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Influence of steam atmosphere on the crack propagation behavior of a 9–12% Cr ferritic/martensitic steel at temperatures from 300 °C to 600 °C depending on frequency and hold time

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A B S T R A C T

This paper deals with the influence of steam atmosphere on the crack propagation behavior in the ferritic/martensitic steel X20CrMoV12-1 depending on frequency (or hold time) and temperature with a focus on the temperature range from 300 °C to 600 °C, which is most important for flexibly operated power plants. Modern conventional power plants must be able to compensate fluctuations in residual load, caused by renewable energy sources. This results in higher numbers of start-up and shut-down cycles and therefore in more damaging loading scenarios than in the past. Due to the ever shorter operating time at constant high temperature, the importance of creep damage decreases, while fatigue damage gains in importance. Furthermore probable interactions of fatigue damage and steam atmosphere have to be considered. For this reason the influence of steam on the crack propagation behavior in X20 was investigated in detail. Steam oxidation strongly depends on temperature and time, i.e. on fatigue testing frequency and temperature. The effect of steam on crack propagation behavior was found to be not generally detrimental (for R = 0.1). Experiments with 3.33×10^{-3} Hz (300 s hold time) in the temperature range from 400 °C to 550 °C yielded significantly higher ΔK values to start crack propagation in comparison to experiments performed in air. In the temperature range from 300 °C to 550 °C the crack growth rate under steam atmosphere in the worst case corresponds to that measured in air, while in the best case it was found to be lower. Generally crack propagation in steam atmosphere was found to be accelerated at increased testing frequency (5 Hz, 20 Hz) starting from 500 °C up to higher temperature.

1. Introduction

Power generation is about to continuously transition to a supply of electricity and heat from renewable sources. For this reason power plant operation already had to be changed from mostly static base load operation in the past to nowadays more – and in the future mainly – dynamic operation with flexible adaptation to the requirements of regenerative energy generation. Due to the resulting increase in start-up and shut-down cycles, fatigue damage gains in importance. The relevance of creep damage decreases, what is caused by shortening base load operation, i.e. decreased time at constant high temperature. As a result structural materials are subject to considerably more demanding loading scenarios than in the past. Thick-wall components of the feedwater and live steam systems, like spheroidal forgings, fittings, collectors, pumps and turbine bypass valves (TBV) are in the main focus. Like in our previous study [1] material (German X20CrMoV12-1 grade) from two ex-service TBVs (operation duration ~ 21 years) was investigated, because the TBV faces most demanding cyclic loading profiles. X20CrMoV12-1 is a tempered 12% Cr ferritic-martensitic steel largely used especially in the German power industry [2,3].

The objective of the study was to characterize the crack propagation behavior in X20CrMoV12-1 in steam atmosphere depending on testing frequency and the implementation of hold times at temperatures from 300 °C to 600 °C, because this temperature range is the most relevant for flexibly operated power plants. In order to characterize the influence of steam atmosphere, the cyclic crack growth data presented in this paper have been compared to those from our previous studies performed in air [1]. The comprehensive experimental data base will be utilized for the development of codes for remaining life assessment by identification of cyclic lifetime reserves of the material [4], which are not properly exploited by existing codes.

In technical alloys, fatigue crack propagation in a wide temperature and frequency range is significantly influenced by oxidation [5]. The 9–12% Cr steels oxidize faster in steam environments than in air [6,7].

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Anomalous temperature dependence was reported for oxide growth of X20 steel in Ar-50% H_2O in the temperature range from 550 °C to 650 °C [8]. Thus, the oxidation rate does not increase steadily with increasing temperature. The cause of the anomalous/bell-shaped temperature dependence is the faster diffusion of Cr in the alloy towards the oxidation front with rising temperature [9–11]. It can be assumed that the complex oxidation of 9–12% Cr under steam atmosphere will significantly influence the crack propagation behavior. Some main characteristics of environmental (moisture) effect on fatigue crack propagation were described by Petit and Sarrazin-Baudoux [12]. The influence of steam is mainly considered to be detrimental to most metals and metallic alloys. Further, the atmospheric effect was found to be particularly pronounced at low growth rates, i. e. in the range of low stress intensity factors.

Mikulova [13] investigated the influence of the testing atmosphere (air, vacuum, steam atmosphere) on the crack propagation behavior of P92 steel at 550 °C. Pure creep stress (constant load) in steam atmosphere caused lower crack growth rates compared to laboratory air, since oxidation of the crack surfaces and the crack tip was more pronounced. The influence of steam containing atmosphere on fatigue crack growth was not investigated. However, a comparison of the crack growth curves recorded in laboratory air and in vacuum showed a significant influence of the atmosphere on fatigue crack growth. Furthermore, King and Cotterill [5] have investigated the crack propagation behavior of a 9Cr-1Mo steel from 25 °C to 525 °C in air and vacuum and confirmed a significant atmosphere effect with the crack growth rate in air being higher than in vacuum in the entire temperature range. Furthermore, a large temperature influence on crack propagation was observed in air, whereas there was no significant effect found in vacuum. Fracture surface investigation has proven the temperature effect in air to result from increased oxidation rates at higher temperatures. In comparison to air fatigue experiments performed with a hold time of 300 s at maximum load, yielded a tendency towards slightly accelerated crack propagation in the area of low stress intensities in steam atmosphere [13]. For higher loads, however, slightly lower crack growth rates were found in steam. The available data shows that there is a clear influence of creep processes and the testing atmosphere on crack growth. However, the atmosphere effect on fatigue crack growth of power plant steels is currently only rudimentary investigated. Furthermore there is a considerable need for specific, in-depth research into the interaction between fatigue crack propagation, creep crack growth and environmental effects especially at low and intermediate temperatures.

2. Material and methods

For the present study material was taken from an ex-service turbine bypass valve (Fig. 1; fabricated by Bopp & Reuther). The TBV was removed after 21 years of operation in a coal-fired power plant operated by KNG Rostock (Kraftwerks- und Netzgesellschaft mbH).

The TBV body is made of X20CrMoV12-1 and has been produced by open-die forging. Table 1 shows the chemical specification of the material.

Due to restricted TBV flange dimensions a modified compact tension (CT) specimen geometry featuring a width (W) of 40 mm, thickness (B) of 10 mm and an initial notch depth (a_0) of 10 mm was utilized in the experimental program. The dimensions are in accordance with the ASTM fatigue crack growth testing standard [14]. The CT-specimens were produced from material, which was cut from the “cold flange” area of the TBV, which had not been in contact with steam during operation (Fig. 2).

“Cold flange” material was used, because no microstructural degradation was expected from service and it was intended to compare the results under steam atmosphere with the results from our previous study in air with identical material in virgin condition. The virgin condition was proofed by determining tensile properties of the used

Fig. 1. Turbine bypass valve (fabricator: Bopp & Reuther) [1].

X20CrMoV12-1 steel at temperatures up to 600 °C. Moreover SEM-analysis proved the martensitic lath microstructure being fully retained [1].

A defined steam atmosphere of Ar + 50 vol% H_2O was used to simulate power plant-like atmosphere conditions. For P91 Thiele [15] has shown that the oxidation rate increases noticeable up to about 7 vol-% of H_2O,– which is considered to be a limit concentration for the oxidation of 9–12% Cr steels. Further rise of the water content caused no noticeable increase in the oxidation rate. For experiments in steam atmosphere a gas tight recipient was installed into a three-zone resistance heated furnace within a servo hydraulic testing machine (Instron Model 1343). The upper and lower end caps of the recipient were oil-tempered, in order to prevent condensation within the recipient (Fig. 3). To ensure gas tightness of the recipient and suitability for cyclic loading with a high numbers of cycles, silicone sealing rings were installed between the end cap and the loading train.

Steam is generated in an evaporator, in which a glass container filled with demineralized water is kept at 81 °C in an oil bath. Argon is first passed through the water, where it saturates up to 50 vol% and is then lead into the recipient. The connecting hose between the evaporator and the recipient is kept above 81 °C utilizing heating sleeves to prevent condensation.

The CT specimens were pre-cracked to an initial crack length to crack width ratio a/W of about 0.4 by cyclic loading at ambient temperature in a resonance testing machine (Instron Model 1603) at ambient temperature. The direct current potential drop (PD) method was applied to monitor the crack length during the fatigue experiments. For this purpose a linear calibration was carried out. A sinusoidal waveform was chosen for the fatigue crack propagation experiments. The cyclic loading schedule for hold time tests is displayed in Fig. 4. Loading was performed within 1 s, the maximum load was then held constant for periods from 300 s up to 600 s, before unloading according to the load ratio R was performed within 1 s. After load reduction the minimum load was held constant for 1 s before the cycle was started over again until one of the termination criteria of either a/W = 0.7 or 5 mm of crack extension was reached.

The cyclic stress intensity factor ΔK was determined according to ASTM E647 [14], the calculation of the cyclic crack growth rate was accomplished applying the 7-point polynomial method according to ASTM E647 [14]. All experiments were conducted using a load ratio R of 0.1. The fatigue crack growth (FCG) experiments were performed at 5 Hz and 20 Hz, the hold time tests with holding times from 300 s (effective frequency = 3.33×10^{-3} Hz) up to 600 s (effective frequency = 1.67×10^{-3} Hz). All tests were started at low stress