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TECHNICAL PAPER

Creep-Fatigue Crack Growth in Power Plant Steels

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Abstract An important consideration in the characterisation of creep-fatigue crack growth rates and the defect assessment of high temperature components is the size of pre-existing or service-induced flaws relative to the dimensions of associated cyclic plastic zones. In particular, long cracks are those whose size exceeds r_p and short cracks are those whose size is less than r_p, and the way in which their propagation is analytically represented can differ depending on the form of loading and the respective contributions of creep and fatigue damage accumulation. Examples are given for a number of power plant steels. There are now published procedures for the assessment of structural integrity in high temperature components subject to creep-fatigue loading, and guidance on how to generate the necessary properties for their implementation, and these are reviewed.

Keywords Creep-fatigue · Crack growth · Steels

List of symbols

a	Crack length
$A(T,\upsilon,t_h)$	Material constant in mid-ΔK fatigue crack growth rate equation
A_{20}	Material constant for 20 °C in mid-ΔK fatigue crack growth rate equation
b	Strain range exponent in short-crack creep-fatigue growth rate equation
B'	Constant in short-crack creep-fatigue crack growth rate equation
C^*	Parameter characterising stress and strain rate fields at tip of crack in material deforming due to creep
da/dN	Total crack growth rate (per cycle)
$(da/dN)_C$	Crack growth rate (per cycle) due to creep
$(da/dN)_F$	Crack growth rate (per cycle) due to fatigue
D_C	Total creep damage fraction
$D(\varepsilon_r)$	Constant in creep crack growth equation
E, E_T, E_{20}	Elastic modulus; Elastic modulus at temperature, T; Elastic modulus at 20 °C
HSFCG	High strain fatigue crack growth
ΔJ	Range of parameter characterising stress and strain fields at tip of crack in material deforming plastically
K, ΔK	Stress intensity factor; Cyclic stress intensity factor
K_c	Critical stress intensity factor (associated with unstable fracture)
K_{max}, K_{min}	Maximum stress intensity factor; Minimum stress intensity factor
ΔK_{eff}	Part of ΔK responsible for crack opening in transients involving a compressive loading component [1]
ΔK_{eq}	Equivalent stress intensity factor [1]
ΔK_{th}	Fatigue crack growth threshold
LEFM	Linear elastic fracture mechanics
LSFCG	Low strain fatigue crack growth
m	Exponent in mid-ΔK fatigue crack growth rate power law
N	Number of cycles
Q	Crack size exponent in short-crack creep-fatigue crack growth rate equation
r_p	Cyclic plastic zone size

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R	Load ratio ($K_{\mathrm{min}}/K_{\mathrm{max}}$)
R_{m}	Ultimate tensile strength
t, t_{h}	Time; Hold time (above the insignificant creep temperature)
t_{max}	Maximum allowable time at temperature
T, T_{ref}	Temperature; Reference temperature
ε, $\Delta\varepsilon$	Strain; Strain range
ε_{r}	Creep rupture ductility
γ	Exponent in C^* creep crack growth equation
$\sigma_{\mathrm{ref,max}}$	Reference stress (maximum in cycle)
υ	Frequency

1 Introduction

Cracks established during component manufacture or service may subsequently propagate during high temperature duty as a consequence of the combined effects of cyclic and creep loading. The operating conditions responsible for crack growth at high temperatures are diverse, ranging from predominantly cyclic to mainly steady loading with infrequent off-load transients. The fatigue component of crack extension may be a consequence of high frequency (time independent) or low frequency (time dependent) transients, applied in either stress or strain control. Moreover, cyclic loading can be linear-elastic, elastic–plastic or highly plastic. The creep component of cracking may be the result of primary (directly applied) and/or secondary (self-equilibrating) loading. As a consequence of the very diverse conditions which can be responsible for crack propagation at high temperatures, the assessment of structural integrity is currently covered by more than one approach, each with its own material property input data requirements (e.g. Table 1). These are reviewed in the following paper.

An important consideration in the characterisation of creep-fatigue crack growth rates and the assessment of high temperature structures is the size of the crack relative to the size of the associated cyclic plastic zone at the surface of the component. In the following review, long cracks are those whose size exceeds r_{p}, and short cracks are those whose size is less than r_{p}.

2 Long Crack Growth

2.1 General

Cyclic crack growth is conventionally considered in terms of three regimes (Fig. 1). These are: (i) a low-ΔK regime close to the fatigue crack growth threshold, ΔK_{th}, (ii) a mid-ΔK regime in which propagation rates are modelled by a power law (Eq. 1), and (iii) a high-ΔK regime in which K_{max} approaches K_{c} (and/or $\sigma_{\mathrm{ref,max}}$ approaches R_{m}).

$$\mathrm{d}a/\mathrm{d}N = A(T, \upsilon, t_{\mathrm{h}}) \cdot (\Delta K)^{m} \tag{1}$$

In Eq. (1), $A(T, \upsilon, t_{\mathrm{h}})$ and m are material constants dependent on temperature, environment, frequency (below a limiting value) and hold time (above the insignificant creep temperature). ΔK_{eff} may substitute for ΔK.

At low-ΔK levels close to ΔK_{th}, the magnitude of da/dN is very sensitive to small increases in ΔK and dependent on the same factors which influence ΔK_{th}, these being: material, microstructure and yield strength, temperature, environment and load ratio (R). Propagation rates in the mid-ΔK regime are less sensitive to microstructure and mean stress (R) effects. In the high-ΔK regime, da/dN becomes increasingly sensitive to the level of ΔK and, in particular K_{max} (and/or $\sigma_{\mathrm{ref,max}}$) as K_{c} (and/or plastic collapse) is approached [3]. Depending on the deformation and fracture characteristics of the material, high-ΔK crack growth rates can be strongly influenced by size and geometry. In these circumstances, a simple LEFM defined ΔK is not the most effective correlating parameter and alternative energy based cyclic loading parameters such as ΔJ or ΔK_{eq} are employed in Eq. (1) [1, 4]. In addition to the factors already mentioned, da/dN in the high-ΔK regime is strongly dependent on microstructure, mean stress, temperature, environment and frequency (strain rate).

At elevated temperatures, the da/dN(ΔK) diagram may be alternatively split into two crack growth regimes (Fig. 1). In the low strain fatigue crack growth (LSFCG) regime, stress/strain transients result in linear elastic loading cycles and low to mid-ΔK crack growth rates for which ΔK (or ΔK_{eff}) still provides the most appropriate correlating parameter. Stress/strain transients responsible for cyclic loading involving a degree of general yield (in particular in tension) are referred to as high strain fatigue

Table 1 Data requirements for the assessment of crack growth at high temperatures

	Higher frequencies/stress control	Lower frequencies/strain control
Short crack growth ($a < r_{\mathrm{p}}$)	$\mathrm{d}a/\mathrm{d}N(\Delta J, R, T, \upsilon, t_{\mathrm{h}})$	$\mathrm{d}a/\mathrm{d}N(\Delta\varepsilon, T, \upsilon, t_{\mathrm{h}})$
Long crack growth ($a > r_{\mathrm{p}}$)	$\mathrm{d}a/\mathrm{d}N(\Delta K_{\mathrm{eff}}, R, T, \upsilon, t_{\mathrm{h}}) + \mathrm{d}a/\mathrm{d}t(C^*, T)/\upsilon$; $\Delta K_{\mathrm{th}}(R, T, \upsilon, t_{\mathrm{h}})$	$\mathrm{d}a/\mathrm{d}N(\Delta K_{\mathrm{eq}}, T, \upsilon, t_{\mathrm{h}}) + \mathrm{d}a/\mathrm{d}t(C^*, T)/\upsilon$

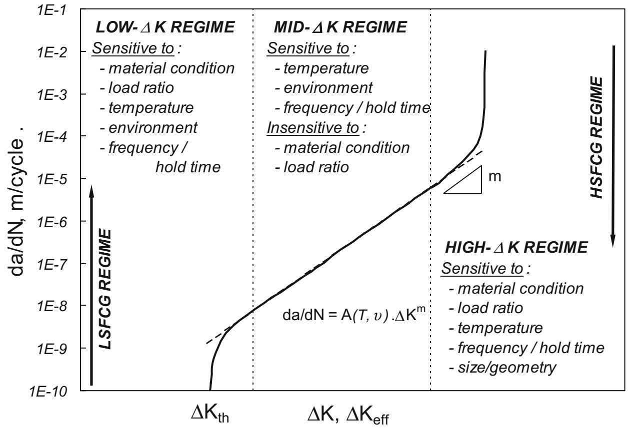

Fig. 1 Cyclic crack growth rate regimes [2]

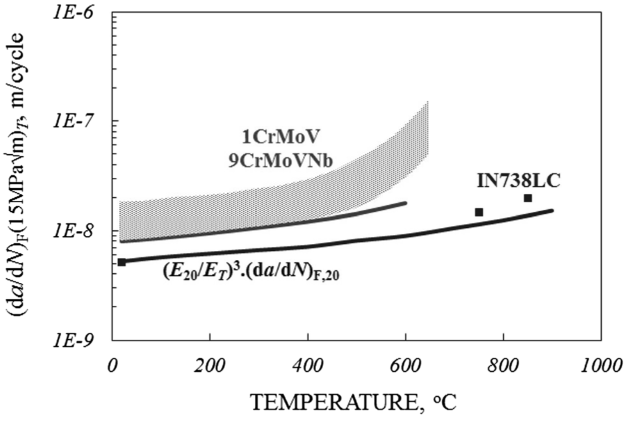

Fig. 2 Effect of temperature on high frequency cyclic crack growth rate [5]

crack growth (HSFCG) cycles. HSFCG rates are due to apparent ΔKs and are influenced by whether deformation is stress or strain controlled, in particular in the material's creep regime. The overlap shown between the LSFCG and HSFCG regimes in Fig. 1 is due to the fact that higher ΔKs can be generated under linear elastic conditions with strain controlled loading because of shakedown into compression.

Fatigue crack growth rates are increasingly sensitive to frequency with increasing temperature.

2.2 High Frequency

At loading frequencies above those for which time dependent effects are influential (i.e. at elevated temperatures where oxidation is not responsible for significant crack tip oxide-wedging and/or creep damage enhancement), the factors affecting $\mathrm{d}a/\mathrm{d}N(\Delta K)$ behaviour are summarised in the previous section. For such conditions, the effect of temperature may be quantified in the mid-ΔK regime by rewriting Eq. (1) to give:

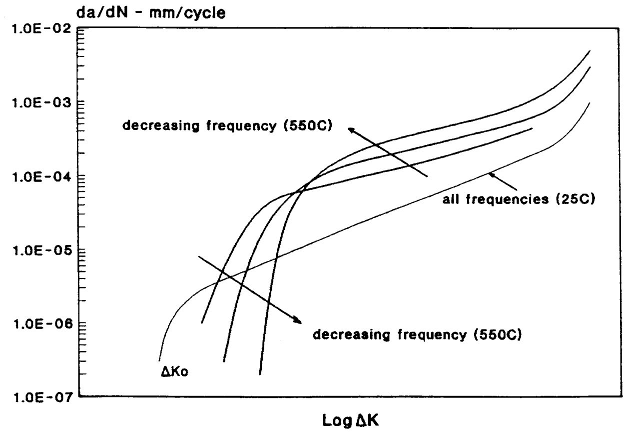

Fig. 3 Effect of frequency on high temperature LSFCG rates in 1CrMoV steel [6]

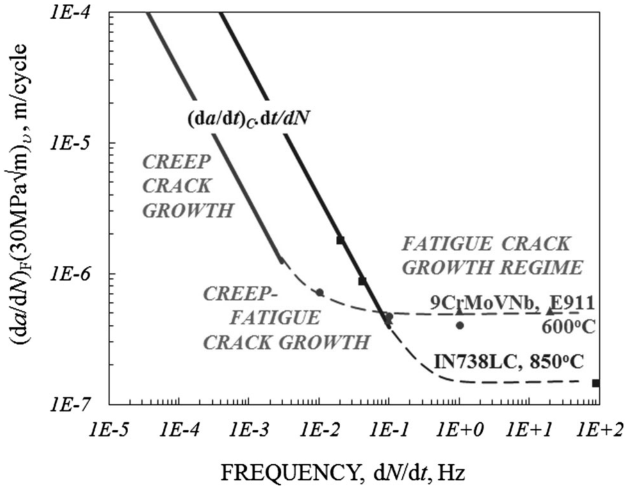

Fig. 4 Effect of frequency on high temperature LSFCG rates in various alloys [5]

$$\mathrm{d}a/\mathrm{d}N = A_{20}(E_T/E_{20})^m \cdot (\Delta K)^m \tag{2}$$

where A_{20} is equal to $A(T,\upsilon)$ at ambient temperature in Eq. (1). The effectiveness of this approximation is shown in Fig. 2 for a number of high temperature materials [5]. It is clear that even at relatively high frequencies, there is a temperature (dependent on material) above which $\mathrm{d}a/\mathrm{d}N$ becomes increasingly influenced by time dependent thermally activated processes. As for Eq. (1), ΔK_{eff} may substitute for ΔK.

2.3 Low Frequency

At lower frequencies, oxidation and creep interaction effects become increasingly more influential at high temperatures (e.g. Fig. 3). In stress control, below a limiting frequency, crack growth rates may be regarded as being

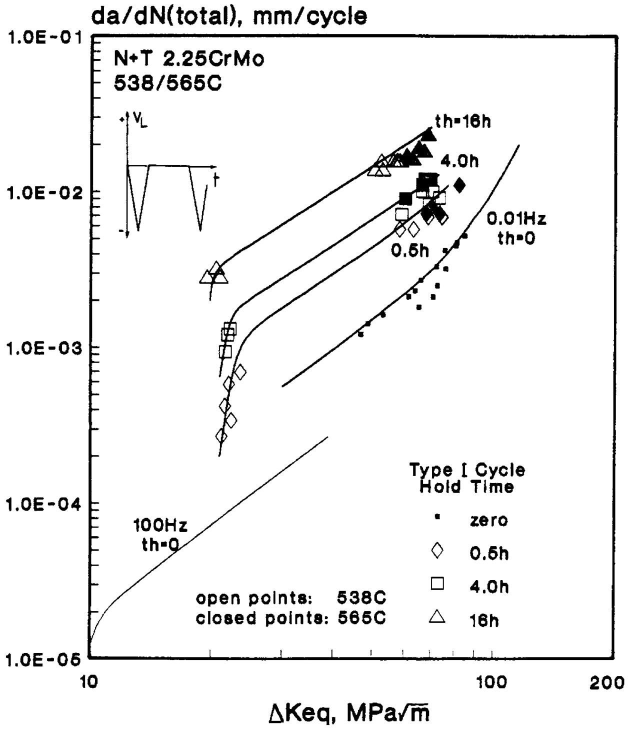

Fig. 5 Long crack cyclic/hold creep-fatigue crack growth test data for 2¼CrMo cast turbine steel at 538/565 °C [1]

dominated by time dependent crack growth mechanisms (e.g. creep crack growth in Fig. 4). The high temperature behaviour shown in Fig. 4 is typical for many engineering alloys subject to stress controlled cycling in the mid-ΔK regime.

In contrast, crack growth rates in the low-ΔK regime can reduce and ΔK_{th} values increase with decreasing frequency due to oxide induced crack closure (Fig. 3).

At high temperatures, the high growth rates associated with the high-ΔK or HSFCG regimes (Fig. 1) can be generated either as a consequence of relatively high magnitude cyclic loading applied remotely to a long crack (e.g. [1]), or (more usually at an initial stage of thermal fatigue crack development) as high strain transients applied locally to a small crack contained in a cyclic plastic strain field (e.g. [7], see Sect. 3). In the former case, cyclic crack growth rate behaviour is modelled using a modified form of Eq. (1), e.g.

$$\mathrm{d}a/\mathrm{d}N = A(T, \upsilon, t_{\mathrm{h}}) \cdot \left(\Delta K_{\mathrm{eq}}\right)^{m} \quad (3)$$

where ΔK_{eq} is ΔK_{eff} for purely elastic loading. Acknowledgement of the dependence of A on hold time reflects the dependence of this parameter on associated oxidation as well as creep damage [1].

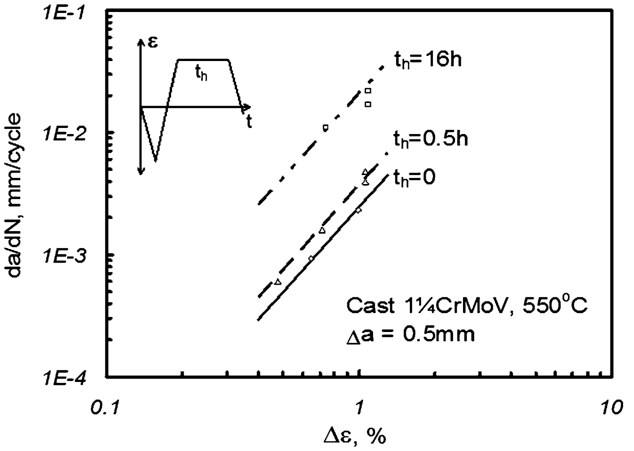

Fig. 6 Comparison of crack growth rates after 0.5 mm crack extension from notch root in large SENB feature specimen creep-fatigue tests on cast 1¼CrMoV steel at 550 °C [7]

The high temperature crack growth properties required for the defect assessment of components subject to fatigue cycles involving hold (steady operating) periods may be derived from pure fatigue and pure creep crack growth rate data in a construction of the form given in Fig. 4 when the loading is directly applied (i.e. load controlled). In such circumstances, the effective frequency may be simply determined from a knowledge of the total cycle time (i.e. transient + hold time). Alternatively, creep-fatigue crack growth behaviour is analytically modelled on the basis of fatigue and creep crack growth rate characteristics for the material, i.e.

$$(\mathrm{d}a/\mathrm{d}N)_{\mathrm{total}} = (\mathrm{d}a/\mathrm{d}N)_{\mathrm{F}} + (\mathrm{d}a/\mathrm{d}N)_{\mathrm{C}} \quad (4)$$

In Eq. (4), $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{F}}$ is given by Eq. (3), where $A(T, \upsilon, t_{\mathrm{h}})$ may be influenced by creep and oxidation damage through its dependence on frequency and prior hold time [1] and $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{C}}$ is given by Eq. (5).

$$(\mathrm{d}a/\mathrm{d}N)_{\mathrm{C}} = \left(\int_{0}^{t_{\mathrm{h}}} D(\varepsilon_{\mathrm{r}}) \cdot (C*)^{\gamma} \cdot \mathrm{d}t\right) \Big/ \upsilon \quad (5)$$

Any enhancement of the total growth rate per cycle due to a creep-fatigue-oxidation interaction is covered by $A(T, \upsilon, t_{\mathrm{h}})$ which is determined experimentally (e.g. Fig. 5).

3 Short Crack Growth

The HSFCG rates associated with small cracks contained in local cyclic plastic strain fields (typically $a \leq 5$ mm) are most effectively modelled as a function of $\Delta\varepsilon$ [7–12] (e.g. Fig. 6), i.e.

$$\mathrm{d}a/\mathrm{d}N = B' \cdot a^{b} \cdot (\Delta\varepsilon)^{q} \; \mathrm{d}a/\mathrm{d}N = B' \cdot a^{Q} \cdot (\Delta\varepsilon)^{b} \quad (6a)$$

although other correlating parameters may be employed [12]. For relatively short cracks contained in high cyclic plastic strain fields, $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{total}}$ is effectively modelled using a refinement of Eq. (6a) for a range of power plant steels [7, 10–12], i.e.

$$(\mathrm{d}a/\mathrm{d}N)_{\text{total}} = B' \cdot a^{Q} \cdot (\Delta\varepsilon)^{b} \cdot (1 - D_C)^{-2} \qquad (6b)$$

Typically, in Eq. (6), Q = 1 [13]. The effect of hold time on HSFCG rate for a cast 1¼CrMoV steel at 550 °C is shown in Fig. 6. In this example, D_C was modelled empirically as a function of hold time (see also [11]), although in a formal assessment it would be determined in terms of ductility exhaustion [14].

For advanced 9/11 % Cr martensitic steels, which are more prone to creep-fatigue deformation interactions, D_C may be replaced by a microstructural (deformation) condition parameter [15].

It is evident that the material property data required for the defect assessment of high temperature components subject to creep-fatigue loading can be strongly dependent on the specific operating conditions relating to the practical application under consideration. This means that the rigorous creep-fatigue defect assessment of a component can require a significant investment in the determination of appropriate material property data. It is therefore important to demonstrate that both creep and fatigue loading are significant at the critical feature to be assessed.

4 Defect Assessment

A creep-fatigue crack growth assessment is only necessary when both creep and faigue are shown to be significant [3, 14].

As a generality, creep is regarded as being significant if, for the total number of cycles, the sum of the ratios of hold time to the maximum allowable time at the temperature of interest is greater than or equal to unity, i.e.

$$\sum_{j=1}^{N} [t_h / t_{\max}(T_{\text{ref}})]_j \geq 1 \qquad (7)$$

Values of $t_{\max}$ depend on material crack size and temperature [3]. For materials with $\varepsilon_r \geq 10$ %, $t_{\max}$ is taken to be the time required to achieve an accumulated creep strain of 0.2 % at a stress level equal to the reference stress. Alternatively for $\varepsilon_r < 10$ %, $t_{\max}$ is determined on the basis of an accumulated creep strain of 0.2 ε_r.

Fatigue is regarded as being significant if cyclic loading influences the development of creep damage. This is likely if the elastic range exceeds the sum of the steady state creep stress and the stress to cause yield at the other extreme of the cycle [14]. Fatigue is also considered significant if the estimated crack growth due to cyclic loading exceeds 10 % of the calculated creep crack growth.

When both creep and cyclic loading are shown to be significant, the extent of creep-fatigue interaction should be determined [3, 14]. As a generality, the effect of creep damage on fatigue crack growth rates has little influence on the total crack growth per cycle provided the latter includes an explicit calculation of creep crack growth (i.e. Eq. 4). In such circumstances, there is no creep-fatigue interaction and no requirement to enhance creep-fatigue crack growth rates. It is only necessary to consider a creep-fatigue interaction when the effect of cyclic loading on creep is shown to be significant despite fatigue crack growth rate having been estimated to be only a small fraction of the total crack growth rate per cycle. For such conditions, the constants in Eq. (3) should be determined from tests with hold times relevant to the service application being assessed (e.g. Fig. 5).

Similarly, in cases where cracks are propagated by fatigue through material heavily damaged by prior creep, propagation rates are likely to be increased. In these circumstances, a factor should be applied to the fatigue crack growth constant to account for the amount of prior creep damage. This should be determined experimentally [3].

5 Concluding Remarks

The crack growth rate data used for the defect assessment of high temperature structures has been reviewed with reference to examples for a number of power plant steels.

The material property parameters necessary for the defect assessment of such components subject to creep-fatigue loading can be strongly dependent on the specific operating conditions relating to the practical application under consideration. The rigorous creep-fatigue defect assessment of a component can therefore require a significant investment in the determination of appropriate material property data.

References

1. Holdsworth S R, *Behaviour of Defects at High Temperatures*, ESIS-15, (eds) Ainsworth R A, Skelton R P, MEP, London (1993), p. 327.
2. Holdsworth S R, *High Temperature Crack Growth in Steam Turbine Materials*, (ed) Marriott J B, CEC COST Monograph EUR 14678EN (1994), p. 129.
3. BS-7910, *Guidance on Methods for Assessing the Acceptability of Flaws in Metallic Structures*, British Standards Institution (2013).
4. Dowling N E, *ASTM STP* **637** (1977) 97.
5. Holdsworth S R, *Materials for High Temperature Power Generation and Process Plant Applications*, (ed.) Strang A, IOM (2000), p. 177.
6. Skelton R P, Haigh J R, *Mat Sci Engng* **36** (1978) 133.
7. Holdsworth S R, *Mater High Temp* **15** (1998) 111.

8. Skelton R P, *Low Cycle Fatigue and Life Prediction*, ASTM STP 770, ASTM Philadelphia (1982), p. 337.
9. Levaillant C, Pineau A, *Behaviour of Defects at High Temperatures*, ESIS-15, (eds) Ainsworth R A, Skelton R P, MEP, London (1982), p. 169.
10. Skelton R P, *Low Cycle Fatigue*, ASTM STP 942, ASTM (1988), p. 209.
11. Skelton R P, *Behaviour of Defects at High Temperatures*, ESIS-15, (eds) Ainsworth R A, Skelton R P, MEP, London (1993), p. 191.
12. Yan W, Holdsworth S R, Kühn I, Mazza E, *Mater High Temp* **31** (2014) 305.
13. Holdsworth S R, Skelton R P, Dogan B, *Mater High Temp* **27** (2010) 265.
14. R5 Panel, *An Assessment Procedure for the High Temperature Response of Structures*, Revision 3 (as amended), EDF Energy Nuclear Engineering, Gloucester, UK (2003).
15. Yan W, *Creep Fatigue Crack Growth in Advanced Turbine Steels*, Ph.D. Dissertation, ETH Zürich (2015).