Influence of temperature and long term ageing on the fatigue crack growth in a precipitation hardened martensitic stainless steel.

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Abstract

The high-temperature Fatigue Crack Growth (FCG) behaviour of a 15-5 PH (precipitation-hardened) martensitic stainless steel was investigated in three different metallurgical conditions, i.e., as-received, aged at 300°C for 1000h and 5000h. FCG tests were conducted at room temperature and 300°C under constant amplitude loading with two load ratios (R = 0.1 and 0.7) and under variable amplitude loading. The results indicate that the fatigue crack growth rates (FCGRs) increase with R-ratio at the lower ΔK regime and merge together in the high ΔK regime, regardless of ageing conditions and temperature. At 300°C, the FCGRs are higher than at room temperature for all ageing conditions. Under variable amplitude loading, the same retardation effect was observed for all the given ageing conditions at room temperature.

1. Introduction

The precipitation-hardened stainless steel has both a natural property of corrosion resistance and high strength. Especially, the 15-5 PH martensitic stainless steel, which contains about 15% of Cr and 5% of Ni, is a high strength material due to the formation of Cu precipitates. Thanks to its high performances, the material has been introduced into heavily loaded structural elements for which a high level of reliability is required in chemical, aircraft, naval and nuclear industries. In addition, this material is also considered for the development of the engine pylons, which are designed using a damage tolerance approach. In service, the engine pylon that transmits loads...
between the engines and the wing is exposed to high temperatures and is subjected to variable amplitude cyclic loading. Indeed, the temperature can vary from -40°C on cruise to 300°C or even 400°C during take-off. Ageing due to this prolonged thermal exposure may have an impact on the fatigue crack growth rate resistance of the material. Furthermore, information on the FCG behaviour under variable amplitude loading is required. Indeed, if a substantial retardation is present, it has to be taken into account in order to prevent over-conservative predictions. The point is that fatigue crack growth data on the 15-5 PH-type steel are not widespread in literature. Some data about the 17-4 PH stainless steel are available; they are however mainly focused on the influence of heat-treatments and related microstructural characteristics on the room-temperature fatigue properties [2-10]. Studies on the high-temperature FCG behaviour are much more limited and do not consider the effects of variable amplitude loading and long-term ageing.

The present study was thus undertaken within the framework of a national program in order to investigate the influence of the temperature (300°C) and long-term ageing on the FCG behaviour of 15-5PH steel under constant amplitude loadings and repeated overloads. The objective is to develop a model that can take into account the respective influence of these different phenomena. More precisely, the present paper reports the experimental fatigue crack growth results obtained so far considering three metallurgical conditions, namely the as-received condition and two ageing conditions.

2. Material and experimental procedures

The material used in the current study is a particular grade of 15-5PH (reference name: X15U5W) stainless steels supplied by AUBERT & DUVAL in the form of a rectangular-section bar. The section of bar was 140mm x 60mm. This material was solution treated at 1040°C for 30min and then heat treated at 505°C for 4h. The chemical composition of this steel in wt% is 0.025 C, 0.38 Si, 0.80 Mn, <0.002 S, 0.019 P, 4.93 Ni, 14.87 Cr, 0.27 Mo, 2.99 Cu, 0.21 Nb, and balance of Fe. Two different types of ageing were applied to the specimens, namely 300°C/1000h,” 300°C/5000h. For clarity sake, the different conditions will be designated as follows in the next sections: AR (as-received), AC1 (ageing 300°C/1000h) and AC2 (ageing 300°C/5000h).

The mechanical properties at room temperature determined for the as-received material by AUBERT & DUVAL are given in Table 1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Orientations</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>Elongation 4d (%)</th>
<th>Elongation 5d (%)</th>
<th>Z (%)</th>
<th>KV (J)</th>
<th>KQ (MPa.m^(1/2))</th>
<th>Orientations</th>
<th>Pmax/FQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received</td>
<td>Long</td>
<td>1250.5</td>
<td>1169</td>
<td>20.2</td>
<td>16.45</td>
<td>65.6</td>
<td>53.3</td>
<td>144</td>
<td>L-T</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Travers</td>
<td>1252</td>
<td>1167.5</td>
<td>19.05</td>
<td>15.5</td>
<td>63.85</td>
<td>47</td>
<td>133</td>
<td>T-L</td>
<td>1.00</td>
</tr>
</tbody>
</table>

FCG tests were carried out on a commercial closed-loop servohydraulic test machine at room temperatures and 300°C in laboratory air. FCG tests were performed according to ASTM E647 under constant load control with a sinusoidal loading waveform at a frequency of 20 Hz and R-ratios ranging from 0.1 to 0.7. Additional tests were conducted under variable amplitude loading (one overload every 1000cycles for test conducted with R=0.1). The overload ratio (Kpeak/Kmax) in these tests was 1.7. The compact tension (CT) specimen with a 40-mm width, 10-mm thickness and were used. All the CT specimens were taken in the L-T direction. A formula was taken to determine the stress intensity factor for this specimen geometry in the ASTM E647 [1].

\[ K = \frac{P \times Y(\alpha)}{B \times \sqrt{W}} \]  
and \[ Y(\alpha) = \frac{(2 + \alpha)(0.886 + 4.64\alpha - 13.31\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)}{(1 - \alpha)^{3.2}} \]
\[
\frac{a}{W} = \alpha
\]
Where K is the stress intensity factor in model I, P is the applied load, B and W are the thickness and width of the test specimen, respectively, and a is the crack length. The crack length was measured by a direct-current potential drop (DCPD) technique. A polynomial equation was identified to establish the relationship between the measured potential drop and the crack length. This polynomial equation was derived from the result of a test conducted at \(R=0.1\) at room temperature where the crack length was monitored by means of a travelling microscope. The secant method was used to analyze the fatigue crack growth rate (FCGR) data. After test completion a crack length correction was made on the basis of optical observation of the crack front shape. As regards testing at elevated temperature, the specimens were first precracked by fatigue at room temperature and then held in the furnace at testing temperature for one hour in order to achieve a thermal equilibrium. Repeated tests were conducted for each given testing condition and little scattering of the experimental data was observed.

3. Results

3.1. FCG behaviour at room temperature

The comparison of FCGR curves obtained under two R ratios (0.1 and 0.7) at room temperature is shown in Fig. 1.a for AR. It can be seen that the FCGR at room temperature is higher at \(R=0.7\) in the lower \(\Delta K\) regime. This difference in FCGR between these two R-ratios decreases with increasing \(\Delta K\) and the curves merge together at the higher \(\Delta K\) regime. This difference can be attributed to the crack closure phenomenon because at \(R=0.7\) crack closure are assumed to be extremely limited, which is not the case at \(R=0.1\). However the crack closure is not easily detectable in this material.

Under repeated overloads, Fig. 1.b, the FCGR is retarded with respect to constant amplitude loading at \(R=0.1\). For instance, at \(\Delta K=20\text{MPa.m}^{1/2}\), FCGRs are almost one order of magnitude lower.

![Fig.1. (a) Comparison of fatigue crack growth rates curves under two R-ratios (0.1 and 0.7) at room temperature for AR, (b) Comparison of fatigue crack growth rates curves under constant loading at R=0.1 with variable amplitude loading (R=0.1+1 OL every 1000 cycles) for AR.](image-url)
3.2. Effect of ageing time

Fig. 2 presents the FCGR curves obtained at room temperature for two values of the R-ratio (0.1 and 0.7) and for two ageing conditions. It can be seen that the FCG behaviour is nearly the same for the different conditions. It can be noticed that in the case of AC2, the da/dN curves at R=0.1 and R=0.7 do not merge at high $\Delta K$ values. The reason is that failure occurs at low K value in the AC2 condition at R=0.7.

![Fig.2. Comparison of fatigue crack growth rates curves under two R-ratios (0.1 and 0.7) at room temperature for variously long term aged 15-5PH stainless steels: (a) AC1 and (b) AC2.](image)

Testing under repeated overloads was also performed on aged materials (AC1 and AC2). The results are presented in Fig. 3 a and b. It can be seen, by comparing with figure 1b, that the ageing conditions under consideration did not affect the retardation effect on FCGRs.

![Fig.3. Comparison of fatigue crack growth rates curves for R=0.1 with variable amplitude loading (R=0.1+1 OL every 1000 cycles) at room temperature for variously long term aged 15-5PH stainless steels: (a) AC1 and (b) AC2.](image)
3.3. Effect of temperature on fatigue crack growth

Tests were performed at temperature of 300°C on the AR and AC1 at R=0.1 and R=0.7. The results are shown in Fig.4. At 300°C, it can be seen that the FCGRs were increased with R-ratio at the lower ΔK regime and merged together in the high ΔK regime for the both aged conditions. The FCGR behaviour of AR and AC1 is nearly the same.
Comparisons of FCGR curves at room temperature and at 300°C with both R-ratios for AR and AC1 shown that the FCGR were generally slightly increased at 300°C for both conditions of materials for a given R ratio value.

![Fig.4. Comparison of fatigue crack growth rates curves under two R-ratios (0.1 and 0.7) at two temperatures (RT and 300°C) for two aged conditions 15-5PH stainless steels: (a). AR, (b) AC1.](image)

4. Discussion

4.1. Effect of ageing on fatigue crack growth behaviour

The results shown in Fig.2 indicate that the ageing durations 300°C investigated so far do not have a marked impact on the FCG behaviour, despite the effect noticed on the transition from transgranular cleavage-like fracture mode to a more ductile failure process. This effect could be related to a possible effect of ageing on fracture toughness that should be addressed. Although no other long term ageing crack growth studies on the current alloy system are available in the literature, insights into likely causes of the long term ageing dependence observed can be inferred from the work in other precipitation-hardened martensitic stainless steel (17-4PH). In these investigations of crack growth propagation in 17-4PH with different heat-treatments, Kuei-Chang et al [12] suggested that heat-treatment has an influence on FCGRs: the crack propagates faster in the hardest material while the crack growth mechanism remains the same for all heat-treated 17-4PH stainless steels. In the present case, it is possible that the 300°C ageing condition did not modify the hardness; hence the FCGR did not vary for the different ageing conditions.

The influence of ageing on fatigue crack growth behavior under variable amplitude loading (VAL) of the 15-5PH steel is not widely documented in literature. It is generally accepted that FCG behavior under VAL is related to load history effects on cyclic behavior in crack tip [13, 14]. This is the reason why ongoing work is devoted to the study of the influence of long term ageing on the cyclic stress-strain behavior of 15-5PH in order to develop a model taking into account load history effects on crack growth.
4.2. Effect of temperature on fatigue crack growth behaviour

At low and at the mid-range crack growth regime, it was shown (Figure 4) that fatigue crack growth rates at 20Hz and R=0.1 and R=0.7 compared to room temperature tests at 20Hz for both R-ratios (0.1 and 0.7). The effect of temperature on the FCG behaviour has been the subject of several studies [14-17]. In these studies a set of causes responsible for FCGR differences between the behaviour at room temperature and high temperature behaviour have been identified. Among the latter we noted the oxidation effects, the effects of oxide-induced closure and the influence of viscoplasticity at the crack tip. If the oxidizing effects are responsible for the difference in FCGR, FCG mechanisms at high temperatures could be time-dependent. Oxidation is generally thermally activated and sensitive to evolution of temperature. Moreover, Cotterill and Knott [16] shown that oxygen acts to form oxides that cause irreversibility of slip and hence enhance growth rates at high temperature. Shahinian et al [17] have related the increase of mid-range growth rates with temperature in Inconel 718 which decreases in the magnitude of the elastic modulus E with increasing temperature. They found that growth rates are unified if plotted as function of ΔK normalized with respect to E. Similar observation have been made in austenitic stainless steels in the temperature range of 25°C to 593°C [15].

Investigation of crack propagation in 17-4PH [11] at high temperature has shown that FCGR increased with temperature. The difference in FCGRs between room temperature and elevated temperatures is affected by heat-treatment. On the other hand, Kuei-Chang et al [11] showed no significant change in FCGRs with frequency for variously heat-treated 17-4PH stainless steels at 500°C. Fracture surfaces are also predominantly transgranular with a noticeable evidence of oxidation on the fracture surface at very low frequencies (0.002Hz). The FCGRs mechanisms at 300°C are not clearly specified. In the present case, the FCGRs for AR and AC1 at 300°C was slightly increased with temperature at 20Hz, and the Paris power law behaviour was maintained. The slopes for the FCGR curve at 300°C are roughly the same with FCGR curve at room temperature and for a given ΔK levels.

In order to isolate the deleterious effect of oxidation and to understand the exclusive impact of temperature to FCGR , we have in perspective to conduct tests under vacuum.

5. Conclusion

- At room temperature and 300°C, the FCGRs increase with R-ratio in the lower ΔK regime and merge together in the high ΔK regime for AR and AC1 conditions. The fracture mode is predominantly transgranular at both testing temperatures.
- The FCGRs for all the given aged conditions slightly increase with temperature.
- Ageing temperature of 300°C did not have an influence on FCGR, but duration of ageing had an impact on the transition from transgranular fracture mode to a more ductile one.
- The intensity of the overload-induced retardation on FCGRs is nearly insensitive to ageing conditions for the conditions examined so far.

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7. References