Effect of high temperature exposure on the fatigue damage development of X10CrMoVNb9-1 steel for power plant pipes

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Abstract. The aim of this research was to compare the effect of 80 000 h exploitation time in high temperature on mechanical properties and microstructure of X10CrMoVNb9-1 (P91) power engineering steel for pipes. The specimens obtained from two pipes: new, as-received and after exploitation were subjected to fatigue loadings to compare their mechanical responses. Additionally, the uniaxial tensile tests on both types of P91 steel were performed. The microstructure evolution before and after deformation was monitored using optical and scanning electron microscopy. The time intensive, high temperature exposure of P91 power engineering steel led to significant phase transformation and subsequent deterioration of mechanical properties and was further described as a function of the fatigue damage measure, φ, and the fatigue damage parameter D. Further proposed methodology of power exponent approximation of the fatigue damage measure, φ, and fatigue damage parameter D, allowed to successfully determine the fatigue life of P91 steel.

Introduction

Assessment of the degradation degree in power engineering steel structures is a difficult, responsible and extremely important issue in terms of service life diagnostics. One of the phenomena affecting the development of structural damage dynamics are changes in the stress state under the influence of operational loads (mechanical, thermal and environmental) and subsequent microstructural evolutions. The problem of material structure degradation caused by variable thermo-mechanical loadings is the key issue in terms of safety and operating costs of industrial installations such as power engineering pipes operating under high pressure and temperature. The continuous operation mode of these installations requires a proper monitoring of their condition and ‘in-situ assessment’ of the damage development. However, the degradation mechanisms have not been fully investigated as yet. Therefore, one of the issues raised in the paper was to assess and describe the effect of 80 000 h operating conditions on the microstructure, strength properties and damage development of P91 steel.

Materials

The mechanical testing was performed on specimens made of P91 heat-resistant steel. Test specimens were wire-cut from two types of P91 steel pipelines. First one was operated for 80 000 h at internal pressure of 8.4 MPa under temperature of 540ºC. The second one came from the unused pipeline of the same diameter in the as-received state (normalizing at 1050℃ for 2 hours with oil cooling, tempering at 750°C for 2 hours with air cooling). The fatigue tests were force controlled with zero mean value and a constant stress amplitude with a frequency of 20 Hz. The range of fatigue loads was established on the basis of the yield strength $R_{0.2}$ determined from the uniaxial tensile test. Taking into account significant differences in mechanical properties of both states, fatigue tests were performed in the range of stress amplitude from ±450 MPa to ±680 MPa for specimens in the as-received state and from ±320 MPa to ±480 MPa for the exploited material.

Results

Fatigue comparative tests were carried out with the main objective to elaborate the S-N curves for both types of the steel in question, as shown in Fig.1a. As it is clearly seen, due to exploitation (80 000 h at internal pressure of 8.4 MPa under temperature of 540ºC) a significant decrease of fatigue strength by a factor of 20% was observed for the entire range of stress amplitudes considered. In majority cases, the strength properties variations of the material subjected to cyclic loading can be observed on the basis of Wöhler curve (S-N curve). A different approach to monitor these properties is based on the evolution of deformation dynamics development due to variable loading programs and a range of stress amplitudes applied. In order to reveal the nature and dynamics of strain development in subsequent cycles of high cycle fatigue, these changes were parametrized using the fatigue damage measure, φ, and the fatigue damage parameter D [1, 2]. Depending on the stress amplitude and the material microstructure, the process of fatigue damage can be characterized by two mechanisms. The feature of the first mechanism may be described by cyclic plasticity generated by dislocation movement at the level of local grains and slip bands. In this case an inelastic strain is the damage indicator characterized by the width of the hysteresis loop at total unloading of the material. The feature of the second mechanism that characterizes materials subjected to cyclic loading is described by ratcheting generated by local deformation around the voids, inclusions and other defects of the microstructure. In this case the damage indicator is attributed to the mean inelastic strain describing a shift of the hysteresis loop under unloaded state. Since in the majority of cyclic loading cases a combination of these mechanisms is responsible for damage development either the mean inelastic strain value or inelastic strain amplitude can be chosen as damage indicator. For the steel tested in this research, a combination of both of these mechanisms was observed. Therefore, using both damage indicators identifying cyclic plasticity and ratcheting, damage measure can be defined by the following relationship**:**

$$\varphi = \varepsilon_w + \varepsilon_m \tag{1}$$

where:

ε_w is the inelastic strain amplitude being damage indicator that characterizes a width of the hysteresis loop at the total unloading,

ε_m is the mean inelastic strain responsible for a shift of the hysteresis loop under unloaded state.

The inelastic strain amplitude was measured at the total unloading of a material. It can be described in a single cycle by the simple expression in the following form:

$$\varepsilon_w = \frac{\varepsilon_{min}^{F=0} - \varepsilon_{max}^{F=0}}{2} \tag{2}$$

The mean inelastic strain was also captured under unloaded state. It can be defined by the following relationship:

$$\varepsilon_m = \frac{\varepsilon_{min}^{F=0} + \varepsilon_{max}^{F=0}}{2} \tag{3}$$

Changes in the fatigue damage measure, φ, were used to determine an evolution of the damage parameter D. The fatigue damage parameter D describes the dynamics of deformation changes in subsequent cycles. It is defined by the relationship:

$$D = \frac{\varphi_N - \varphi_{min}}{\varphi_{max} - \varphi_{min}} \tag{4}$$

where:

φ_N - current value of the fatigue damage development measure in the cycle *N*,

φ_{min} - minimum value of the fatigue damage development measure at the beginning of the cyclic loading, i.e. for the cycle *N=1*,

φ_{max} - maximum value of the fatigue damage development measure for the last cycle of the period of stable damage development N_f.

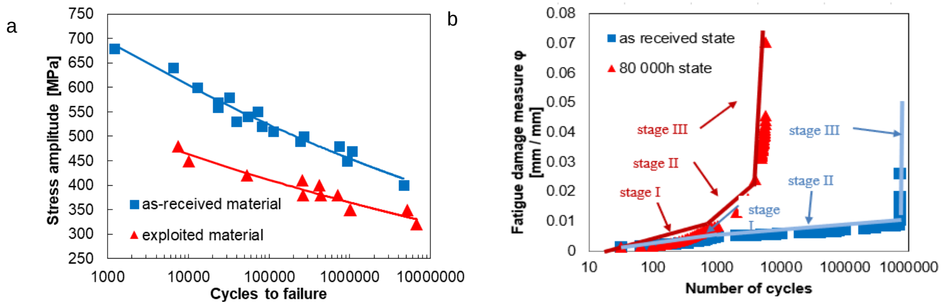

Figure 1. S-N curves for the steel in the as-received state and after exploitation (a); development of the fatigue damage for a stress amplitude of ±480 MPa expressed by fatigue damage measure φ variations as a function of number of cycles (b).

Conclusions

The quantitative assessment proposed in this research revealed how fast the process of material degradation can be, especially in the first stage of fatigue up to 1000 cycles. This method seems to be successful in the prediction of the fatigue stress amplitude limit and may further serve as an effective indicator of the fatigue damage development.

References

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