THERMO-MECHANICAL AND ISOTHERMAL FATIGUE BEHAVIOR OF AUSTENITIC STAINLESS STEEL AISI 316L.

ŠKORÍK Viktor[1,2], ŠULÁK Ivo[1], OBRTLÍK Karel[1], POLÁK Jaroslav[1,2]

[1]*Institute of Physics of Materials, Academy of Science of the Czech Republic, Brno, Czech Republic, EU*

[2]*CEITEC, Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Brno, Czech Republic, EU*

Abstract

Many structural components of nuclear power plant systems are made of austenitic stainless steels. These structures undergo degradation by thermo-mechanical fatigue (TMF) caused by simultaneous cyclic straining and temperature cycling, particularly during start-up, shut-down and transient operations. The present work reports the cyclic deformation behavior and fatigue damage of austenitic stainless steel AISI 316L during TMF and isothermal fatigue (IF) testing in air. Total strain controlled in-phase TMF loading in the temperature range 200 - 600 °C and isothermal fatigue (IF) at 600 °C were performed. Hardening/softening curves, cyclic stress-strain response and fatigue life diagrams were obtained both for TMF and IF tests. Fatigue damage was documented using surface relief and fracture surface observations. Mean stress evolution and fatigue degradation data are employed to discuss the fatigue behavior of 316L steel both in TMF and IF regimes.

Keywords: Thermo-mechanical fatigue (TMF), Isothermal fatigue (IF), In-phase cycling (IP), AISI 316L, Fatigue life

1. INTRODUCTION

Constant need to increase the performance and safety of components used in energy, aerospace or automotive industry leads to the necessity of understanding the behavior of materials in complex conditions. Considerable temperature gradients in components operating at elevated temperatures result in cyclic loading [1]. Induced deformations have their origin as a mechanical load, as well as thermal fields and exhibit synergistic effect. Under such conditions, the cyclic loading leads to a complex thermo-mechanical fatigue (TMF) damage of the material. Three major damage mechanisms, namely, fatigue, creep and environmental damages are involved. During operation these mechanisms work independently or together in various combinations depending on operating conditions [2, 3]. This leads to crack initiation, subsequent crack propagation across the section of components and to ultimate failure. Numerous studies have been devoted to dislocation structure and surface relief observations [4-8], to low [9-12] and high cycle fatigue [13-15] behavior in austenitic stainless steels tested at room, depressed and high temperatures. Several studies have been dedicated to the TMF [16-21], nevertheless they were conducted in a narrow range of deformation and temperature. It was found that the lifetime of components under TMF differs considerably from data obtained during isothermal low cycle fatigue tests carried out at a maximum of TMF operation temperature [16-23].

Thermo-mechanical fatigue tests are a variant of fatigue testing designed to simulate real-world operating conditions. Modern laboratory testing techniques allow realistic simulation of loading cycles. The selection varies from component to component and consists of operating conditions, geometry and application components. Most common TMF loading cycles are In-phase (IP) and Out-of-phase (OP). For description of the cycle we use phase shift δ, defined as the angular difference between mechanical and thermal cycling. It is possible to select any phase shift in the range of 180 ° > δ > -180 ° [24].

The austenitic stainless steels of type 316L are widely used in structural applications across a broad range of temperature beginning from cryogenic to high temperatures up to 700 °C and exhibit sufficient corrosion resistance and satisfying mechanical properties. A strong dependence of TMF life of austenitic stainless steel on minimum and maximum temperature and temperature range as well as strain rate has been observed. The cause of this dependence can be explained by the presence of various degradation mechanisms in three temperature diverse areas: i) low temperature area with predominant fatigue damage ii) area of intermediate temperatures (200 – 600 °C), where an important roleplays dynamic strain aging (DSA) and iii) high temperature area with dominating damage by oxidation and creep [17-19, 21, 25].

The present works aims at a comparative investigation of the isothermal and IP TMF behaviors of type 316L stainless steel. Selected characteristic features of the fractography and surface relief are also reported.

2. EXPERIMENTAL DETAILS

2.1 Materials

The material used in this investigation was AISI 316L austenitic stainless steel whose chemical composition is given in Table 1. Steel was supplied by Thyssen as a cylindrical rod of 22 mm in diameter in a standard state, i.e. austenitizing at 1060 °C for 4 h and the quenching into water. The average grain size was 25 ± 13 μm.

Table 1 The chemical composition of the experimental steel AISI 316L (wt%)

C	Si	Mn	P	S	Cr	Mo	Ni	Fe
0.03	1.00	2.00	0.045	0.03	18.50	2.50	13.00	bal.

2.2 Mechanical testing

For fatigue tests, cylinder-shaped samples with a diameter of 7 mm and a gauge length of 16 mm were machined in the longitudinal direction. After turning, the gauge length of the samples was electrochemically polished to avoid any surface influence on life time and to facilitate observations of the surface relief after cycling. All tests were performed using computer controlled servo-hydraulic MTS system equipped with high frequency inductive heating device. Cooling of specimens was achieved by water cooled clamping jaws above and underneath the gauge length. The temperature was controlled with ribbon thermocouple (Type K) wrapped around the sample at the middle of the gauge length. The thermocouple was fixed by a spanned ceramic textile ribbon. The strain was measured and controlled with an extensometer having 12 mm base. To avoid drifting in strain measurement the extensometer was cooled by air. TMF tests were performed in accordance to the “Validated Code-of-Practice for Strain-Controlled Thermo-Mechanical Fatigue Testing” [26].

The TMF tests have been carried out in temperature interval 200 - 600 °C with constant mechanical strain amplitudes and with a cycle time of 200 s (4 K / s). IP TMF is characterized by a phase angle of 0 ° between the temperature and mechanical strain. The mechanical strain, ε_{mech}, was calculated from the total measured strain by subtraction of the thermal expansion strain. Isothermal LCF tests were performed at the same strain rate and strain amplitude on samples of identical geometry at the maximum temperatures of TMF cycling (T_{max}). The fatigue life N_f is defined by a 10 % drop of the stress range under a tangent line through the saturated part of the stress response curve in linear scaling.

3. RESULTS AND DISCUSSION

3.1 TMF and IF cycling

Fig. 1 shows representative hysteresis loops of AISI 316L for three numbers of cycles, i.e. for N = 2, 9 and N_f / 2 for IP TMF and isothermal LCF cycling with a strain amplitude of 8 x 10^{-3}. Due to the cyclic hardening, the stress amplitude increases and the plastic strain amplitude, which is equal to the half-width of the hysteresis loop at the mean stress, decreases with increasing number of cycles bot in TMF and IF cycling.

(a) (b)

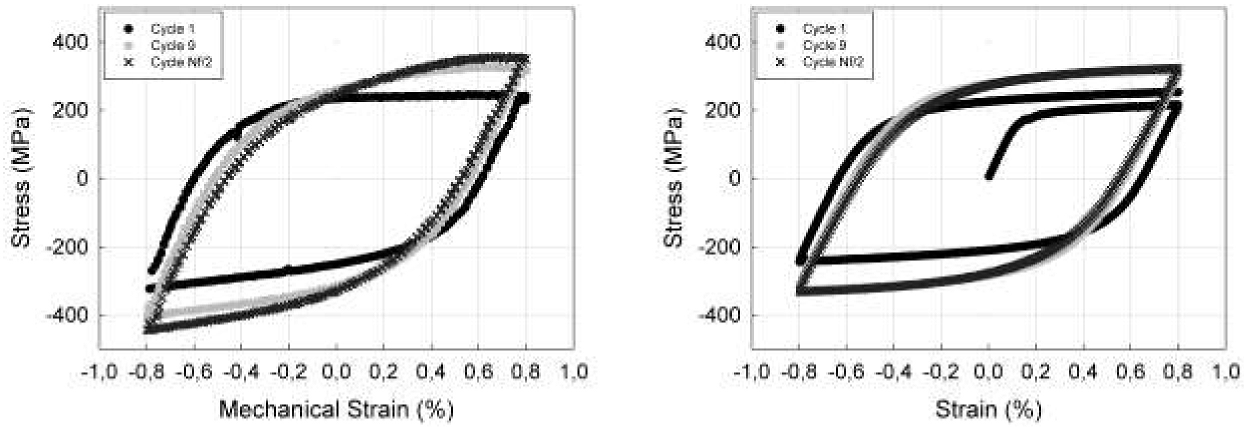

Fig. 1. Stress-strain hysteresis loops at N = 2, 9 and N_f / 2 of AISI 316L (a) IP TMF cycling at $\Delta\varepsilon_{mech}$ / 2 = 8 x 10^{-3} and (b) IF cycling at $\Delta\varepsilon$ / 2 = 8 x 10^{-3}

Fig. 2a shows cyclic hardening/softening curves in IP TMF cycling for different total strain amplitudes. Both stress amplitude and mean stress are plotted vs. number of cycles. All curves indicate an initial hardening regime, with a tendency to saturation in the case of $\Delta\varepsilon_{mech}$ / 2 = 6 x 10^{-3} and 8 x 10^{-3} which is followed by softening in the case of $\Delta\varepsilon_{mech}$ / 2 = 1.2 x 10^{-2} and 2 x 10^{-2}.

(a) (b)

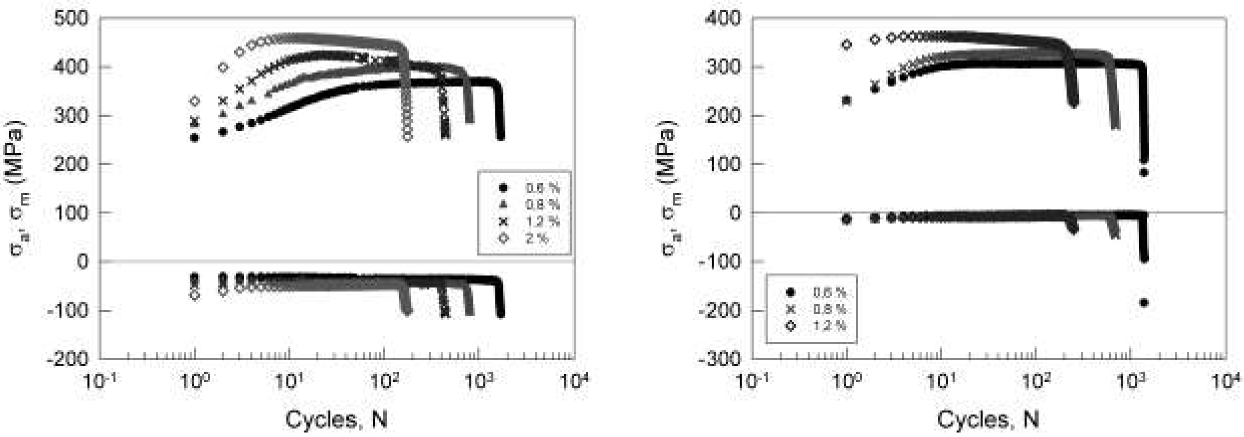

Fig. 2. Stress amplitude and mean stress vs. number of cycles, (a) IP TMF cycling, (b) IF cycling

The results of the isothermal LCF tests are shown in Fig. 2b. Also here all curves indicate an initial hardening regime with saturation. However, tendency to softening is apparent in only the case of mechanical strain amplitude of $\Delta\varepsilon_{mech}$ / 2 = 1.2 x 10^{-2} .

Cyclic stress response behavior of austenitic stainless steel has been studied in details over the years. It is characterized by primary hardening at an early stage, which is due to: (a) the generation of dislocations; (b) their mutual interaction; and (c) the interaction of interstitial solute atoms with the dislocations, also known as dynamic strain ageing (DSA). This stage is typically followed by a softening or a distinct saturation regime, characterized by a rearrangement of dislocation structures favoring cyclic strain localization [27].

The major part of the fatigue life can be characterized by the stress and plastic strain amplitudes at half-life. These values were thus used for the construction of the cyclic stress-strain curves (CSSCs). Fig. 3a shows CSSCs for IF and IP TMF cycling. Both curves were fitted by the power law

$$\sigma_a = K'\left(\varepsilon_{ap}\right)^{n'} \tag{1}$$

K´ is fatigue hardening coefficient and *n´* is fatigue hardening exponent. Fatigue life curves were plotted in derived Wöhler plot in Fig. 3b. Both fatigue laws were originally defined to describe the fatigue behavior without explicit consideration of mean stress. Fatigue lives for IP TMF cycling are longer than for IF cycling. Experimental data in derived Wöhler plot were fitted with the Basquin relation

$$\sigma_a = \sigma_f'(2N_f)^b \tag{2}$$

with σ_f' being the fatigue strength coefficient and *b* the fatigue strength exponent, respectively. The parameters of the CSSCs and derived Wöhler curves evaluated by regression analysis are given in Table 2.

Table 2 Fatigue parameters of AISI 316L for IP TMF and IF cycling

Test	*K´* (MPa)	*n´*	σ_f' (MPa)	*b*
IP TMF	712	0.114	699	-0.0791
IF	714	0.151	550	-0.0738

(a) (b)

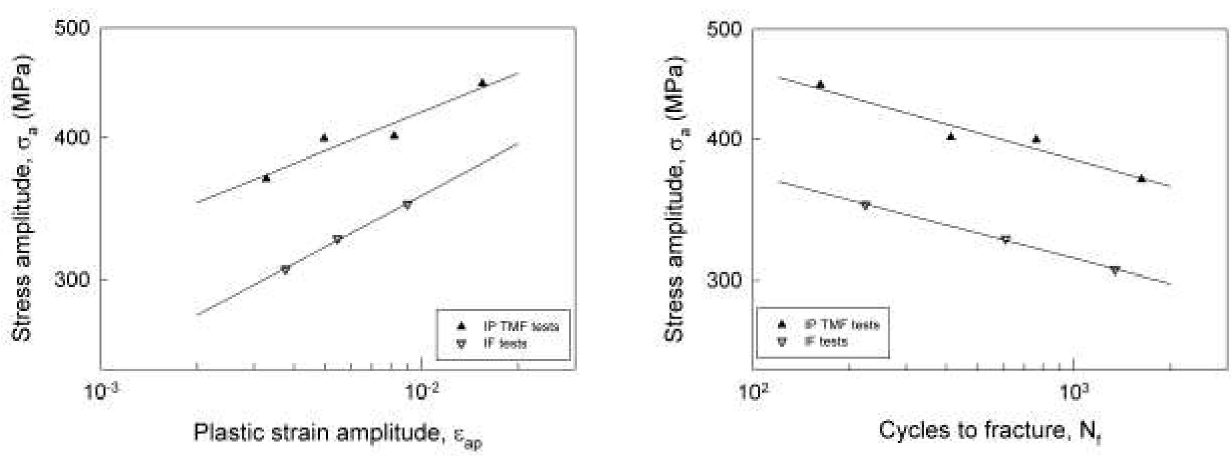

Fig. 3. Fatigue life curves for IP TMF and IF cycling (a) CSSCs and (b) Wöhler-Basquin

3.2 Surface and fractography observations

Fractography examination of specimens cycled in IF conditions revealed that the crack initiation and propagation occurred in a transgranular mode. An example of striations on the fracture surface is shown in

Fig. 4a. Mixed transgranular and intergranular cracking was observed in IP TMF cycling in the temperature range 200 – 600 °C (Fig. 4b-c). Fig. 4b shows surface relief covered with a layer of oxides. A fatigue crack growing perpendicularly to the specimen axis is apparent in Fig. 4b. Mixed mode cracking can be seen also on fracture surface in Fig. 4c.

(a) (b) (c)

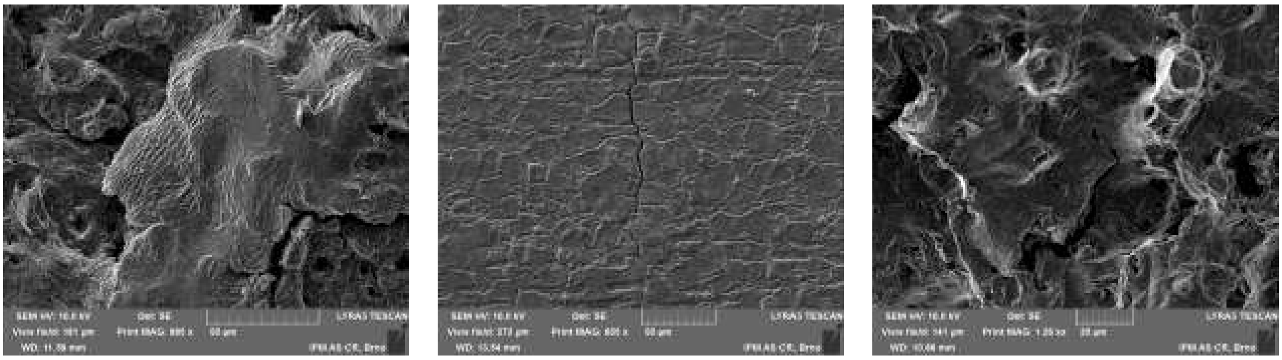

Fig. 4. (a) Transgranular cracking with striations under IF cycling, (b) and (c) mixed mode cracking under IP TMF cycling.

CONCLUSIONS

Isothermal and thermo-mechanical fatigue study of AISI 316L stainless steel can be summarized as follows. Both cases of cycling lead to the cyclic hardening with a tendency to saturation for $\Delta\varepsilon / 2 \leq 0.8 \times 10^{-3}$ and followed by softening for $\Delta\varepsilon / 2 \geq 1.2 \times 10^{-2}$. Cyclic stress-strain response is higher in TMF mode. The CSSC in IF cycling is shifted to lower stress amplitudes in comparison with that for TMF. The isothermal tests conducted at the peak temperatures of the TMF cycles is characterized by lower fatigue lives in the representation of the stress amplitude vs number of cycles to fracture compared to the IP TMF cycling. Surface and fractography observations of the fatigued samples reveal transgranular cracking with striations for IF tests and mixed mode cracking for IP TMF tests.

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