HIGH-TEMPERATURE FATIGUE CRACK GROWTH BEHAVIOR OF 17-4 PH STAINLESS STEELS

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ABSTRACT

The fatigue crack growth (FCG) behavior was investigated for 17-4 PH stainless steels in three heat-treated conditions, i.e., unaged (Condition A), peak-aged (Condition H900), and overaged (Condition H1150), at temperatures ranging from 300 to 500 ^{o}C. The high-temperature fatigue crack growth rates (FCGRs) of Condition H1150 were increased with an increase in temperature. However, for Conditions A and H900 tested at 500 ^{o}C, the FCGRs were lower than the lower temperature ones. At 300 and 400 ^{o}C, H1150 and H900 generally showed the lowest and highest FCGRs, respectively, with Condition A demonstrating behavior between the two. At 500 ^{o}C, the FCGR curves for all material conditions were merged together. The anomalous FCG behavior of 17-4 PH stainless steels at 500 ^{o}C was mainly caused by an in-situ precipitate-coarsening effect during test.

1 INTRODUCTION

Precipitation-hardening stainless steels have been widely used as structural components for various applications, such as nuclear, chemical, aircraft and naval industries, due to their excellent mechanical properties, good fabrication characteristics and excellent corrosion resistance. Of the former, 17-4 PH stainless steel is currently one of the most commonly used alloy [1]. 17-4 PH is a typical martensitic precipitation-hardening stainless steel and most often supplied from the mill in solution-annealed condition (Condition A). By applying suitable heat treatments in the temperature range of 482 to 621 ^{o}C (900 to 1150 ^{o}F), a wide range of mechanical properties can be obtained [1-6]. In general, the maximum strength and hardness values are obtained after aging at 450 to 510 ^{o}C, during which the precipitation of coherent copper-rich clusters occurs [1-3]. Aging at higher temperatures (above 540 ^{o}C) results in the precipitation of incoherent, large copper-rich precipitates which leads to lower strength and hardness and enhancement in toughness [1-3].

Engineering structures often contain flaws or crack-like defects such that the fatigue crack growth (FCG) behavior of a given material is of great importance in design and life prediction [7]. As some applications of 17-4 PH stainless steel are subjected to cyclic loading at high temperatures, it is important to characterize the FCG behavior of this alloy at high temperatures. Most of the previous investigations on 17-4 PH stainless steel were focused on the analysis of microstructure, mechanical and fatigue properties at room temperature [2,8-12]. Although a limited number of studies on the high-temperature characteristics of 17-4 PH alloy have been reported [8,13-16], the high-temperature FCG behavior of this alloy has not been reported yet. As part of a series of studies on the high-temperature fatigue properties of 17-4 PH stainless steel [14-16], the objective of this study is therefore to characterize the high-temperature FCG behavior of variously heat-treated 17-4 PH stainless steels by conducting systematic experiments at room temperature (RT), 300, 400, and 500 ^{o}C.

2 EXPERIMENTAL PROCEDURE

The material used in the current study is a commercially available 17-4 PH stainless steel, with nominal wt% composition of 15.18 Cr, 4.47 Ni, 3.47 Cu, 0.65 Mn, 0.38 Si, 0.2 (Nb + Ti), 0.15

Table 1 Room-Temperature Mechanical Properties of 17-4 PH Stainless Steel in Different Conditions.

Condition	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elastic Modulus (GPa)	Elongation (in 25 mm) (%)	Hardness (HRc)	V-Notch Impact Toughness (J)
Condition A	1018	992	199	13.4	32	67
H900	1414	1387	223	12.5	44.5	21
H1150	966	880	196	18.4	31.5	75

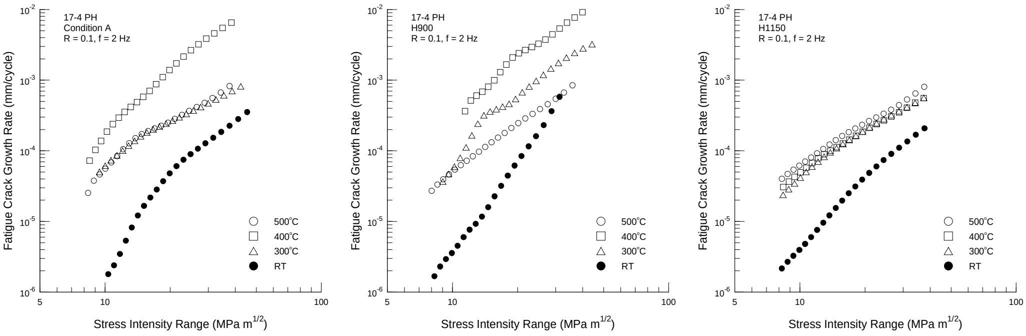
Mo, 0.03 S, 0.02 C, 0.016 P and Fe (balance). Three different types of heat treatments were applied, i.e. as-received “Condition A,” peak-aged “Condition H900,” and overaged “Condition H1150.” The mechanical properties at room temperature for each condition are listed in Table 1.

FCG tests were carried out on a commercial closed-loop servohydraulic test machine at RT, 300, 400, and 500 °C in laboratory air. A commercial two-zone, SiC-heated furnace was used to heat the specimens. FCG tests were conducted under load control with a triangular loading waveform at a load ratio of R = 0.1 and a frequency of 2 Hz. Pin-loaded single-edge-notched (SEN) specimens with a 25.4-mm width, 3-mm thickness and 6.35-mm-deep notch were used. Before each high-temperature FCG test, specimen was first fatigue precracked at RT and then held in the furnace at testing temperature for 15 min in order to reach thermal equilibrium. Crack length was measured by a direct-current potential drop (DCPD) technique. Transmission electron microscopy (TEM) was used to analyze the microstructure of the FCG specimens. Thin foils for TEM analysis were prepared by cutting out 3-mm-diameter disks from FCG specimens, followed by standard grinding and twin-jet electropolishing procedures.

3 RESULTS AND DISCUSSION

3.1 Effects of environmental temperature on the fatigue crack growth behavior

The fatigue crack growth rate (FCGR, da/dN) as a function of stress intensity factor range (ΔK) at various temperatures (RT, 300, 400, and 500 °C) are shown in Fig. 1 for each condition. The FCGRs for H1150 (Fig. 1(c)) were generally, slightly increased with temperature, even though the

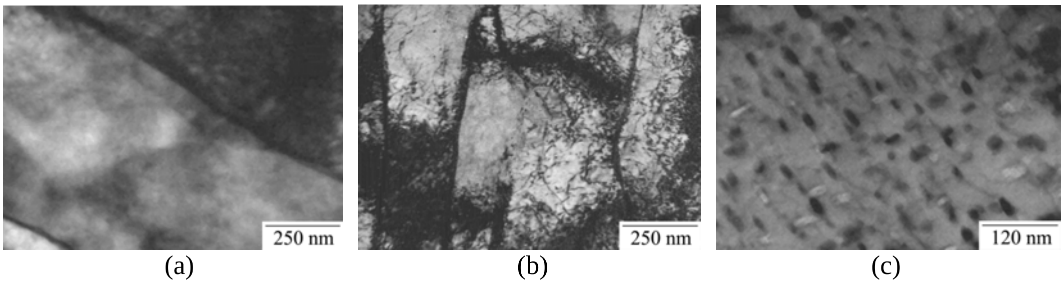


(a) (b) (c)

Fig. 1 Comparison of fatigue crack growth rate curves at various temperatures for 17-4 PH stainless steel in different conditions: (a) Condition A, (b) H900 and (c) H1150.

differences of FCGR among the given high temperatures were not so large. The FCG behavior of Conditions A and H900 (Figs. 1(a) and 1(b)) had the same tendency as H1150 except that at 500 °C, the FCGRs were lower than or equivalent to those at 300 and 400 °C. However, for Conditions A and H900, the differences in FCGR among the given testing temperatures were more pronounced than H1150 indicating that the FCG behavior of H900 and Condition A was more sensitive to environmental temperature.

The TEM micrographs of the microstructure prior to FCG test for each condition are shown in Fig. 2. The microstructural changes and the corresponding tensile properties of variously heat-treated 17-4 PH stainless steels exposed at high temperatures have been investigated by two earlier studies [14,15]. It was found that the H900 and H1150 conditions did not show any significant microstructure change when exposed at temperatures below the initial aging temperature. When exposed at temperatures higher than the initial aging temperature, the precipitates would become coarser leading to a decrease in strength and hardness [14,15]. The TEM analysis in the current study similarly indicated that no significant change in the microstructure was found for the H1150 specimens after testing at all given temperatures as well as for the H900 ones after testing at 400 °C and below. Note that the initial aging temperatures for H900 and H1150 are 482 and 621 °C, respectively. Therefore, the FCGRs were increased with temperature for H900 tested at 400 °C and below and for H1150 tested at all given temperatures, as exhibited in a wide range of materials [7]. On the other hand, for H900 tested at 500 °C, a temperature higher than the initial aging temperature, the precipitate-coarsening effect could take place during the testing period and thus incoherent coarse precipitates could be clearly seen in the specimen after FCG test, as shown in Fig. 3. Compared with the original coherent precipitates which can be easily cut by dislocations, large, incoherent precipitates formed at 500 °C for H900 have to be bypassed by dislocations, resulting a homogeneous slip distribution and an



(a) (b) (c)

Fig. 2 The TEM micrographs of the microstructure prior to FCG test for 17-4 PH stainless steel in different conditions: (a) Condition A, (b) H900 and (c) H1150.

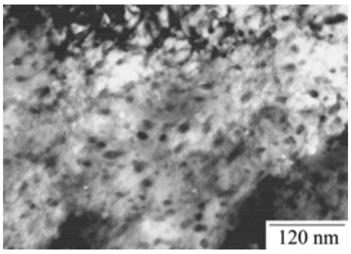


Fig. 3 TEM micrograph of the microstructure for an H900 specimen after testing at 500 °C.

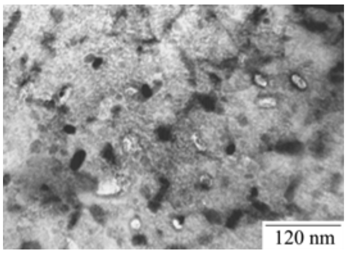


Fig. 4 TEM micrograph of the microstructure for an Condition A specimen after testing at 500 °C.

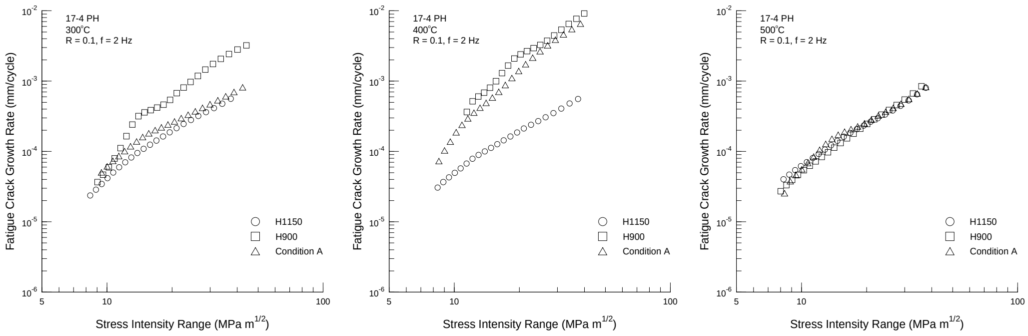
enhancement in FCG resistance. Thus, the FCGRs of H900 at 500 ^{o}C would be significantly reduced as compared to those at 300 and 400 ^{o}C.

Condition A, as a solution-annealed condition, would undergo an in-situ aging treatment when tested at high temperatures. When tested at 500 ^{o}C, a precipitation-hardening effect would increase the strength and hardness of Condition A in the first few hours and then the precipitates would become coarser and cause a reduction in hardness and strength [14,15]. The existence of incoherent, large precipitates in the matrix of Condition A after testing at 500 ^{o}C in the current study was evidenced by the TEM micrograph shown in Fig. 4. Because of this in-situ overaging treatment and accompanied enhancement of FCG resistance due to the formation of incoherent precipitates, the FCGRs of Condition A at 500 ^{o}C were lower than those at 400 ^{o}C. Apparently, the anomalous FCG behavior in Conditions A and H900 at 500 ^{o}C was closely related to this precipitate-coarsening effect.

3.2 Effects of heat-treatment on the fatigue crack growth behavior

Fig. 5 compares the FCGR curves of three different material conditions at each given temperature. At 300 ^{o}C, H900 exhibited the highest FCGRs and H1150 exhibited the lowest ones, while Condition A stood in between. At 400 ^{o}C, H900 and H1150 still exhibited the highest and lowest FCGRs, respectively, while FCGRs of Condition A were very close to those of H900. At 500 ^{o}C, the FCGR curves of the given three material conditions were somewhat merged with each other.

The microstructure of H1150 and H900 was not significantly changed during test at 300 and 400 ^{o}C, as described above. For Condition A, a certain long period of time (longer than the given testing period) was needed to complete the precipitation process at 300 ^{o}C [9,10] and the TEM observation in the current study indeed showed that the microstructure was nearly unchanged after testing at 300 ^{o}C. It was therefore suggested that the incomplete precipitation process had little effect on the FCG behavior of Condition A tested at 300 ^{o}C. In this regard, the differences in FCGR for the given three material conditions at 300 ^{o}C could be mainly attributed to the differences in the degree of coherency of the precipitates resulting from the different, initial aging treatments. In other words, a higher degree of coherency would induce a lower FCG resistance and result in higher FCGRs. As H1150 and H900 conditions had the lowest (large, incoherent precipitates) and highest (fine, coherent precipitates) degree of coherency of the precipitates, respectively, they thus showed the lowest and highest FCGRs at 300 ^{o}C, respectively (Fig. 5(a)).



(a) (b) (c)

Fig. 5 Comparison of fatigue crack growth rate curves for differently heat-treated 17-4 PH stainless steels at various temperatures: (a) 300 ^{o}C, (b) 400 ^{o}C and (c) 500 ^{o}C.

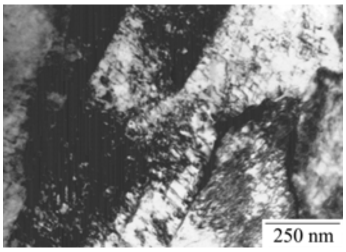


Fig. 6 TEM micrograph of the microstructure for a Condition A specimen after testing at 400 °C.

For Condition A tested at 400 °C, the TEM micrograph shown in Fig. 6 exhibited a similar microstructural morphology to that of H900 prior to FCG test (Fig. 2(b)). Earlier studies [14,15] indicated that an in-situ precipitation-hardening effect would take place for Condition A tested at 400 °C, resulting in the formation of fine, coherent copper-rich precipitates. This would increase the strength and hardness and also make the material behavior of Condition A at this temperature similar to that of H900. In this regard, the FCGRs of Condition A were very close to those of H900 at 400 °C (Fig. 5(b)).

The equivalent FCGRs of the three given material conditions at 500 °C provided further evidence for the effect of precipitate-coarsening on the anomalous FCG behavior of Conditions A and H900. In fact, FCG testing of Conditions A and H900 at 500 °C resulted in an in-situ overaging treatment leading to formation of large, incoherent copper-rich precipitates (Figs. 3 and 4) . In this regard, such an in-situ precipitate-coarsening effect could significantly reduce the FCGRs of Conditions A and H900 at 500 °C to a level similar to that of H1150 (Fig. 5(c)) and also lower than those of themselves at 300 and 400 °C (Figs. 1(a) and 1(b)). Although 500 °C is very close to the initial peak-aging temperature 482 °C, the optimal treatment time for peak-aging at 482 °C is 1 h [1,8,15] and overaging will take place for treatment longer than this optimal time. As the typical duration of a FCG test at 500 °C in the current study was around 20 to 30 h, the H900 and Condition A would indeed undergo an in-situ overaging process during test.

4 CONCLUSIONS

1. For a given material condition, the FCGRs were increased with temperature, except for Conditions A and H900 tested at 500 °C.
2. For a given temperature, the FCGRs generally took the following rank: H900 > Condition A > H1150, except for 500 °C, at which the FCGRs of all given material conditions were very close to each other.
3. The exceptions of FCG trend in Conditions A and H900 shown at 500 °C could be attributed to an in-situ precipitate-coarsening effect during test.

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