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Effects of temperature and frequency on fatigue crack growth in 18% Cr ferritic stainless steel

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The fatigue crack growth behaviour of a ferritic stainless steel has been investigated as a function of test temperature, thermal exposure and frequency at intermediate growth rates. In general, fatigue crack growth rates increased with increasing temperature and in the temperature range 500–700 °C growth rates were described by a kinetic process with an activation energy of 48 kJ/mole. Higher than normal growth rates at 475 °C were observed and attributed to an embrittlement process which is known to occur in this temperature regime in high-chromium ferritic stainless steels. The influence of frequency on fatigue crack growth rates was examined at 500 and 655 °C for a load ratio of 0.1 and over four decades of frequency. A transition from time-independent to time-dependent behaviour was observed at each temperature as frequency was lowered. The frequency at which this transition occurred was dependent on temperature. For all temperatures investigated, near threshold crack propagation occurred by a crystallographic or faceted propagation mechanism. At high crack growth rates, crack-tip plasticity was significant and propagation proceeded by a ductile striation formation process. At intermediate growth rates a mixed-mode fatigue crack growth mechanism was observed where some intergranular fracture occurred.

Key words: high-temperature fatigue; embrittlement; frequency effects; creep–fatigue interactions; crystallographic fracture

Ferritic stainless steels, containing between 11.5 and 27% Cr, have been widely used in elevated temperature applications for many years because of their good resistance to general aqueous corrosion, high-temperature oxidation, and stress corrosion cracking. They have good cold-formability and generally are less expensive than the austenitic grades.[1] However, few studies of the fatigue crack propagation behaviour of ferritic stainless steels have been performed. In a previous study[2] we reported on the influence of temperature on the near-threshold fatigue crack growth behaviour in an 18% Cr–Nb stabilized alloy. The results of that study indicated that roughness-induced crack closure and its variation with temperature was the probable controlling factor in the influence of temperature on threshold level. Plasticity-induced crack closure was thought to play a role, at least at intermediate temperatures, where anomalous threshold levels were observed. In the present study we report on the influence of temperature and test frequency on fatigue crack growth behaviour in the same alloy at intermediate levels of stress intensity range, ΔK.

The temperature dependence of fatigue crack growth at intermediate values of ΔK, where growth rates between 10^{-6} and 10^{-9} m/cycle are observed, has generally been attributed to one or more damage accumulation processes resulting from environmental attack and creep damage. These damage processes contribute to crack advance to a degree dependent on environmental sensitivity and susceptibility to embrittlement by creep damage and have been generally found to enhance fatigue crack growth rates.[3,4] However, in some instances, these same processes can also reduce crack propagation rates. For example, oxide-induced crack closure caused by increasing the test temperature is found to decelerate near-threshold fatigue crack growth rates and increase ΔK_{th}.[5,6] Also, for lower-strength materials, crack-tip blunting at elevated temperatures can reduce crack growth rates and can even lead to crack arrest.[7] These elevated-temperature damage processes often result in a cyclic frequency dependence for crack growth behaviour at intermediate growth rates and ΔK levels.

In ferritic stainless steels, there is an additional complication which arises because of embrittlement due to thermal exposure at low to intermediate temperatures (*eg* 475 °C). The embrittlement is unrelated to the oxidation or creep damage. A study of the effects of embrittlement on a number of ferritic stainless steels has shown that thermal exposure in particular temperature ranges increases room temperature yield strength and dramatically decreases ductility.[8,9] These effects are more pronounced with higher Cr content[8,10] and are attributed to the precipitation of a very fine, coherent, Cr-rich bcc phase.[10] Knowing that embrittlement significantly affects the room-temperature mechanical properties of ferritic stainless steels, it is possible that similar deleterious effects on the fatigue behaviour of ferritic stainless steels may occur at these intermediate temperatures.

With these considerations in mind, the effects of temperature, cyclic frequency and embrittlement on midrange growth rates in an 18% Cr–Nb stabilized ferritic stainless steel have been investigated.

Experimental procedures

The chemical composition of the alloy used in this study is given in Table 1. Single edge notch (SEN) specimens with a width of 25.4 mm were machined from sheet stock of 1.42 mm nominal thickness and used in all fatigue experiments.

Near-threshold and mid-range fatigue crack growth rates were determined as a function of temperature from room temperature to 800 °C, at constant R ratio ($\sigma_{min}/\sigma_{max}$) of 0.1 and constant frequency of 15 Hz using a computer-controlled servohydraulic test system equipped with a resistance furnace. Crack growth was monitored using a combination of a travelling microscope and a dc potential drop technique for room temperature experiments and only the potential drop technique for elevated temperature experiments. Near-threshold fatigue crack growth rates and ΔK_{th} were determined using the unloading schedule recommended by ASTM E647-88a[11] in which both K_{max} and K_{min} decrease exponentially with crack extension while the R ratio remains constant. Mid-range growth rates were determined using a constant P_{max} mode in which the maximum load is kept constant while ΔK increases as crack length increases. All specimens were precracked at room temperature at a constant ΔK of 16 MPa$\sqrt{m}$ followed by a load-shedding experiment to a stress intensity just above ΔK_{th}.

For the study of the effects of frequency on fatigue crack growth rates, crack growth tests were conducted under constant ΔK at a K_{max} level of 16 MPa$\sqrt{m}$ and R = 0.1, using standard load-shedding techniques. The level of K_{max} was chosen to minimize closure effects without causing excessive crack tip plasticity. Tests were conducted at frequencies ranging from 0.01 to 50 Hz at 500 and 655 °C. A sinusoidal waveform was used for all tests.

Preliminary studies indicated that mid-range growth rates at 475 °C did not follow the effects of temperature observed for the other test temperatures. Because of the possibility of embrittlement at this temperature a more systematic study involving specimens given a thermal exposure at this temperature was undertaken. Specimens were exposed at 475 °C for 20 or 30 h followed by a water quench, and fatigue crack growth experiments on the embrittled specimens were conducted at room temperature. The results were then compared with fatigue data generated on specimens in the as-received condition at room temperature and at 475 °C.

Fractographic examinations of specimens from the various fatigue studies were conducted on a Hitachi 520 scanning electron microscope operated at an accelerating voltage of 20 kV.

Results

Effects of temperature on fatigue crack growth rates

The influence of temperature on the near-threshold fatigue crack growth rate as a function of ΔK at room temperature, 500, 600 and 700 °C for tests conducted at a load ratio of 0.1 and a frequency of 15 Hz is shown in Fig. 1 from our previous study.[2] Threshold values determined from this study are shown in Table 2. ΔK_{th} decreased monotonically with increasing temperature except at 500 °C, where threshold levels were actually higher than those observed at room temperature. In addition, the increase of ΔK_{th} at 500 °C with respect to the room temperature value was observed at all R ratios studied including R ratio of 0.75 generated using the constant K_{max}, increasing R ratio test procedure. Crack closure measurements indicated that the anomalous behaviour

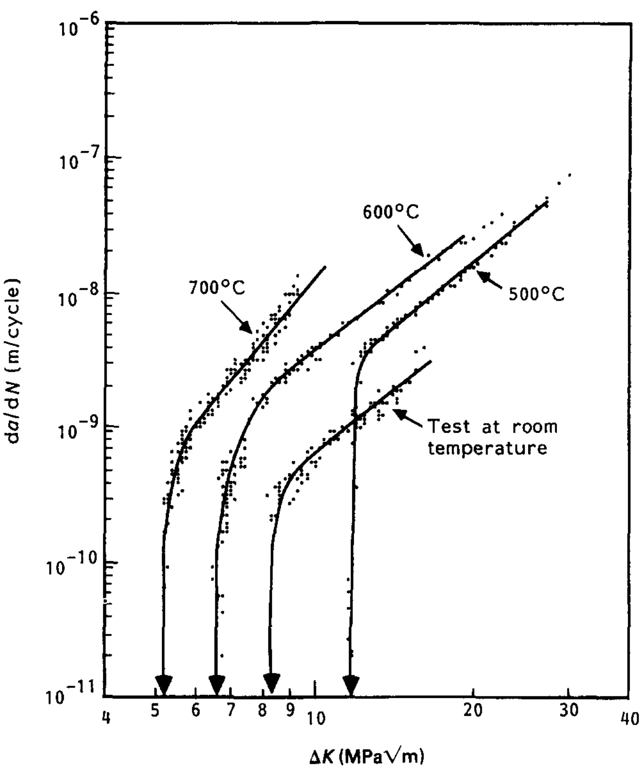

Fig. 1 Influence of temperature on the near-threshold fatigue crack growth behaviour of 18%Cr–Nb ferritic stainless steel. Tests conducted at R = 0.1, f = 15 Hz

Table 2. ΔK_{th} values and Paris equation parameters ($da/dN = C(\Delta K)^n$) at different temperatures for R = 0.1 (units are MPa$\sqrt{m}$ and m/cycle)

Temperature (°C)	ΔK_{th}	C	n
25	8.2	3.1×10^{-13}	3.3
475	—	6.8×10^{-12}	2.8
500	11.8	6.8×10^{-12}	2.4
600	6.5	5.5×10^{-12}	2.9
700	5.1	2.6×10^{-11}	2.6
800	–	2.4×10^{-12}	5.1

Table 1. Chemical composition

Composition (wt %)	Fe	Cr	C	Mn	Si	Ti	P	S	Nb
18%Cr–Nb	bal	18.04	0.031	0.33	0.473	0.206	0.031	0.015	0.706

seen at 500 °C was attributed to plasticity-induced crack closure.

The influence of temperature on fatigue crack growth rates at intermediate levels of ΔK is shown in Fig. 2 for $R = 0.1$ and a frequency of 15 Hz. In general, increasing the test temperature from 25 °C to 800 °C resulted in significantly increased crack growth rates at all levels of ΔK. At all temperatures, fatigue crack growth rates were well described by the Paris[12] relation, $da/dN = C(\Delta K)^n$. Table 2 summarizes the values of the Paris constants C and n observed at the different test temperatures. At a ΔK level of 20 MPa√m, at 700 °C, fatigue crack growth rates were an order of magnitude higher than the room temperature growth rates and five times higher than growth rates measured at 600 °C. At 800 °C, growth rates depended more sensitively on ΔK, with n roughly twice the value observed at the lower test temperatures.

Embrittlement effects on fatigue crack growth

At 475 °C, crack growth rates over the range of ΔK examined were equivalent to those observed at 600 °C. In order to confirm that this effect was attributable to an embrittlement normally associated with thermal exposure at 475 °C, an additional series of tests were performed in which room temperature fatigue crack growth rates were determined for specimens heat-treated at 475 °C for 20 and 30 h followed by water quenching. These conditions were chosen to accentuate the influence of 475 °C embrittlement, and room-temperature crack growth rates were examined in an effort to separate the effects of environment and temperature from the influence of embrittlement on crack growth rates. Figure 3 compares the room temperature fatigue crack growth behaviour of the as-received material and the material heat-treated at 475 °C with the behaviour of a specimen tested at 475 °C. All these experiments were performed at a load ratio of 0.1 and a frequency of 15 Hz. Although not shown, the 30 h thermal exposure resulted in roughly the same increase in mid-range growth rates as the 20 h exposure. As seen in Fig. 3, room-temperature growth rates for the embrittled specimen were substantially higher than room-temperature growth rates for the unembrittled material but somewhat below the growth rates observed at 475 °C. In fact, comparison of the data in Figs 2 and 3 indicates that the room temperature growth rate in the embrittled specimen is equivalent to the growth rate observed at 500 °C. These observations indicate that the high growth rates observed at 475 °C result mainly from an embrittlement effect and depend to a lesser extent on temperature.

Frequency effects on fatigue crack growth

The effects of frequency on fatigue crack growth rates were investigated at a constant K_{max} of 16 MPa√m, at 500 and 655 °C. Growth rates were obtained over a range of four decades of frequency ranging from 0.01 to 50 Hz and are shown as a function of frequency in Fig. 4 for both temperatures. At each temperature, the dependence of crack growth rate can be divided into two regions where distinctly different behaviour is observed. At higher frequencies, crack growth rate is independent of frequency and as frequency is reduced a transition frequency f_c is reached, below which the crack growth rate increases monotonically with a decrease in frequency. The transition frequency is sensitive to temperature and is equal to approximately 0.05 Hz at 500 °C and 1 Hz at 655 °C. Figure 5 shows the same data depicted on a time basis, da/dt, rather than a cycle basis. Similarly, the data at each temperature can be represented by two linear regions.

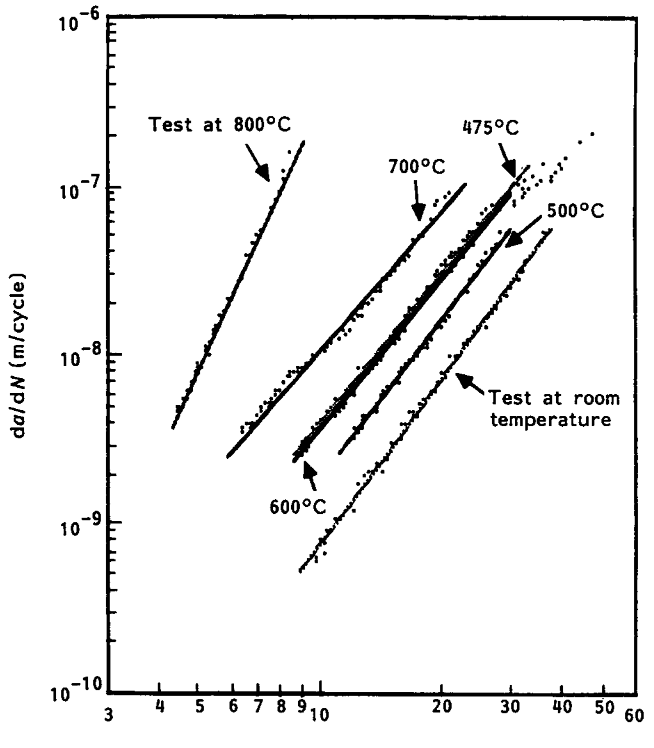

Fig. 2 Mid-range fatigue crack-growth rates with alternating stress intensity factor for 18%Cr–Nb ferritic stainless steel at room temperature, 475, 500, 600, 700 and 800°C; $R = 0.1$, $f = 15$ Hz

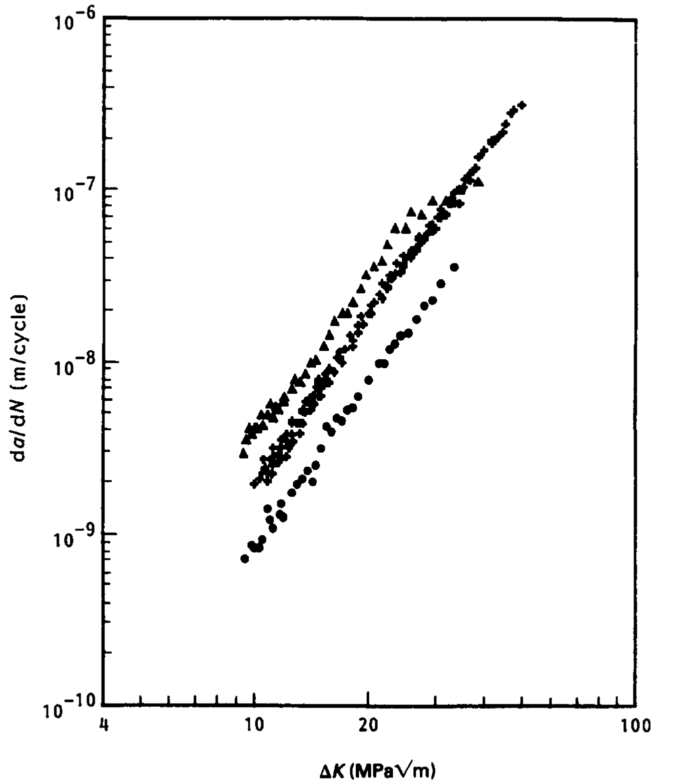

Fig. 3 Fatigue crack propagation data on specimens in the as-received condition and tested at room temperature (●) aged for 20 h at 475 °C and tested at room temperature (+), and as-received and tested at 475 °C (▲). All tests were at $R = 0.1$ and $f = 15$ Hz

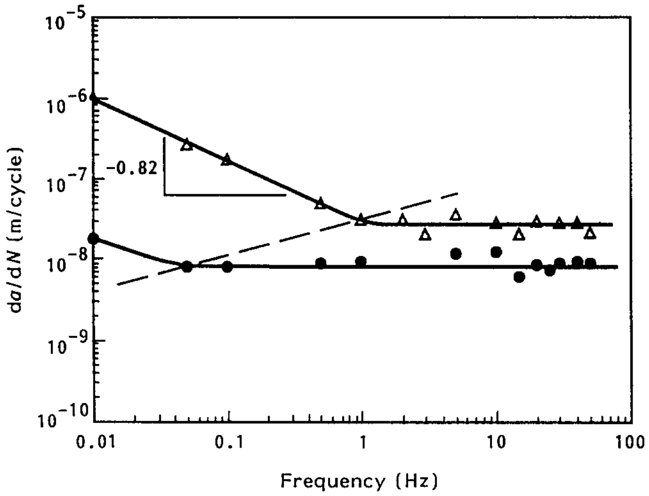

Fig. 4 Fatigue crack propagation rates d*a*/d*N* as a function of frequency at (●) 500 and (△) 655 °C, constant K_{max} = 16 MPa√m and constant R = 0.1

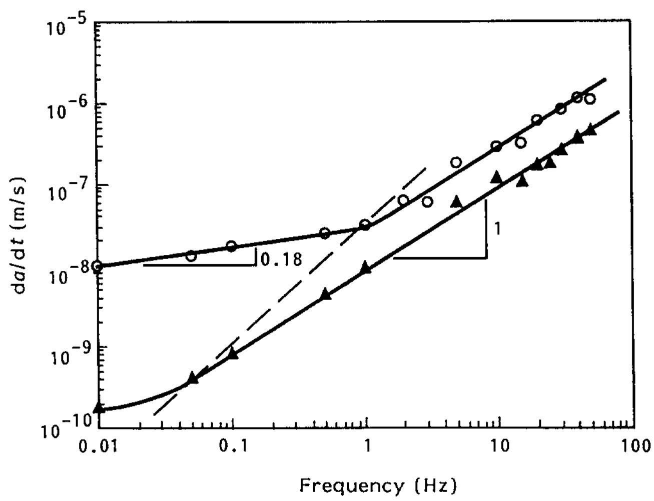

Fig. 5 Fatigue crack propagation rates d*a*/d*t* as a function of frequency at (▲) 500 and (○) 655 °C, constant K_{max} = 16 MPa√m and constant R = 0.1

At frequencies higher than f_c, log d*a*/d*t* is proportional to log *f*, reinforcing the fact that in this regime, growth rates are time-independent. Below f_c, d*a*/d*t* varies as $f^{0.18}$, indicating that fatigue crack growth at these lower frequencies is partially time-dependent. Note that a pure time-dependence requires an exponent of unity. Aside from the observed temperature-dependence of the transition frequency, the influence of frequency on crack growth rate was reasonably independent of temperature for the two temperatures examined.

Crack growth mechanisms

The fracture surfaces of specimens fatigued at room temperature, 475 °C and at 500 °C were examined using scanning electron microscopy. Fracture surfaces were examined at low (near-threshold), intermediate and high ΔK levels. Fatigue fracture morphology is shown in Fig. 6 for near-threshold behaviour at room temperature and 500 °C. At near-threshold, crack growth proceeds along nearly parallel transgranular facets similar to the near-threshold behavior found in other systems.[13–15] No evidence of fatigue striations is observed at ΔK levels near threshold. It should be noted that visible

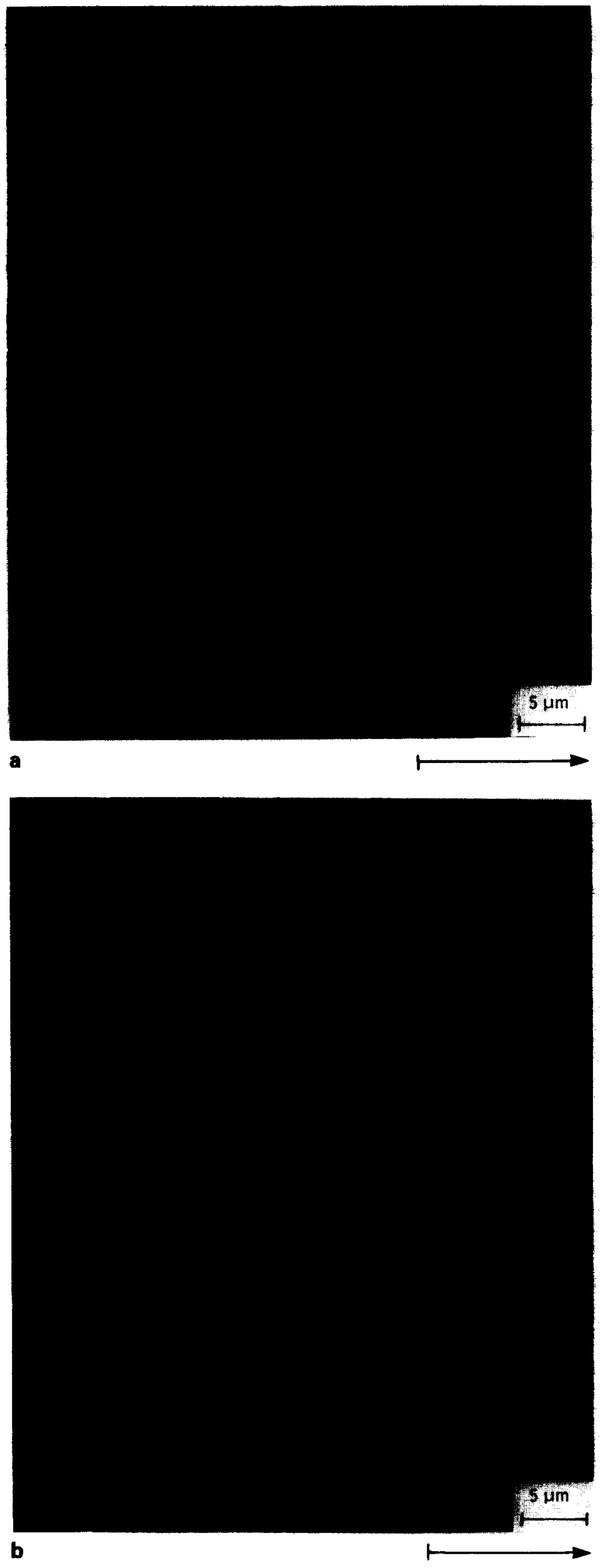

Fig. 6 Fatigue crack propagation morphology at $\Delta K = \Delta K_{th}$, R 0.3 and f = 15 Hz: (a) room temperature; (b) 500 °C. Arrow indicates direction of fatigue crack growth

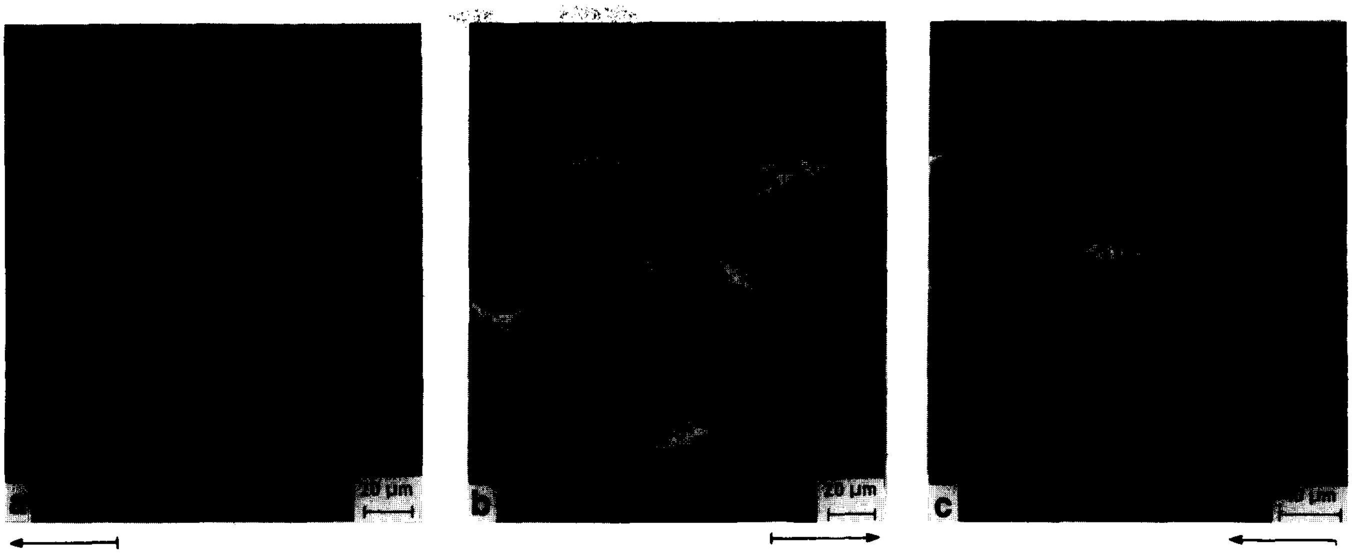

Fig. 7 Fatigue crack propagation morphology at intermediate ΔK level, $R = 0.1$ and $f = 15$ Hz: (a) room temperature and $\Delta K = 16$ MPa√m; (b) 500 °C and $\Delta K = 13$ MPa√m; (c) room temperature on sample aged at 475 °C for 30 h and tested at room temperature, $\Delta K =$ AMPa√m

evidence of oxidation of the fatigue fracture surface can be observed for the near-threshold condition at 500 °C while no evidence of oxidation is seen at 500 °C for the high ΔK fatigue surfaces. This is to be expected given the longer exposure of the fatigue surfaces produced under near-threshold conditions.

Interestingly, at intermediate ΔK levels fatigue crack growth occurred by a combination of intergranular and transgranular mechanisms at both room temperature and 500 °C. Additionally, room-temperature crack growth of the embrittled specimen at intermediate ΔK levels produced the same mixed-mode behaviour. At room temperature (Fig. 7(a)) the area fraction of intergranular fracture is approximately 14% and little variation in the area fraction of intergranular fracture is observed for the other conditions investigated. Fatigue crack propagation at high ΔK occurred by ductile processes and the fracture surface consisted entirely of fatigue striations for all test conditions examined, as can be seen in Fig. 8.

Discussion

Effects of temperature

Near-threshold fatigue crack growth rates increased and ΔK_{th} decreased with increasing test temperature as illustrated in Fig. 1. A detailed analysis of the effects of temperature on near-threshold fatigue crack growth and ΔK_{th} has been reported in previous studies[2,16] which also included a study of the crossover behaviour observed between the room temperature and 500 °C fatigue data shown in Fig. 1. It was concluded in these studies that the crossover behaviour was caused by plasticity-induced crack closure whereas at temperatures higher than 500 °C, greater crack-tip openings caused ΔK_{th} to decrease with increasing temperature.

In the mid-range crack growth regime, fatigue crack growth rates at 15 Hz and R ratio of 0.1 are shown here to increase considerably with increasing temperature from room temperature to 800 °C at all levels of ΔK as shown in Fig.

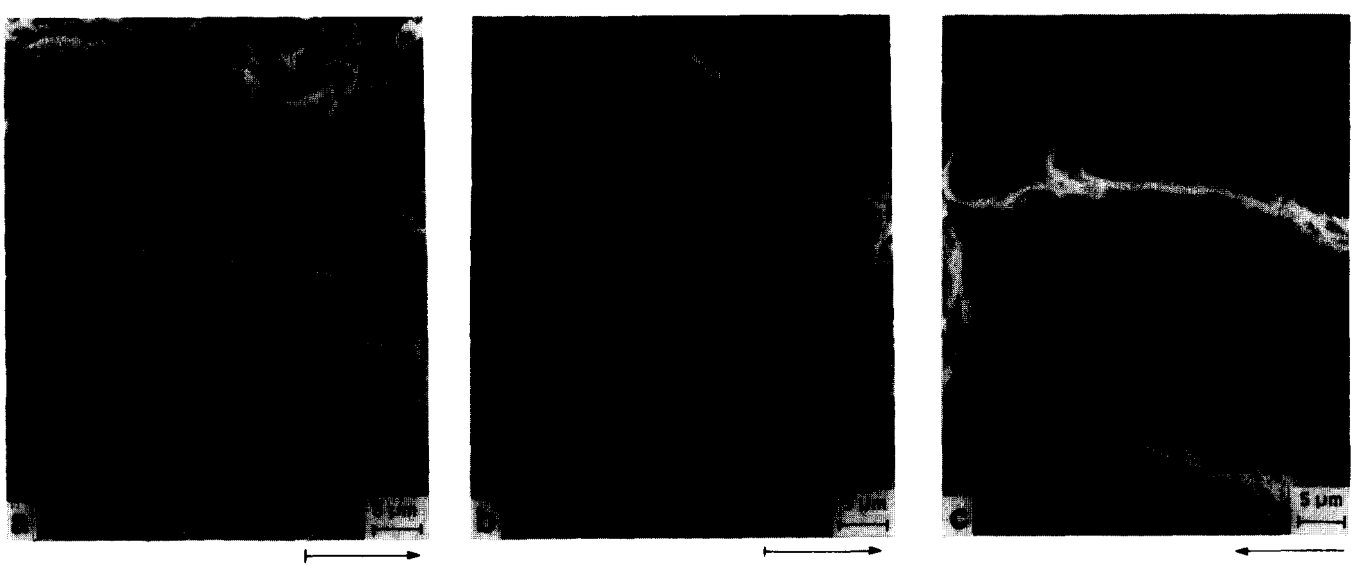

Fig. 8 Fatigue crack propagation morphology at high ΔK level, and $f = 15$ Hz: (a) room temperature at $\Delta K = 30$ MP√m and $R = 0.3$; (b) 500 °C at $\Delta K = 30$ MPa√m and $R = 0.3$; (c) 475 °C at $\Delta K = 35$ MPa√m and $R = 0.1$

2, with the exception of anomalously high growth rates at 475 °C.

The increase of mid-range growth rates with temperature, at least at high frequencies, is more probably caused by oxygen penetration at the crack tip,[17–20] rather than by creep.[21] Although no other high-temperature crack growth studies on the current alloy system are available in the literature, insight into the likely causes of the temperature dependence observed can be inferred from work in other systems. In their investigation of fatigue crack propagation behaviour in Inconel 718 at elevated temperature, Smith *et al*[19] suggested that oxygen acts to reduce the alloy ductility through inhibition of planar slip and through the reduction of grain boundary ductility. Moreover, Cotterill and Knott[22] have shown that oxygen acts to form oxides that cause irreversibility of slip and hence enhance growth rates at high temperature. Shahinian *et al*[23] have related the increase of mid-range growth rates with temperature in Inconel 718 to a decrease in the magnitude of the elastic modulus E with increasing temperature. They found that growth rates could be unified if plotted as a function of ΔK normalized with respect to E. Similar observations have been made in austenitic stainless steels in the temperature range 25–593 °C.[24]

In this material, at the temperatures of 500, 600 and 700 °C, the fatigue crack growth rates increased with temperature and Paris power law behaviour was maintained. The slopes for these three curves are roughly the same, averaging 2.6. However, the fatigue crack growth data at 800 °C exhibited a slope of 5.1, which is much higher than the common slope for the other temperatures, indicating that the crack growth mechanism involved at 800 °C may be different from that dominated at 500, 600 and 700 °C. In the Paris regime, fatigue crack growth rates can often be described by a thermally activated process[21,22,25] and for a given ΔK level the temperature dependence of crack growth rate can be expressed as:

$$\frac{da}{dN} = C(\Delta K)^n \exp\left[-\left(\frac{Q}{RT}\right)\right] \quad (1)$$

where Q is the activation energy, R is the gas constant, T is the absolute temperature, and C and n are constants, $C = 9.5\ 10^{-9}$ m/cycle and $n = 2.6$.

In Fig. 9 the crack growth rates at ΔK levels of 12.2 and 16 MPa$\sqrt{\text{m}}$ are plotted as a function of $1/T$. From these

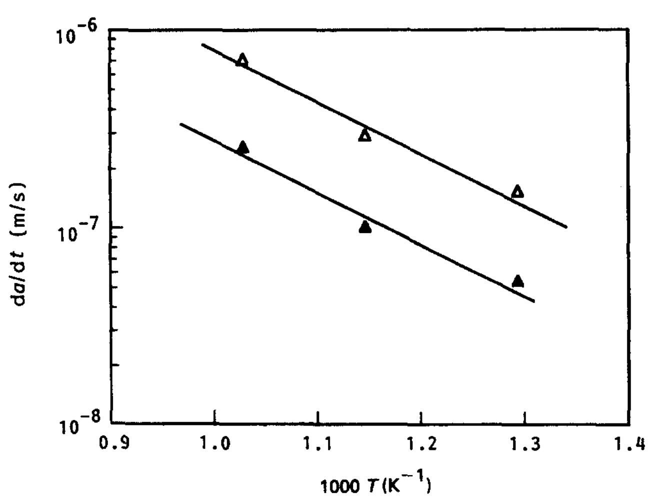

Fig. 9 Fatigue crack growth rates as a function of reciprocal of the test temperature at ΔK = 12.2 and 16 MPa$\sqrt{\text{m}}$, R = 0.1 and f = 15 Hz, Q = 48 kJ/mole

plots an activation energy of approximately 48 kJ/mole was determined. The calculated activation energy is much lower than the activation energy reported for the oxidation of iron where a parabolic rate constant is expected. In the temperature range of 400–600 °C, Davis *et al*[26] reported a value of 190 kJ/mole and Paidassi *et al*[27] reported a value of 153 kJ/mole. Additionally, Bernard[28] measured a value for the activation energy of 190 kJ/mole for oxidation of iron for temperatures from 700 to 1250 °C. These values are at least three times higher than the activation energy calculated for fatigue crack growth in this ferritic stainless steel in the present study. Similary, Joblonski *et al*[29] calculated an activation energy for fatigue crack growth in Multimet, an Fe base solid solution strengthened superalloy, in the temperature range 538–871 °C and found it to be approximately 48 kJ/mole. This value, while in remarkable, if somewhat coincidental, agreement with the value measured here, is also much lower than the activation energy for oxidation reported for Ni–Fe–Co superalloys (250 kJ/mole). The low activation energy observed may be associated with oxidation of surfaces that are newly created with each cycle. For example, Skelton *et al*[30] showed that oxidation rates on a fatigued surface were twice as high as those on naturally exposed surfaces under the same environment.

At 800 °C, flow strength is substantially reduced and additional factors such as creep deformation may be responsible for the change in the dependence of crack growth rate on ΔK which is seen at this temperature. It is, however, noteworthy that stable crack growth rates can be measured in quite thin specimens.

Embrittlement effects

Midrange fatigue growth rates at 475 °C, as observed in Fig. 2, were approximately twice as high as the 500 °C growth rates and approximately equal to the growth rates at 600 °C. Additionally, room temperature crack growth rates for specimens aged at 475 °C were equivalent to growth rates at 500 °C in unaged material as shown in Fig. 3. These phenomena appear to be associated with the so-called 475 °C embrittlement commonly observed in ferritic stainless steels described in the introduction and which are known to occur in the present material.[31] To the authors' knowledge, these findings represent the first measurement of the influence of such embrittlement on fatigue crack growth behaviour in ferritic stainless steels and indicate that such phenomena should be taken into account when fatigue crack propagation at intermediate temperatures in ferritic stainless steels is an issue.

Frequency effects on growth rates

At both 500 °C and 655 °C a critical frequency was observed above which crack growth was independent of frequency and below which crack growth depended on frequency. The transition frequency was temperature-dependent and, as expected, decreased with decreasing temperature. Below the ctitical frequencies, creep and environmental interactions which depend on time are presumed to enhance fatigue crack growth rates. The slope of the da/dN vs frequency plot from Fig. 4 was $\alpha = 0.82$, indicating that pure time-dependent behaviour was not achieved for the frequencies studied. Similar transitions in frequency-dependent crack growth are not uncommon.[20,32] For example, Weerasooriya[20] in his examination of fatigue crack growth behaviour in Inconel 718 at 650 °C using a triangular waveform over six decades of frequency, observed the same type of transition from frequency-independent to frequency-dependent crack growth.

He also observed a third region at much lower frequencies where purely time-dependent behaviour occurred, *ie* the slope of the da/dN vs frequency plot was −1. In the transition or mixed-mode region between pure cycle-dependent and cycle-independent behaviour a slope of −0.82 was observed.

Matuszyk *et al*[17] have related the increase of growth rates with decreasing frequency to the increased oxidation time available at the crack tip during slower cycling. At high frequency, they suggest that the crack propagation is more rapid than the oxygen-induced embrittlement in the process zone ahead of the crack. This is verified by conducting similar experiments in vacuum in which the environmental interactions are not observed.[17] Moreover, Sadananda *et al*[24] attributed the influence of frequency on high-temperature fatigue crack growth rates to a creep component or a creep–fatigue interaction.

In the present study it was not possible to perform tests in inert environments to separate the effects of creep and environmental attack. However, in the range of temperatures examined (500–700 °C) it is possible to incorporate the effects of temperature and frequency into a general growth-rate relationship for growth rates at intermediate ΔK and frequencies in the frequency-dependent regime as

$$\frac{da}{dN} = C(\Delta K)^n \exp\left(-\frac{Q}{RT}\right)\left(\frac{f}{f_c(T)}\right)^{-\alpha}, \quad f \leq f_c \qquad (2)$$

In this equation, C,n and α are material constants, Q is the activation energy and R is the gas constant. f is the cyclic frequency and $f_c(T)$ is the transition frequency which must be determined for every temperature. In the frequency-independent regime, growth rates can be determined using Equation 1.

Fatigue crack growth mechanisms

In the near-threshold regime, the fracture surfaces of specimens fatigued at room temperature consist primarily of transgranular faceted features as shown in Fig. 6. These features appear to be crystallographic in nature. It is well established that, at near-threshold, the plastic zone size is generally less than the grain size, causing the fatigue crack to propagate by a single shear mechanism with associated mode I and mode II displacement (Forsyth stage I mechanism[33]) which results in faceted fracture surfaces. Moreover, it has been suggested that fatigue cracks propagate by decohesion along active shear bands and that this process leads to faceted fracture morphologies.[13–15] The observation of faceted fracture is consistent with the observations of other investigators.[14,34] It should also be noted that the crystallographic dependence of the crack growth direction produces a serrated or zig-zag fracture path. This fracture morphology correlates well with the roughness-induced crack closure which appears to be prominent at near-threshold levels at room temeprature.[2]

Although these crystallographic features, characteristic of near-threshold fatigue crack growth mechanisms, have not been studied extensively, there is general agreement that these facets correspond to {100} and {110} planes for bcc materials.[35,36] Etch-pits produced by Bailon *et al* on fracture surfaces of Fe–3% Si and mild steel showed that the primary facets generally had {100} and {110} orientation made up of different pair combinations of microfacets corresponding to {110} and {112} slip planes with very fine striation-like markings at the site where the micro-facets meet.[37] These observations indicate that, on a microscopic scale, transgranular fatigue cracking involves decohesion on slip planes in the same manner as in fcc materials.

At high ΔK levels, the crack advances by striation formation as shown in Fig. 8. Fatigue striations indicate a microscopic process of fracture by crack arrest and reinitiation which involves extensive crack tip plasticity. Here the width of each striation represents the increment of crack advance for each loading/unloading cycle.[38] This is not an unexpected finding given the substantial ductility of these materials, especially at elevated temperatures.

However, at intermediate ΔK levels a mixture of crack growth along crystallographic facets and along grain boundaries was observed at both room and elevated temperature. Moreover, the proportion of the intergranular facets is found to increase with ΔK from just above the threshold to a critical ΔK value and then diminish at higher ΔK values in the mid-growth-rate regime. Note that no intergranular fatigue crack growth was observed at the extremes of ΔK. This type of crack growth mechanism had been observed in other materials and it has been suggested that the maximum proportion of the intergranular facets occurs when the cyclic plastic zone size approaches the grain size.[39,40] This mixed-mode fatigue crack growth behaviour is illustrated in Fig. 7 for both room temperature and 500 °C.

Above 500 °C significant oxidation of the fracture surfaces occurred and only limited fractographic studies were conducted because of this. It is noteworthy, however, that samples fatigued at 500 °C exhibited similar fractographic features to those tested at room temperature at all levels of ΔK. Unlike the situation for other materials such as superalloys, no significant change in crack propagation mode was observed at the lower frequencies where higher growth rates occurred. Presumably the increased growth rates at lower frequencies reflect a change in the contribution of environmentally assisted crack growth without an appreciable change in the mechanism of fatigue crack propagation.

Conclusions

1) At a load ratio of 0.1, increasing the test temperature from room temperature to 700 °C resulted in a significant increase of near-threshold crack growth rates and a substantial decrease in ΔK_{th}. At 500 °C, a sharply defined threshold occurred at a ΔK level higher than the room temperature ΔK_{th} resulting in a crossover behaviour.
2) Mid-range growth rates increased significantly with temperature at an R of 0.1 and are believed to be controlled by a crack-tip oxidation process. The associated activation energy for this process was calculated to be 48 kJ/mole in the temperature range 500–700 °C. At 800 °C, creep damage may be the responsible mechanism for the higher slope of growth rates vs ΔK curve.
3) 475 °C embrittlement caused substantial enhancement of fatigue crack growth rates at 475 °C. Moreover, exposure of specimens at 475 °C for 20 h resulted in room-temperature growth rates 2.5 times higher than RT growth rates on specimens in the as-received condition. This indicates the significant effects of embrittlement on room-temperature fatigue properties.
4) At 500 and 655 °C and a load ratio of 0.1, two frequency regimes for fatigue crack growth were observed: a fully cycle-dependent regime above a transition frequency f_c, and a mixed regime below the transition frequency. Increasing the temperature from 500 to 655 °C resulted in a significant increase in the transition frequency from 0.05 to 1 Hz.

5) At room temperature and at 500 °C, faceted crack growth was observed at near-threshold. At high growth rates, the fracture surfaces consisted of fatigue striations, indicating the change in crack growth mechanism from one involving fracture by a single shear mechanism to one involving generalized plastic deformation. At intermediate growth rates, a mixed intergranular-transgranular fiacture mode was observed.

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