress amplitudes were 240, 260, 280, 290, and 300 MPa. Also the tests using the prestrained specimen (CW20) were conducted under the mean stress of 50 MPa or 100 MPa with the stress amplitude of 350, 360 and 370 MPa. The test frequency was 0.2 Hz until 1000 cycles, and then, it was increased to 40 Hz at the maximum case. By controlling the test speed, the temperature of the specimen was suppressed. The fatigue life was defined as the instant when the elongation measured by the extensometer exceeded 1.0 mm or when complete separation of the specimen occurred. The load-controlled tests using the same material (CW0 and CW20) under various stress amplitude and mean stress conditions have been conducted in previous studies [13,14]. In these tests, the tests were conducted under relatively large mean stresses whereas the mean stress of 50 or 100 MPa was applied in this study. These results are referred to in the following discussions.

All fatigue tests were conducted in a room temperature laboratory environment including the tests conducted in the previous studies cited here. The 12.5 mm gage length extensometer was used for strain measurement both for the load-controlled and strain-controlled tests.

3. Test results

3.1. Fatigue lives of prestrained specimens without mean stress

Fig. 3 shows fatigue lives obtained by the strain-controlled fatigue tests together with those obtained using non-prestrained specimens. The results from the previous study [14] are also plotted, in which load-controlled fatigue tests using the prestrained (CW20) and non-prestrained specimens were conducted. The measured stress amplitude or strain range when the number of cycles was $0.5N_f$, where N_f denotes the fatigue life, was used for the ordinate of the graphs. The stress amplitude of CW20 and CW40 specimens became much higher than that of the non-prestrained specimens under the same strain range. The fatigue life of the prestrained specimens became longer than that of the non-prestrained specimens under the same stress amplitude. On the other hand, as shown in Fig. 3b, the fatigue life was almost comparable regardless of the degree of prestraining under the same strain range. The change in the fatigue life with the strain range was collapsed into a single curve regardless of the type of control (load or strain control) and the degree of prestraining, although fatigue life of non-prestrained specimens obtained by the load-controlled fatigue tests was slightly longer.

As mentioned in the introduction, it has been shown that the fatigue life of stainless steel correlates better with the strain range than the stress amplitude even in the high-cycle regime. However, this fact does not mean that the stress amplitude has no effect on the fatigue life. In the literature [11,15,16], the fatigue life has been correlated not only with strain range but also with various parameters derived using stress components. The results shown in Fig. 3 implied that the stress amplitude and the maximum peak stress had little influence on the fatigue life. The longer fatigue life of the prestrained specimens under the same stress amplitude was brought about by the reduction in the strain range due to the prestraining.

It is noteworthy that the mean strain has little effect on the fatigue life under the same strain range because no change was found in the fatigue life under the same strain range even if the plastic strain of 40% was induced by the tensile loading.