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Influence of mean stress and light water reactor environment on fatigue life and dislocation microstructures of 316L austenitic steel

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ABSTRACT

Influence of mean stress on fatigue life of the austenitic stainless steel 316 L in air and light water environments (boiling water reactor/hydrogen water chemistry) at 288 °C was determined with a series of tests carried out in load-control mode. Fatigue life was found to increase with application of compressive and tensile mean stress in air and light water reactor environments. Secondary hardening was regarded as the main reason for this behavior. A modified Smith-Watson-Topper (SWT) model was considered to account for mean stress and was shown to predict fatigue life accurately in air and water environments. The reduction of fatigue life in water environment, determined with the SWT curves, was about 2.5. Observations of the end-of-life dislocation arrangements by transmission electron microscopy showed that the dislocation microstructure depends essentially on plastic strain amplitude, which in turn is strongly correlated to stress amplitude and mean stress. The microstructures were found consistent with those usually observed after strain-controlled experiments. At rather low plastic strain amplitudes, corduroy structure consisting of small dislocation loops was observed. Acting as significant obstacle to dislocation motion, corduroy structure affects overall dislocation mobility therefore contributing to notable secondary cyclic hardening.

1. Introduction

It is now well established that, when tested in light water reactor environment, fatigue life of the austenitic stainless steels is reduced with respect to that in air [1,2]. The fatigue life reduction depends in particular on strain rate, temperature, strain amplitude and dissolved oxygen level, and is observed only if three threshold conditions are met simultaneously, namely when both the strain amplitude and the temperature are above their respective threshold, and when the loading strain rate is below a minimum value [3].

Cyclic loading on pressure boundary components of light water reactors stems from changes in the overall configuration of the mechanical and thermal loading. As a rule, the design life of components should not exceed 10^5 cycles but is usually even less than several thousand, which requires testing in the low cycle regime in strain-controlled mode. Therefore, most available data were obtained with fully reverse strain-controlled uniaxial tests performed at constant strain amplitude, constant temperature, constant strain rate, with well-polished specimens and without the application of a mean stress or mean strain. However, such ideal conditions are evidently quite different from those experienced by components in operation in nuclear power plants. During service, the components undergo cyclic deformation due to thermal stratification that can induce thermal fatigue [4], or due to flow-induced vibrations [5] for instance. Clearly, the thermo-mechanical loading and associated time history of real components is much more complex than the usual well defined experimental testing conditions selected for laboratory tests. This situation led the scientific community to identify a number of scientific knowledge gaps in environmental assisted fatigue (EAF), which were summarized in two comprehensive reports [6,7]. Mean stress, non-proportional multiaxial loading, deformation/temperature history, water chemistry transients, surface roughness, strain amplitude (low cycle fatigue (LCF) versus high cycle fatigue (HCF)), hold time are just examples of parameters with potential effects on EAF that are not sufficiently

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understood and that have to be investigated more in detail. Furthermore, the combination of these parameters can act either in a synergistic or competitive way. Therefore, only long-term research programs with extensive testing matrix can provide the phenomenological basis to derive physically-based assessment methods to predict component fatigue life reliably in actual LWR environment. As an example, the INCEFA + project, started in mid-2015 within the European Commission Horizon2020 program, was designed to deliver new experimental fatigue data to ultimately develop improved guideline in EAF [8]. Within the first testing phase of INCEFA + project, three parameters were chosen, namely mean strain, hold time, and surface finish, to assess fatigue life sensitivity in light water reactor environment to these parameters. Mean stress effects were also among the parameters highlighted in Refs. [6,7] with potential detrimental effect on fatigue.

Hence, the activities undertaken in this study were designed to gain insight into the influence of mean stress on fatigue life of austenitic stainless steels both in air environment and boiling water reactor/hydrogen water chemistry environment. The mechanical environmental-assisted fatigue investigation is complemented by detailed observations of the resulting microstructure based on the transmission electron microscopy. High resolution characterization of the alloy microstructural state after load-controlled tests is correlated to the results reported for strain-controlled experiments. Complex approach combining both thorough analysis of the mechanical testing and microstructure characterization is fundamental to an improved understanding of the overall cyclic response of the material under load and corresponding mechanisms affecting fatigue life.

2. Material and experimental procedures

2.1. Material

The investigated material was from a non-stabilized 316 L austenitic stainless steel pipe with an outer diameter of 219 mm and a wall thickness of 23 mm provided by DMV Stainless France. The seamless pipe was manufactured and processed according to the requirements of the ASME BPV Code. The processing sequences of the seamless pipe material consisted of hot working, solution annealing, water quenching to room temperature, pickling and grinding. The chemical composition of the material in the as-received condition is given in Table 1. The material had equiaxed grains with an average grain size of 35 μm.

2.2. Test facilities and experimental conditions

The load-controlled fatigue tests were performed at 288 °C and 150 °C in air and in pressurized water environment characterized by high-purity, deoxygenated (nitrogen purging) water with 150 ppb dissolved hydrogen. The conductivity in the inlet and outlet water was 0.055 μS/cm and smaller than 0.07 μS/cm, respectively.

Fig. 1 shows a schematic of the used water loop facility, which allows the simulation of boiling and pressurized water reactor chemistry conditions. The hollow specimens are heated by the pressurized water, which circulates through them. Three different internal pressures were used: 80, 100 and 200 bars. These hollow specimens have a wall thickness of 2.5 mm and an outer diameter of 10 mm. A detailed description of the facility can be found in Ref. [9].

For the tests in air, round bar specimens of 8 mm diameter and 18 mm gage length were used. The technical drawings of both specimen geometries are shown in Fig. 2. The tests were run in load-controlled mode using a triangular waveform at a frequency of 0.17 s^{-1}. That frequency corresponds to the fastest rate that can be achieved with the electro-mechanical Instron 8862 machines used for the comparative tests in high-temperature water. With such a frequency, the testing was focused on the low-cycle regime, namely below $N_f = 10^5$, essentially for two reasons. First, from a practical point of view, a test performed at a frequency of 0.17 s^{-1} needs one week to reach 10^5 cycles, which basically precludes testing at conditions leading to $N_f >> 10^5$. Second, it is well known that for the austenitic stainless steels three concomitant threshold conditions need to be met for environmental effects on fatigue to occur. These conditions are a minimum strain range of ≈0.2%–0.3%, a strain-rate lower than ≈0.4% s^{-1}, and a testing temperature greater than 150 °C. As it will be shown below, the fatigue limit of the investigated material at 288 °C was estimated around 140–150 MPa. For load-controlled experiment, a stress amplitude of 150 MPa corresponds to a strain range lower than 0.25% after several thousands of cycles. Therefore, to have the strain range condition for environmental effects fulfilled, the testing was focused at stress amplitude larger than 150 MPa that were found to lead to N_f smaller than 10^5. Typically, the strain-rates at $N_f/2$ were in the range 0.1–0.3% s^{-1}. The strain was measured with an extensometer attached to the specimens. In this exploratory study, moderate mean stresses of few tens of MPa were selected.

For the tests performed in pressurized water environment, the 200 bars internal pressure in the hollow specimens, which have to be regarded as closed end cylinders, creates a nominal axial stress of 6.7 MPa. Before starting an experiment, this stress has to be balanced by applying a compressive load of −392 N on the specimens. The electrical zero of the load signal is done only after the application of that compressive load, which actually corresponds to the zero axial stress reference level.

In this work, N_f represents the number of cycles to break the specimens in two parts. For the test in water, in few cases, the experiment was automatically stopped with the occurrence of a leakage leading to a quick pressure drop in the loop. However, for load-controlled experiments, the number of cycles between the occurrence of leakage and the final failure is quite small, typically smaller than 100.

2.3. Transmission electron microscopy

The microstructure was investigated using conventional transmission electron microscopy (CTEM) and scanning transmission electron microscopy (STEM). The spatial arrangement of dislocations in grains was determined using the technique of oriented foils [10,11]. Thin plates were cut from the wall in the gauge section of the specimen by electric-discharge machine. Plates were extracted parallel to the loading axis and then mechanically grinded to obtain thin foils of 0.08 mm in thickness. These were then punched out to produce discs having a diameter of 3 mm and marked to indicate

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

Steel 316 L	C	Si	Mn	P	S	Cr	Mo	Ni	N	Nb	Ti
	0.021	0.26	1.69	0.033	0.003	17.5	2.15	11.14	0.0601	0.012	0.003