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The Effect of an Oxygen Atmosphere on the Creep-fatigue Failure of Iron–Chromium Alloys at 600 °C

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A systematic study was conducted of the effect of an oxygen environment on the creep-fatigue failure of iron–chromium alloys at 600 °C. The materials tested were ferrite steels containing up to 18 per cent chromium, namely low-carbon steel (no chromium), 3CR12 (12 per cent chromium), and 430 stainless steel (18 per cent chromium). The cyclic loading encountered creep tension and plastic compression according to the CP mode of the strain-range partitioning method under low-cycle fatigue conditions. The strain ranges varied from 0,2 to 0,45 per cent. The tested environments consisted of different mixtures of oxygen and argon, as well as an air atmosphere. The crack-growth behaviour was studied by scanning electron microscopy, EDAX analysis, and X-ray diffraction.

The results showed that, when chromium was absent, as in the case of mild steel, the fatigue life was greater in argon than in air. The effect was reversed when 12 per cent chromium was present, as in the case of 3CR12. The presence of 18 per cent chromium, as with 430 stainless steel, produced similar fatigue lives in argon and in environments containing up to 20 per cent oxygen.

Introduction

Ferrite steels containing chromium are used for components in the power-generating and chemical industries operating under the combination of creep-fatigue loading conditions and oxygen-containing environments[1,2]. Lately, newly developed chromium steels with improved mechanical properties and corrosion resistance have become the focus of interest. Among them, for example, is 3CR12 steel, which was developed as an alternative material of construction in environments where low-carbon and other structural steels had inadequate corrosion and heat resistance. The present paper gives the initial results of an evaluation of the effect of an oxygen atmosphere on the creep-fatigue failure of ferritic steels containing various amounts of chromium.

Experimental

The materials investigated were low-carbon steel, 3CR12 corrosion-resistant steel, and 430 ferritic stainless steel, with the chemical compositions given in Table I. The chemical compositions were in accordance with the specifications for the equivalent commercial grades.

The experimental set-up consisted of a universal MTS loading machine, a split-oven furnace, and a gas-mixing system that was able to produce a controlled gaseous atmosphere. The latter flows around the fatigue-specimen constriction with a positive pressure of about 1,5 atmospheres. The fatigue-specimen constriction was 4 mm in diameter and 25 mm in length. The strain was measured with an extensometer having two pairs of strain-transfer rods, each attached to the constriction-length collars cut on the specimen, and the transferred strain was measured by use of an LVDT positioned outside the furnace. A detailed description of the experimental arrangement and procedure has been given in a previous paper[3].

The low-cycle creep-fatigue tests were performed under varying loading conditions that encountered creep tension and plastic compression following the CP mode of the strain-range partitioning method[4]. This included tensile-strain rate varying between $1,0 \times 10^{-4} s^{-1}$ and $2,25 \times 10^{-4} s^{-1}$, and compression between $20 \times 10^{-4} s^{-1}$ and $45 \times 10^{-4} s^{-1}$, within strain ranges of $\pm$ 0,1 per cent and $\pm$ 0,225 per cent, as illustrated in Figure 1. It should be pointed out that this type of loading condition was selected as a result of significant reduction in fatigue life caused by the interaction between fatigue-crack and fatigue-creep damages[5] that is commonly experienced by materials in real high-temperature service conditions.

Tests were carried out under oxidizing and inert environments of argon and oxygen, pure argon, and air atmosphere. As an evaluation of the effect of the environment by itself, unloaded disk specimens were tested within a corrosion chamber. These disks were also used in X-ray-diffraction analyses to determine the type of phases that evolved under a specific environment and temperature. The mechanism of

TABLE I
CHEMICAL COMPOSITION OF THE MATERIALS INVESTIGATED IN WEIGHT PERCENTAGES

Material	C	Mn	S	P	Si	Cr	Ti	Fe
Low-carbon steel	0,15	0,85	0,033	0,027	0,21	–	–	Bal.
3CR12	0,028	1,04	0,005	0,019	0,45	11,7	0,36	Bal.
430	0,049	0,46	0,005	0,028	0,67	17,7	–	Bal.

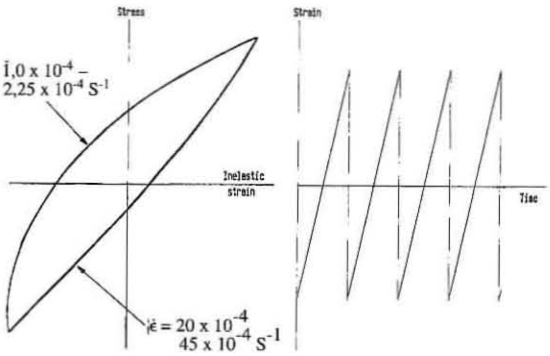


FIGURE 1. Hysteresis loop for $\Delta\epsilon$ = 0,002 to 0,0045 at CP = 0,047 Hz in accordance with the strain-range partitioning method

crack growth was studied by detection of the crack incubation, initiation, and propagation using scanning electron microscopy and spot chemical analysis.

Results and Discussion

Tests on the plain low-carbon steel under creep-fatigue loading in pure argon and in an environment containing 20

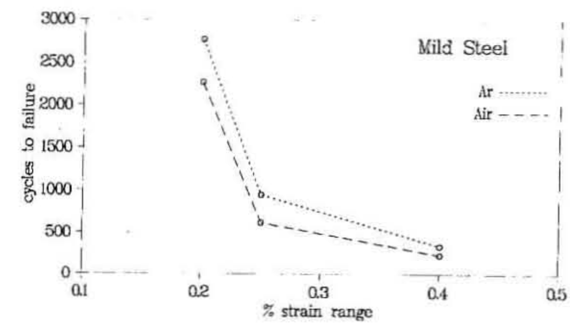


FIGURE 2. The effect of oxidation on creep-fatigue lives (following the CP mode of the strain-range partitioning method) of mild steel at 600 °C

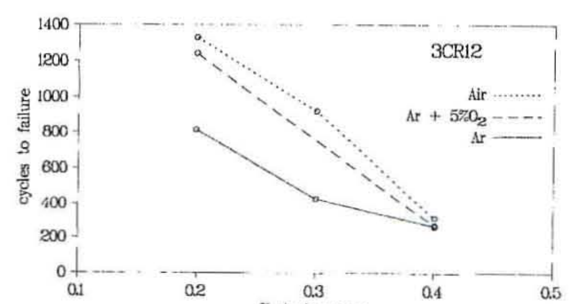


FIGURE 3. The effect of an oxygen-containing environment on creep-fatigue lives (following the CP mode of the strain-range partitioning method) of 3CR12 alloy at 600 °C

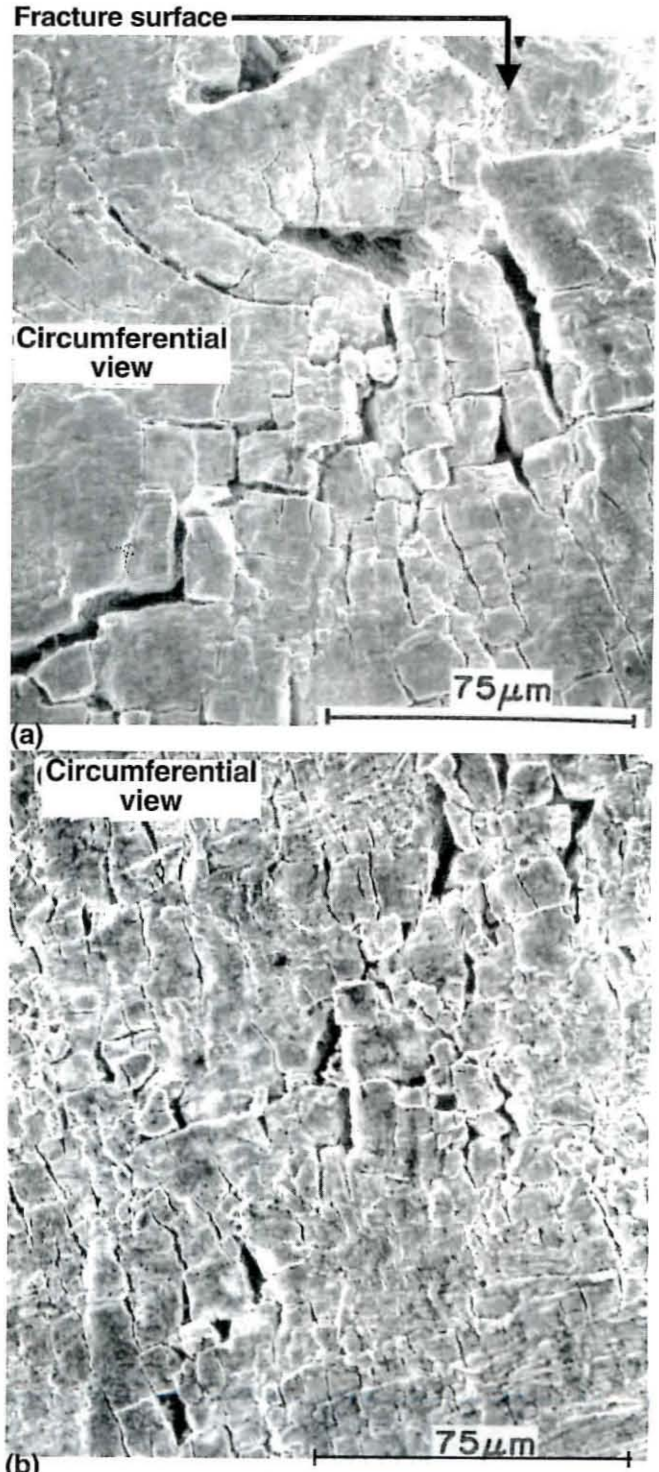
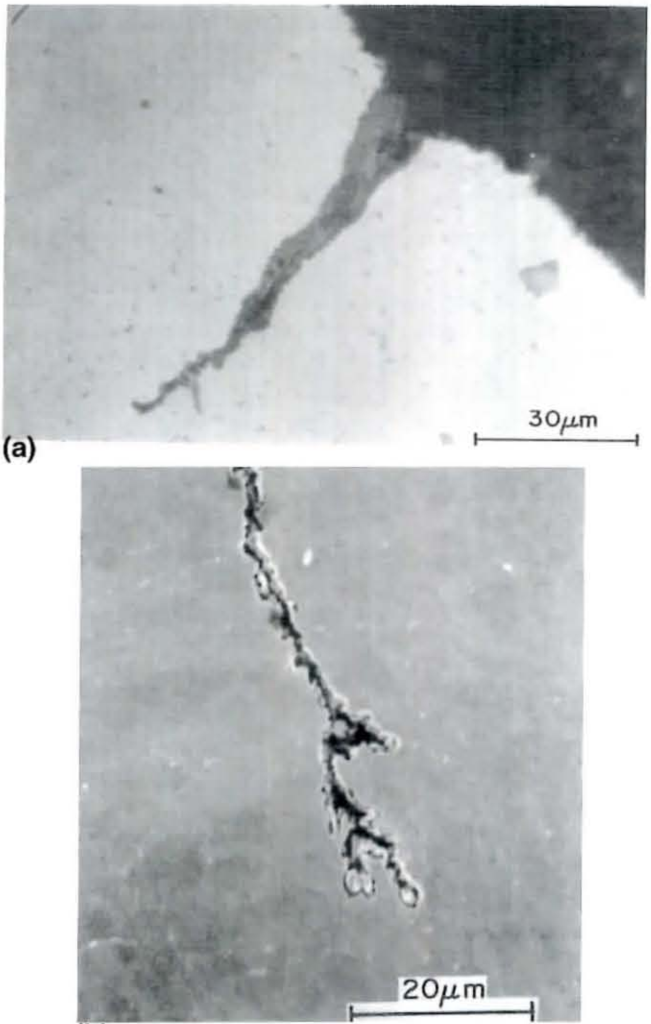


FIGURE 4. The fracture surface and the circumferential view of 3CR12 obtained after creep-fatigue testing in an environment containing 20 per cent oxygen within a strain range of
(a) 0,3 per cent (b) 0,2 per cent



(a)

(b)

FIGURE 5. A close-up view of a fatigue crack close to the fracture surface obtained after creep-fatigue testing of 3CR12 in an atmosphere containing 20 per cent oxygen at 600 °C
(a) initial stage (b) crack tip

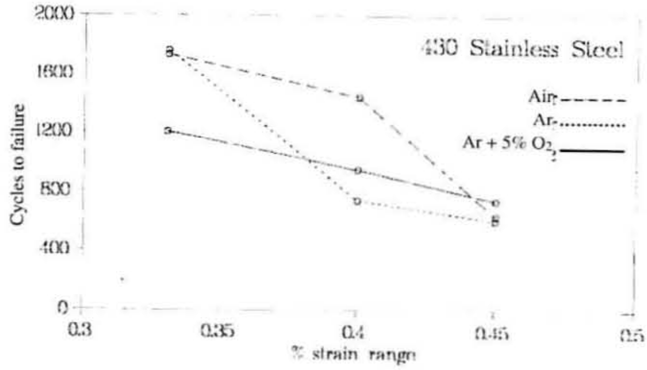
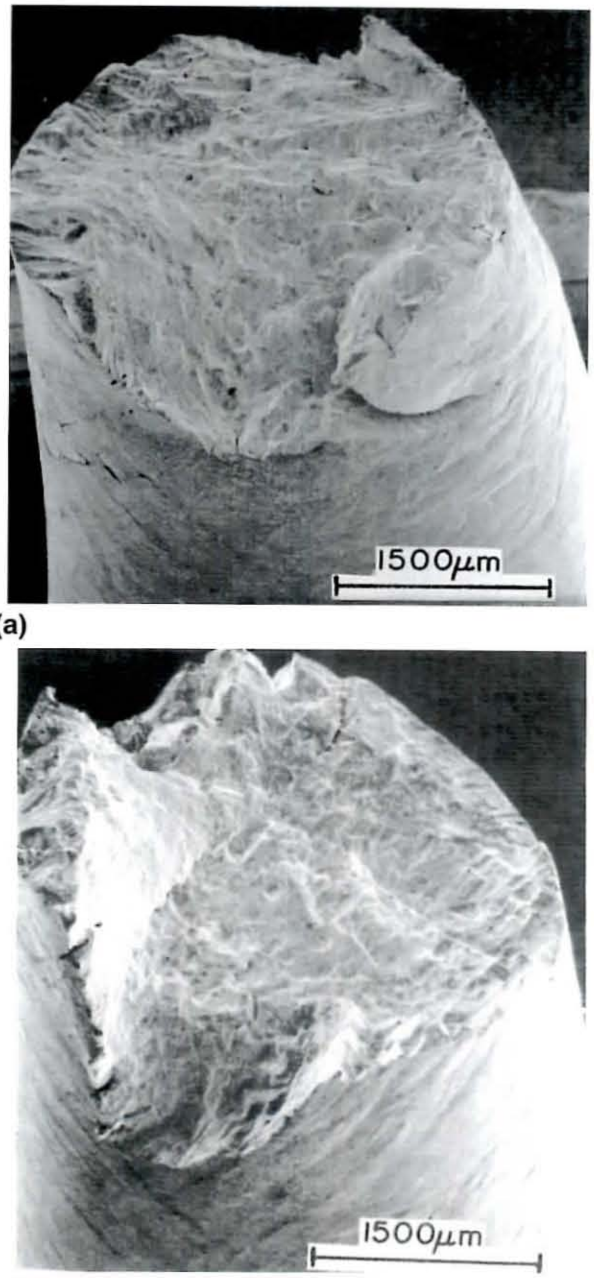


FIGURE 6. The effect of an oxygen-bearing atmosphere on creep-fatigue lives (following the CP mode of the strain-range partitioning method) of 430 stainless steel at 600 °C



(a)

(b)

FIGURE 7. The fracture surface and the circumferential view of 430 stainless steel after creep-fatigue testing within a strain range of 0,4 per cent
(a) in pure argon (b) in an environment containing 20 per cent oxygen

per cent oxygen (air) indicated that the fatigue lives were greater in pure argon, as shown in Figure 2. This effect was reversed in the case of 3CR12, as illustrated in Figure 3.

The fracture surface, as well as the circumferential view of 3CR12 obtained after creep-fatigue testing (0,2 per cent and 0,3 per cent strain range) in an atmosphere containing 20 per cent oxygen is shown in Figure 4. It is evident from the circumferential view that the external layer was severely cracked, which initiated several fatigue cracks. A close-up view of one of the fatigue cracks at a cross-section close to the fracture surface is shown in Figure 5. It is clear that the crack initiation and propagation encountered crack blunting and branching. These two phenomena may explain the extended life of 3CR12 in an environment containing up to 20 per cent oxygen compared with the lives obtained in pure argon. According to this explanation, the branching effect is caused by the favourable condition of cracking ahead of the crack tip due to the formation of brittle oxide phases. At a later stage, the volume of the crack is filled up with oxides as an indication that the crack propagation was restrained, allowing sufficient time for a chemical interaction between the oxidizing environment and the crack edges.

These phenomena were not obtained in an inert environment of pure argon, where the failure was purely mechanical and the crack propagated right across the fatigue specimen without encountering any crack blunting or branching effects. X-ray-diffraction analysis obtained from an unloaded disk specimen of 3CR12 exposed to the same oxygen-containing environment and temperature revealed the presence of oxide phases Cr_2O_3, Fe_2O_3, and Fe_3O_4. These phases probably played a major role in retarding the fatigue failure in an oxygen-bearing atmosphere, as manifested by the blunting and branching effect.

A different response was obtained with 430 ferritic stainless steel tested under pure argon and environments containing up to 20 per cent oxygen. In this case, the fatigue lives showed little significant difference owing to the effect of oxidation, as shown in Figure 6. This result was supported by the fractography analysis, which also showed that the effect of oxygen on the mode of failure was not substantial (Figure 7). X-ray-diffraction analysis of unloaded disk specimens made from 430 stainless steel revealed an extensive presence of Cr_2O_3, which, in fact, introduced an adequate environmental resistance in the tested oxidizing atmosphere. Finally, it should be pointed out that the fatigue lives shown in Figures 2, 3, and 6 were quite consistent and, as a result, the behavioural trend of the various alloys could be established.

Conclusion

In conclusion, the fatigue life of ferritic steels under high-temperature creep-fatigue conditions in an oxygen-containing environment depended on the chromium content of the steel. It was evident that the fatigue life of a plain low-carbon steel was shorter once it had been exposed to an oxidizing environment, and this effect was reversed in 3CR12 containing about 12 per cent chromium. The examination of 430 ferritic stainless steel showed that the creep-fatigue lives of the steel were not affected by the oxidizing environment. This was probably due to the adequate resistance provided by the presence of 18 per cent chromium.

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