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Monitoring of fatigue damage development in as-received and exploited for 280 000 hours 10CrMo9-10 power engineering steel supported by Digital Image Correlation

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Abstract. This research aimed to compare the effect of long-time degradation of two different states of 10CrMo9-10 (10H2M) power engineering steel by using different experimental and analytical approaches. The specimens machined from the as-received and exploited for 280 000 hours at the temperature of 540°C and the internal pressure of 2.9 MPa pipe were subjected to fatigue loadings and simultaneously monitored by using Digital Image Correlation (DIC) technique. The effect of long-time degradation on the mechanical response of 10H2M steel was studied through fractographic observations and was finally described as a function of the fatigue damage measure, φ, and the fatigue damage parameter D.

Keywords: fatigue development, damage, 10H2M steel, digital image correlation (DIC).

Introduction

Degradation of power engineering steel structures requires instant monitoring to maintain their properties, ensure the safety of working components and estimate their service life. One should highlight, that the operational loads and simultaneous microstructural changes occurred due to high temperature exposure accelerate the development of damage dynamics significantly Thus it is of the highest importance to maintain the safe state of power engineering steel pipes subjected to the continues operations under high pressure and temperature to further minimized the operating costs of industrial structures [1]. Among power engineering steels, 10H2M one is characterized by M23C6 carbide emissions, and hydrogen degradation resistance in medium pressure equipment and devices up to 500°C [2]. The degradation process of such steel involve it's phase transformation from as-received fine tempered martensitic laths into broader ferrite laths and eventually into an equiaxed ferrite grain structure [3]. This microstructure evolution significantly decreases the creep resistance. On the other hand, the coarsening of M2X carbides into M23C6/M6C carbides and their concentration on ferrite grain boundaries effectively lower its mechanical response as well. Since the microstructural changes occurred during long-time exposure, the micromechanical behaviour of the material is changing accordingly. A comparative studies of as-received and exploited materials are in such case the most valuable approach for proper determination of life service. They are enabling for the actual assessment of the mechanical response of materials subjected to long-term operations and are serving as an indicator if these materials could be further used in prolongation of a resource without a decrease in safety and reliability of the power engineering constructions. Therefore, this paper aims to assess and describe the effect of 280 000 h operating conditions on the microstructure, strength properties and dynamics of fatigue damage development of 10H2M steel. The quantitative assessment of the degradation state in 10H2M power engineering steel was described as a function of the fatigue damage measure, φ, and the fatigue damage parameter D.

Results

The fatigue tests were force controlled with zero mean level and a constant stress amplitude with a frequency of 20 Hz in the range of stress amplitude from 300 MPa to 430 MPa. The range of fatigue loads was established on the basis of the yield strength $R_{0.2}$ determined from the uniaxial tensile test. The fatigue development was monitored by DIC Aramis 12M equipped with lenses of a total focal length of 75mm and calibration settings appropriate to the measuring area equal to 170x156mm. The calibration was performed prior to testing using a certified GOM calibration plate. The quantitative assessment of the fatigue damage development in 10H2M steel was performed by coupling DIC measurements with the methodology of the fatigue damage measure, φ, and the fatigue damage parameter D described in [1, 2]. The fatigue damage parameter D used to describe the dynamics of deformation changes in subsequent cycles was represented by the relationship:

$$D = \frac{\varphi_N - \varphi_{min}}{\varphi_{max} - \varphi_{min}} \tag{1}$$

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.

In this equation, damage measure was defined by**:**

$$\varphi = \varepsilon_w + \varepsilon_m \tag{2}$$

where:

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

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

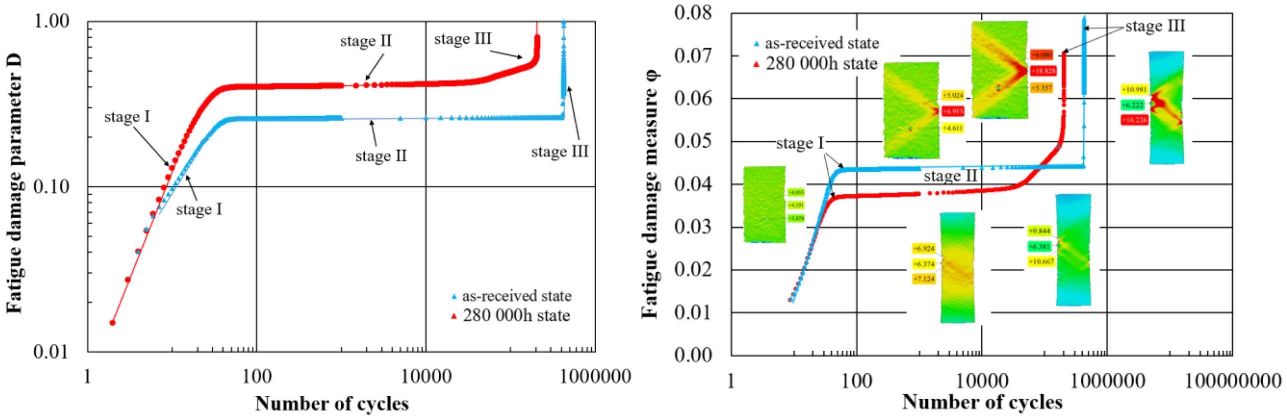
The inelastic strain amplitude was measured at the total unloading of a material and was described in a single cycle by:

$$\varepsilon_w = \frac{\varepsilon_{max}^{F=0} - \varepsilon_{min}^{F=0}}{2} \tag{3}$$

The mean inelastic strain was also captured under unloaded state and was further defined by relationship:

$$\varepsilon_m = \frac{\varepsilon_{min}^{F=0} + \varepsilon_{max}^{F=0}}{2} \tag{4}$$

An evolution of the fatigue damage parameter D as a function of the number of cycles to failure for the stress amplitude of 400 MPa was presented in Figure 1a. It could be observed, that dynamics of fatigue damage development is highly dependent on the stress amplitude since the notable changes in parameter D are observed within the first 100 cycles. One can find, that for relatively low values of strain amplitude, the fatigue damage development is processing gradually till the plateu stage is reached. Subsequently, the damage is progressing steadily till the crack and final decohesion of the specimen in stage III occur. It should be mentioned, that the values of parameter D are much higher for exploited material which could further confirm the developed state of material degradation resulted from 280 000 hours of high-temperature exposure. Such behaviour might be attributed to the transformed tempered martensite microstructure, which is sufficient for microcrack nucleation during fatigue as its significantly accelerate the damage dynamics in the first stage of deformation. It could be observed, that for the exploited material, the fatigue damage plateau region is observed at the very early stage of fatigue before the first 100 cycles. Furthermore, the III stage of material degradation, ie when the crack is formed and further nucleates, occurred much earlier for exploited material as shown in Figure 1b. One should mention, that the DIC system alone was not able to reveal the dynamics of fatigue damage within 100 cycles. Some strain increase might be find in the central area of the specimen, however its prominent intensification occurs in the second stage of fatigue damage development.



(a) (b)

Fig. 1. Development of the fatigue damage for a stress amplitude of 400MPa expressed by fatigue damage parameter D (a) and fatigue damage measure φ (b) variations as a function of the number of cycles.

In this paper, the comparison of the mechanical response of the as-received and exploited 10H2M steel revealed a drastic decrease of the service life of up to 400% after exploitation for 280 000 hours at the temperature of 540°C and the internal pressure of 2.9 MPa. On the other hand, the dynamics of the fatigue damage development for both states of steel were successfully monitored by the DIC system and quantitatively assessed using the fatigue damage measure ϕ, and fatigue damage parameter D. The proposed methodology might be successfully used to compare the response of materials subjected to long term operation.

References

[1] M. Kopec., A. Brodecki, D. Kukla, Z.L. Kowalewski, *Effect of high temperature exposure on the fatigue damage development of X10CrMoVNb9-1 steel for power plant pipes*, International Journal of Pressure Vessels and Piping, 189, 104282-1-16, 2021 https://doi.org/10.1016/j.ijpvp.2020.104282

[2] M. Kopec., A. Brodecki, D. Kukla, Z.L. Kowalewski, *Suitability of DIC and ESPI optical methods for monitoring fatigue damage development in X10CrMoVNb9-1 power engineering steel*, Archives Of Civil And Mechanical Engineering, 21, 167-1-13, 2021 https://doi.org/10.1007/s43452-021-00316-1