Fatigue behavior of 316L austenitic stainless steel in air and LWR environment with and without mean stress

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Abstract. The fatigue life design curves in nuclear codes are generally derived from uniaxial strain-controlled fatigue test results. Evidently, the test conditions are very different from the actual components loading context, which involves much more complex thermo-mechanical loading including mean stress, static load holding time and variation in water chemistry, etc. In this work, the mean stress and environmental effects on fatigue life of 316L austenitic stainless steel in air and light water reactor (LWR) environment were studied using hollow fatigue specimens and testing under load-controlled condition. Both positive (+50 MPa) and negative (-20 MPa) mean stresses showed beneficial effect on fatigue life in LWR environment and in air. This is tentatively attributed to mean stress enhanced cyclic hardening, which leads to smaller strain response at the same loading force. -20 MPa mean stress was found to increase fatigue limit, whereas the effect of +50 MPa mean stress on fatigue limit is still unclear. The preliminary results illustrate that the environmental reduction of fatigue life is amplified in load-controlled fatigue tests with tensile mean stress.

1 Introduction

Fatigue is a common mode of failure of structural materials. Austenitic stainless steels (SSs) are extensively used as structural materials in aggressive environments, such as in pressure-boundary components in the primary reactor coolant circuit of light water reactors (LWR). These components are in contact with high-temperature water and subjected to complex thermo-mechanical loading conditions during service [1]. Design against fatigue of primary pressure boundary components is usually based on Section III, Division 1 of the ASME Boiler and Pressure Vessel Code (hereafter called ASME Code). It relies on the use of fatigue curves and endurance limits, derived mainly from strain-controlled low-cycle fatigue (LCF) tests with small, smooth specimens in air at room temperature, which do not explicitly consider the possible effects of LWR environments [1]. The ASME III design fatigue curves are based on best-fit "mean" curves of the test data, which were reduced by a factor of 2 on stress/strain range or 20 on cycles (whichever is most conservative). The design margins of 2 and 20 on stress/strain and cycles, respectively, in the ASME Code design curve were intended to cover the effects of some variables (e.g., surface finish/roughness, material variability, load sequence, size effects and atmosphere) that can influence the fatigue life of components, but were not actually investigated in the tests, which provided the original data for the curves. They did not intend to cover the effects of LWR environments. Conservatism in the ASME Code

fatigue evaluations may arise from (a) the fatigue evaluation procedures and/or (b) the fatigue design curves. The sources of conservatism in the procedures include the use of design transients that are significantly more severe than those experienced in service, conservative grouping of transients, and use of simplified elastic-plastic analyses that result in higher stresses/strains. However, the ASME Code permits new and improved approaches to fatigue evaluations (e.g. finite-element analyses) that can significantly decrease the conservatism in the current fatigue evaluation procedures. Uncertainties on conservatism remain due to the significant differences between the original "crude" fatigue design and real, complex fatigue loading and water chemistry conditions of large components with complex geometry in service. The original fatigue design ignores environmental effects and is derived from laboratory fatigue testing with small standard samples.

Significant environmental reduction of fatigue lives were observed in laboratory investigations under simulated LWR coolant conditions in recent years (Figure 1) [2-6] (namely environmental-assisted fatigue (EAF)). Under certain environmental and loading conditions, fatigue lives of SSs can be lower than in the fatigue design curve (Figure 1). Therefore, the margins in the ASME code may be less conservative than originally intended. The decrease in fatigue life of SS in high-temperature water depends on strain rate, dissolved oxygen (DO) level in water, and temperature and is usually more pronounced in hydrogenated pressurized water reactor (PWR) and boiling water reactor/hydrogen

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water chemistry (BWR/HWC) conditions at low corrosion potentials (low DO) than in oxidizing boiling water reactor/normal water chemistry (BWR/NWC) conditions (high DO). The fatigue life is reduced significantly when three threshold conditions are satisfied simultaneously, i.e., when the applied strain amplitude and service temperature are above a minimum threshold level ($\approx 0.15\%$ and 150°C), and the loading strain rate is below $0.4\ \%/s$. Environmental effects are absent or moderate, e.g., less than a factor of 2 decrease in life, when any one of the threshold conditions is not satisfied.

Figure 1. Comparison of fatigue test data in LWR environments with the ASME Code fatigue mean and design curves [7].

Meanwhile, based on laboratory investigations, different proposals [7, 8], such as Environmental Factors Approach, US NRC Regulatory Guide 1.207 and NUREG/CR-6909 or other national equivalents (JSME in Japan), were established for incorporating environmental effects into the fatigue design procedure of the ASME Code. These procedures are related to some relevant uncertainties and potential undue conservatism and their practical application is rather complex. Thus, they have found little acceptance in the nuclear industry so far and new international efforts (EPRI EAF, INCEFA+) were started to close some important knowledge gaps. These gaps are related to the effects of mean stress, surface conditions, long static load hold periods, multiaxial loading, load history or changing temperature and strain rates.

It is well known that mean stress can affect fatigue life with tensile and compressive mean stress being detrimental and beneficial, respectively. In pressurized piping, mean stress may arise from, e.g., internal pressure, weld residual stress, dead weight loading or static temperature gradients. Mean stress effects on EAF were not investigated so far. If at all, mean stress is taken into account in the ASME Code through a modified Goodman correction, which shows that positive tensile mean stress has a detrimental effect on fatigue life. Solomon, on the other hand, observed an increase in fatigue life with positive tensile mean stress in load-controlled LCF tests with SSs [9].

The goal of the present work is to evaluate the magnitude of mean stress effects in air and high-temperature water and the adequacy or inadequacy of the

typical mean stress corrections for EAF. For this purpose, load- and strain-controlled fatigue tests were performed with hollow specimens in air and hydrogenated high-temperature water and the first preliminary results of these experiments are discussed in this paper.

2 Materials and Experimental Procedure

2.1 Material and specimens fabrication

The material was provided by Sandvik as a tube of 316L low-carbon austenitic SS, with a 219.1 mm outer diameter, 19.5 mm wall thickness, and 130 cm in length. The AISI 316L steel was produced following ASTM A-511-12 and ASTM A-312-15 technical requirement. The material composition is given in Table 1. The material was delivered in heat treated solution annealed (non-sensitized) and quenched condition. It has a homogeneous texture-free grain structure (Figure 2) with equiaxed austenite grains and a high share of twin boundaries (31%) and a mean grain size of $53\ \mu\text{m}$ (ASTM grain size 5.2).

Table 1. Chemical composition of the investigated austenitic stainless steel (in wt.%).

Steel	C	Si	Mn	P	S	Cr	Mo	Ni
316L	0.011	0.56	1.77	0.031	0.024	17.20	2.02	11.14

Figure 2. Grain structure (EBSD) of original material.

The mechanical behavior was characterized by tensile tests (DIN 50125, $10 \times 50\ \text{mm}$ cylindrical B specimens) at room temperature, 100, 200 and 300°C and a nominal strain rate of $0.1\ \text{s}^{-1}$ (Figure 3). The measured 0.2% yield stresses decrease from 260 MPa at 20°C to 150 MPa at 300°C (Figure 4). In the same temperature range, the material provider reported elastic Young modulus decreases from 200 to 179 GPa (Figure 4).

Figure 3. Engineering stress-strain curves of 316L SS tested at room temperature, 100, 200 and 300°C.

Figure 4. Measured 0.2% yield stress at 22 to 300°C and the material provider reported elastic modulus from 22 to 500°C.

Hollow specimens with an outer diameter of 10 mm and wall thickness of 2.5 mm and 2 mm were fabricated for fatigue tests in water and in air (Figure 5). The gauge length/tensile axis of the hollow specimens is parallel to the longitudinal direction of the tube. The inner and outer surface roughness of the specimens was $0.41 \mu\text{m}$ in R_a / $3.57 \mu\text{m}$ in R_{zD} and $0.15 \mu\text{m}$ in R_a / $1 \mu\text{m}$ in R_{zD} , respectively. The grinding scratches of the outer surface are parallel to the tensile axis and scratches of the inner surface slightly tilted to the tensile axis. The scratches on the inner surface may act as local stress raiser and thus affect fatigue initiation. However, the crack planes after fatigue tests were found perpendicular to the loading axis and scratches indicating that their influence on fatigue life is limited.

Figure 5. Hollow specimens used for the tests in high-temperature water (left) and in air (right).

2.2 Fatigue test facilities and experimental conditions

The facility for fatigue tests in high-temperature water (Figure 6) consists of an Instron 8862 electro-mechanical fatigue test machine and a water loop that allows thermo-mechanical loading under BWR or PWR water chemistry conditions. A detailed description of the facility is described in [10]. The fatigue tests were conducted at 288°C and pressurized water was characterized by high-purity, hydrogenated water with 150 ppb dissolved hydrogen (BWR/HWC). The conductivity in the high-purity inlet and outlet water were around $0.055 \mu\text{S}/\text{cm}$ (impurity content < 1 ppb). The specimen was heated by the high-temperature water flowing through the hollow specimen with minimal axial and through-wall temperature gradients. The internal pressure was 200 bars. Fatigue tests in air were performed with a Schenck RMC 100 type electro-mechanical machine. High-temperature air environment was sustained by an ATS series 2961 oven with three heating cells and a EUROTHERM 2704 type thermal controller.

Figure 6. Schematic of facility for fatigue test in high-temperature water [10].

The tests were run both in load- and strain-controlled modes using a sinusoidal waveform at a frequency of 0.17 s^{-1} , mainly in the LCF region ($N_f \leq 10^5$). The load-controlled fatigue tests were typically performed with stress amplitudes larger than 170 MPa at 288°C, which induced elasto-plastic deformation. For EAF study, the strain amplitudes of interest were in the range of 0.1 to 0.8%. This corresponds roughly to stress amplitude in load-controlled experiment between 170 and 250 MPa at 288°C. In load-controlled fatigue tests, the strain was measured by a calibrated MTS 635.53F-30 type extensometer for high-temperature water (HTW) condition and an Epsilon model 3648-010M-025-ST extensometer for high-temperature air (HTA) condition. In strain-controlled fatigue tests, a Sandner Sensor EXA15-1u type extensometer was applied for more precise strain control. The extensometer for testing in high-temperature air was liquid cooled by Huber Minichiller 300. A stepwise ramping loading scenario was implemented to avoid over loading during the first cycles. For tests in high-temperature water, the specimens were stepwise loaded with amplitudes of +1 kN, -2 kN, +3 kN, -4 kN and coming analogous force levels each for single cycle to the desired amplitude. 1 kN corresponds to 16.98 MPa stress for HTW specimen.

Same stress step, namely 16.98 MPa, was used to start tests in HTA to ensure same loading history was imposed on the specimens in both environmental conditions.

3 Results and Discussion

3.1 Fatigue tests

Fatigue tests were conducted without mean stress and with mean stresses (-20, -10, 10, +50 MPa) in water and in air at 288°C under load-controlled mode. Strain-controlled fatigue tests were performed for comparison with load-controlled test results. The stress-life (S-N) results in water condition and in air condition are plotted in Figure 7 and Figure 8 respectively. For strain-controlled tests, the calculated average stress amplitude was considered for S-N plotting. For the tests in water environment, fatigue life was determined when a water leakage was detected. For the tests in air condition, fatigue life was defined when the measured elongation was larger than 1.0 mm or when the specimen totally broke into two parts. Optical and scanning electron microscopy observations showed that, the cracks initiated on the inner surface for tests in water and in air. In Figure 7 and Figure 8 the curves were fitted with Langer equation (1) :

$$\sigma_a = B(N_f)^{-b} + \sigma_{fs} \quad (1)$$

where σ_a stands for stress amplitude, N_f is fatigue life, σ_{fs} for fatigue strength, B and b are fitting constants to experimental data. The Langer equation fits well the load-controlled test results in Figure 7, where a fixed value of the exponent b was chosen equal to 0.9:

In 288°C BWR/HWC:

$$\sigma_m = 0 \text{ MPa:} \quad \sigma_a = 72112.17(N_f)^{-0.9} + 170 \quad (2)$$

$$\sigma_m = +50 \text{ MPa:} \quad \sigma_a = 144312.26(N_f)^{-0.9} + 170 \quad (3)$$

$$\sigma_m = -20 \text{ MPa:} \quad \sigma_a = 166395.38(N_f)^{-0.9} + 194.52 \quad (4)$$

From Figure 7, we conclude that -20 MPa mean stress rises up the fatigue limit with respect to that without mean stress. However, +50 MPa mean stress does not show obvious effect on fatigue limit. While tests in air are still in progress, the available data are currently sufficient to show some trends. Only tests with $N_f < 10^5$ are presented, so that the determination of the fatigue limit (namely for $N_f > 10^6$) could not be determined. From the preliminary results, the fatigue tests with zero mean stress in air condition follow the Langer equation well.

In 288°C air:

$$\sigma_m = 0 \text{ MPa:} \quad \sigma_a = 105919.57(N_f)^{-0.9} + 162 \quad (5)$$

Figure 7. S-N of fatigue tests conducted under load-controlled with different mean stresses in 288°C BWR/HWC; Strain-controlled tests performed in 288°C BWR/HWC plotted with green star.

Figure 8. S-N of fatigues tests conducted under load-controlled with different mean stresses in 288°C air condition.

In 288°C air and BWR/HWC conditions, the most salient results show that both negative mean stress and positive mean stress increase fatigue life when comparing with the tests without mean stress. In air condition, more tests in the HCF region are necessary to determine the fatigue limits precisely and provide sufficient data points for a reliable fitting. However, it was still possible to estimate the fatigue life difference of the obtained results with different mean stress: for +50 MPa mean stress, the fatigue life increases by a factor of 2-3.5 and for -20 MPa mean stress the increase is about 5.7-6.5 comparing with the tests without mean stress in 288°C air. This is clearly a non-standard behavior, where one generally observes a detrimental effect of positive mean stress and beneficial one of negative mean stress on fatigue life. Solomon also reported that 100 MPa mean stress extends fatigue life on 304L stainless steel in air and PWR water at 150°C and 300°C [9, 11]. More recently, Spätig et al. reported that +50 MPa increase the fatigue life of 316L stainless steel based on load-controlled tests with different mean stresses. However, the effect of a smaller mean stress of 20 MPa or 10 MPa was quite modest and within the usual fatigue life scatter of the test without mean stress [4].

The strain-controlled test results are plotted together with the load-controlled results in Figure 7 for comparison. The calculated average stress amplitudes of strain-controlled tests are globally consistent with the S-N fitting curve at 288°C BWR/HWC without mean stress, even though different stress/strain distribution and microstructures evolution may be developed in these two loading control modes.

The strain-life (ϵ -N) data in 288°C BWR/HWC and 288°C air is plotted in Figure 9 and Figure 10 respectively. The strain amplitude in vertical axis is the average strain amplitude value ($\bar{\epsilon}_a = \Delta\epsilon/2$) over whole fatigue life of load-controlled tests.

The test data are fitted with Equation (6):

$$\bar{\epsilon}_a = A(N_f)^{-B} + C \quad (6)$$

The fitted curves are:

In 288°C BWR/HWC:

$$\bar{\epsilon}_a = 2.61(N_f)^{-0.773} + 9.527 \times 10^{-4} \quad (7)$$

In 288°C air:

$$\bar{\epsilon}_a = 1.29(N_f)^{-0.654} + 9.527 \times 10^{-4} \quad (8)$$

For some tests, the average strain amplitude is not presented in Figure 10 because the strain was not measured. We assumed however that the material has same fatigue strain limit in 288°C water and 288°C air. Thus, the fatigue strain limit (namely the constant C) in high-temperature water was considered for fitting the test data in air.

In Figure 9 and Figure 10, the test data with $N_f < 1000$ cycles fit the strain-life model (Equation (6)) well. However, when $N_f > 1000$ cycles, mean stress slightly deflects the test points away from the fitting curves. Kujawski [12] also found similar phenomenon when he tried to correlate experimental data of 7075-T651 Al with positive and negative mean stress.

Drawing firm conclusions on mean stress influence on average strain vs. fatigue life relationship requires more tests, both in high-temperature water and high-temperature air. However, the sole stress or average strain parameter seems to be insufficient to correlate fatigue tests data with mean stress. An approach using a parameter accounting simultaneously for stress amplitude and strain amplitude is certainly more appropriate to correlate the data with each other. For instance, correlating the data using Smith-Watson-Topper (SWT) parameter or a modified SWT parameter has already been shown to be a powerful method to correct the effect of mean stress/strain on non-symmetric cyclic loading in SSs. A modified SWT parameter correlation will be presented in a separated paper. In load-controlled fatigue test of SSs, which have FCC structure, mean stress hardens the material which is reflected by decreasing strain amplitude in comparison to tests with zero mean stress. More detail of mean stress hardening effect is addressed in the section 3.2.

Figure 9. Strain-life of fatigue tests in 288°C BWR/HWC under load-controlled condition, the strain amplitude is the averaged value over whole fatigue life.

Figure 10. Strain-life of fatigue tests in 288°C air under load-controlled condition, the strain amplitude is the averaged value over whole fatigue life.

Figure 11. Fitting curves of load-controlled test data in 288°C BWR/HWC water and in 288°C air respectively based on Equation (6).

The fitted strain-life curves in water and in air conditions are plotted together in Figure 11. The F_{en} factor ($N_f^{288^\circ\text{C air}} / N_f^{288^\circ\text{C BWR/HWC}}$) is roughly determined to be 1.56-2.0 in the LCF region, where the average strain amplitude is larger than 0.25%. This is consistent with JSME Code's claim that F_{en} is constant for all strain

amplitude larger than 0.11%. In JSME Code, no environmental effect is involved when the strain amplitude is equal or less than 0.11%. However, Kamaya [13] recently reported that the reduction of fatigue life of 316L steel in PWR water environment is not significant when the strain amplitudes are 0.25% and 0.22 %. He also observed that F_{en} varies with strain range. He concludes that larger strain range induces bigger environment detrimental effect and result in larger F_{en} value. Nevertheless, JSME Code, Kamaya's finding and most environmental detrimental effect study are based on strain-controlled tests. Their conclusions should be carefully translated to load-controlled cases. In general, reactor environment does not shift the fatigue strain limit in strain-controlled tests. Whether load-controlled tests present a similar phenomenon remains to be confirmed with more tests in HCF regime.

3.2 Means stress effect

In Figure 7 and Figure 8, both positive and negative mean stresses clearly indicate a beneficial effect on fatigue life. This effect is tentatively attributed to mean stress hardening effect, which leads to reduce strain. The strain vs. cycle relationship of several selected tests condition, namely $\sigma_a = 190$ MPa, $\sigma_m = 0, +50, -20$ MPa in both environments, is presented in Figure 12 and Figure 13. For the test without mean stress, the material firstly undergoes hardening, then softening and finally follows relatively stable amplitude for most of the fatigue life. This is similar to the behavior in strain-controlled cyclic loading. The tests with mean stress show smaller initial strain than the tests without mean stress in both environmental conditions. This may stems from a larger plastic strain hardening for the tests with mean stress, which occurs during the stepwise ramping loading cycles. The initial strain of the test with +50 MPa mean stress is smaller than the one of the test with -20 MPa mean stress. This trend continues until around 20000 cycles, where the strain amplitude of -20 MPa mean stress test becomes lower than the strain amplitude of +50 MPa mean stress test, reflecting a stronger secondary hardening with -20 MPa mean stress. The secondary hardening initiated around 1000 cycles in the test with -20 MPa mean stress.

The average strain amplitudes of -20 MPa mean stress tests are calculated to be the smallest of 0.134% (in water) & 0.234% (in air), following those of +50 MPa mean stress tests with 0.176% (in water) & 0.214% (in air). The average strain amplitudes of tests without mean stress are 0.371% (in water) & 0.5% (in air). The strain evolution in water is analogous with the one in air. With $\sigma_a = 190$ MPa, the tests without and with +50 MPa mean stress have approximately a similar fatigue life in water and in air conditions. However, the fatigue life of -20 MPa mean stress tests is much higher in water than in air. This may attribute to relatively higher strain amplitude in air than in water. When strain amplitude is below 0.2% for -20 MPa mean stress test, environmental effect is limited. In addition, fatigue life is extremely sensitive to strain range change in low strain amplitude

region, namely where the strain amplitude close to the fatigue limit. These reasons may lead to higher fatigue life in water than in air for tests with -20 MPa mean stress. However, the intrinsic scatter in fatigue also has to be considered. Let's us mention that higher strain amplitude in air than in water is found in the tests with relatively low stress amplitude (such as 190 MPa).

Figure 12. Strain amplitude vs. cycle of fatigue tests with $\sigma_a = 190$ MPa, $\sigma_m = 0, +50, -20$ MPa in 288°C BWR/HWC.

Figure 13. Strain amplitude vs. cycle of fatigue tests with $\sigma_a = 190$ MPa, $\sigma_m = 0, +50, -20$ MPa in 288°C air.

Comparing Figure 12 with Figure 13, tests in air have systematically higher starting strain than tests in water for all mean stress levels. A plausible reason is the effect of the internal pressure in the specimen tested in water. A pressure in the range 100-200 bar pressurized hollow specimen induces an asymmetric strain response in load-controlled condition [4]. More FEM stress/strain state computation is necessary to better understand the stronger hardening in water.

The physical mechanisms of cyclic hardening, softening and stabilization in strain-controlled of austenitic steels have been studied via microstructures characterization in the last decades [14-17]. However, the physical processes in load-controlled condition are not thoroughly understood, especially the mechanism of cyclic secondary hardening. In Spätig et al dislocation investigation [18], the secondary hardening is accompanied with formation of corduroy structures, which is consistent with nano-scale dislocation loops and

defects free channels. This kind structure is supposed to acts as obstacles for mobile dislocations and thus strengthens the material.

3.3 Environmental effect

As mentioned in the introduction section, when temperature, strain amplitude and strain rate are simultaneously larger than critical values ($\approx 150^\circ\text{C}$, 0.15 %, and 0.4%/s respectively), the water environment significantly assists fatigue damage. The environmental correction factor F_{en} factor was originally defined as the ratio of the fatigue life in room temperature air to the fatigue life in water reactor environment in strain-controlled conditions [19]. F_{en} factor depends on temperature, strain-rate, and dissolved oxygen content for austenitic stainless steels [1, 3, 20, 21]. In this paper, the environmental factor in load-controlled condition is defined analogously as $N_f^{288^\circ\text{C air}}/N_f^{288^\circ\text{C water}}$.

Figure 14. $N_f^{288^\circ\text{C air}}/N_f^{288^\circ\text{C water}}$ vs. σ_a under different mean stress of 0, +50, -20 MPa.

$N_f^{288^\circ\text{C air}}/N_f^{288^\circ\text{C water}}$ calculated from the experimental N_f is plotted in Figure 14 for the different mean stresses. For $\sigma_m = 0$ MPa, high-temperature water environment starts to take effect around $\sigma_a = 185$ MPa, where the corresponding average strain amplitude ($\bar{\epsilon}_a$) is about 0.3%. For $\sigma_m = +50$ MPa, environmental effects seem to happen at a higher σ_a of about 195 MPa corresponding to $\bar{\epsilon}_a = 0.2\%$. Finally, for $\sigma_m = -20$ MPa, environmental effects appear around $\sigma_a = 215$ MPa, where the strain amplitude ($\bar{\epsilon}_a$) is around 0.26%. In load-controlled condition, -20MPa mean stress increases the stress amplitude threshold for environmental effect. When $N_f^{288^\circ\text{C air}}/N_f^{288^\circ\text{C water}} > 1$, the results with +50 MPa and -20 MPa mean stress shown in Figure 14 suggest larger environmental factors than those without mean stress. Positive mean stress amplifies environmental influence was commonly reported. However, the exact reason for the observed non-standard phenomenon originated from -20 MPa mean stress is unclear.

4 Conclusions

In this work, a series of load-controlled fatigue tests were conducted to investigate the mean stress and light water reactor environment effect on fatigue. From the presented results, it clearly show both negative mean stress (-20 MPa) and positive mean stress (+50 MPa) increase fatigue life in air or in water conditions. -20 MPa mean stress improves the fatigue life more notably than +50 MPa. The stress-life and strain-life data were fitted using Langer equation. -20 MPa mean stress increases the fatigue limit obviously, whereas +50 MPa mean stress effect on fatigue limit is unclear.

In an average strain $\bar{\epsilon}_a$ versus fatigue life N_f representation, the F_{en} factor appears practically independent of average strain amplitude.

In stress-life representation, both negative and positive mean stress seems to enhance the environment detrimental effect. The exact reason is still unclear. The reactor water environment effects on crack initiation and crack propagation need to be investigate.

The beneficial effect of tensile mean stress is attributed to a primary and secondary cyclic hardening effect, which lead to a lower strain response under same stress amplitude. However, the physical mechanism of load-controlled cyclic hardening is not thoroughly understood. Microstructures investigation is necessary for mean stress hardening effect understanding.

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