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INFLUENCE OF MATERIAL CHARACTERISTICS ON EFFECTIVE LOAD RATIOS AT ELEVATED TEMPERATURES

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ABSTRACT

An important consideration in the assessment of defect integrity for structures subjected to cyclic loading is a knowledge of crack opening and closure stresses, and thereby the effective stress range responsible for crack development. The published guidance for high temperature power plant components subjected to negative R loading does not always acknowledge that the relationship between opening/closure stress and minimum to maximum stress ratio (R) can be influenced by material characteristics, in particular when the minimum stress is in compression (i.e. the negative R regime). The paper examines new results for advanced martensitic 9/10%Cr steels at 600-625°C with reference to existing evidence for low alloy ferritic CrMo(V) power plant steels at 538-565°C, and to alternative crack opening stress range solutions.

INTRODUCTION

For cyclic stress intensity factors (ΔKs) above the fatigue crack growth threshold and below the critical value for unstable fracture, in the mid-ΔK regime, fatigue crack growth rates may be correlated in terms of ΔK_{eff}, Paris (1963).

$$\mathrm{d}a/\mathrm{d}N = A(\Delta K_{\mathrm{eff}})^m \tag{1}$$

where

$$\Delta K_{\mathrm{eff}} = q_{\mathrm{o}} \Delta K \tag{2}$$

and where $\Delta K = K_{\max} - K_{\min}$. and q_{o} is the fraction of ΔK or the total stress range ($\Delta\sigma$) for which the crack is judged to be open during fatigue loading, i.e. $(K_{\max} - K_{\mathrm{o}})/\Delta K$ or $(\sigma_{\max} - \sigma_{\mathrm{o}})/\Delta\sigma$. In practice, the effective stress range depends on alloy strength, grain structure, crack morphology, loading conditions and environment, Kemp (1990), and so it is unlikely that there can be a universal $q_{\mathrm{o}}(R)$ relationship for all engineering materials, in particular when part of the stress range is in compression, i.e. when $R < 0$ (where $R = \sigma_{\min}/\sigma_{\max}$). The adopted stress terminology is given in Figure 1.

Published high temperature defect assessment guidance (R5) indicates that q_{o} may conservatively be estimated from:

$$\begin{aligned} q_{\mathrm{o}} &= 1 && \text{for } R \geq 0 \\ q_{\mathrm{o}} &= (1 - 0.5R)/(1 - R) && \text{for } R < 0 \end{aligned} \tag{3}$$

where this relationship is mainly based on evidence for low alloy ferritic steels, and assumes that the crack is open for all the tensile part and half the compressive part of the applied load (ΔK) range, Holdsworth (1993), Skelton (1993). As will be seen, there is evidence to indicate that this relationship can be excessively conservative at low negative R values for some alloys, e.g. the advanced martensitic rotor steels, and for such materials an alternative formulation such as that of Newman (1984) can be more appropriate, i.e.

$$q_o = (1 - f)/(1 - R) \tag{4}$$

where

$$f = \max(R; A_0 + A_1R + A_2R^2 + A_3R^3) \quad \text{for } R \geq 0$$
$$f = A_0 + A_1R \quad \text{for } -2 \leq R < 0$$
$$f = A_0 - 2A_1 \quad \text{for } R < -2$$

and where

$$A_0 = (0.825 - 0.34\alpha + 0.05\alpha^2).[\cos(\pi.\sigma_{max}/2R_F)]^{-1/\alpha} \tag{5}$$
$$A_1 = (0.415 - 0.071\alpha)(\sigma_{max}/R_F)$$
$$A_2 = 1 - A_0 - A_1 - A_3$$
$$A_3 = 2A_0 + A_1 - 1$$

with α and σ_{max}/R_F often being considered as fitting parameters which are typically determined empirically, ideally in tests involving representative component/operation conditions (e.g. the large bend specimen configuration adopted in Holdsworth (1993)). The effectiveness of the adopted $q_o(R)$ formulations should be verified for each material class to avoid excessive conservatism.

It should be acknowledged that α and σ_{max}/R_F were not originally intended to be determined empirically with, for example, α reflecting deformation condition, being equal to 3 for plain strain deformation and equal to 1 for plane stress deformation, Newman (1984).

Other formulations for $q_o(R)$ (or $q_c(R)$) have been proposed but these are mainly applicable for stress ratios in the positive R regime (or R >-1), e.g. Kemp (1990).

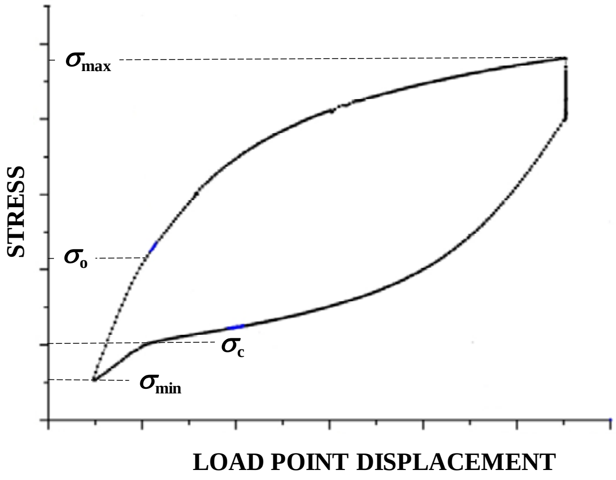

Figure 1. Opening and closure stresses

For some defect assessment applications, it may be appropriate to adopt very conservative $q_o(R)$ values such as those derived from Equation 1. However, for others, it is more important that high temperature component design calculations are safe and reliable, but not excessively conservative. In such circumstances for which commercial interests and component efficiency and performance design requirements are important considerations, it could be necessary to consider alternative $q_o(R)$ solutions.

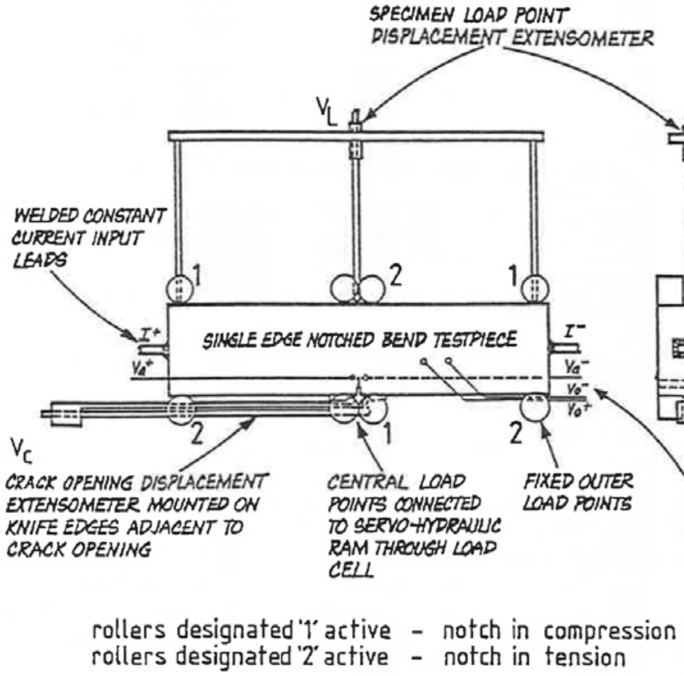

Figure 2. SENB3 testing arrangement adopted in Holdsworth (1993)

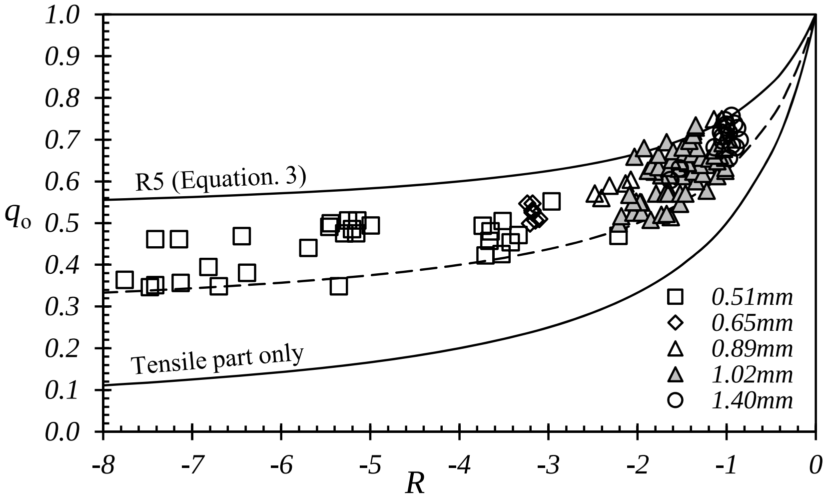

Figure 3. Variation of q_o with R for N+T cast ½Cr½Mo¼V and 2¼CrMo turbine casing steels at 538-565°C, Holdsworth (1993)

Notes: The intermediate broken line relates to cracks open for all the tensile part and one quarter of the compressive part of the stress range. The legend figures refer to the control load point displacement ranges ($2V_L$). All the ±V_L cycles included a 30min hold time at $+V_L$.

LARGE SENB SPECIMEN TESTING (LOW ALLOY FERRITIC STEELS)

The basis for Equation 3 in part originated from high strain fatigue (HSF) with hold time tests conducted on large 75x100mm section fully reverse loaded single edge notched bend (SENB) specimens conducted on N+T cast ½Cr½Mo¼V and 2¼CrMo turbine casing steels at temperatures in the range 538-565°C (Figure 2).

These tests clearly indicated that single edge cracks in CrMo(V) SENB specimens subjected to a displacement-controlled HSF cycle with a 30 minute hold time at peak displacement in tension were open for all of the tensile stress range and up to half of the compressive stress range for negative *R* loading (Equation. 3), Figure 2. The observation was consistent with that for ½Cr½Mo¼V steel at 550°C when examined for a wider range of specimen geometries, Skelton (1993).

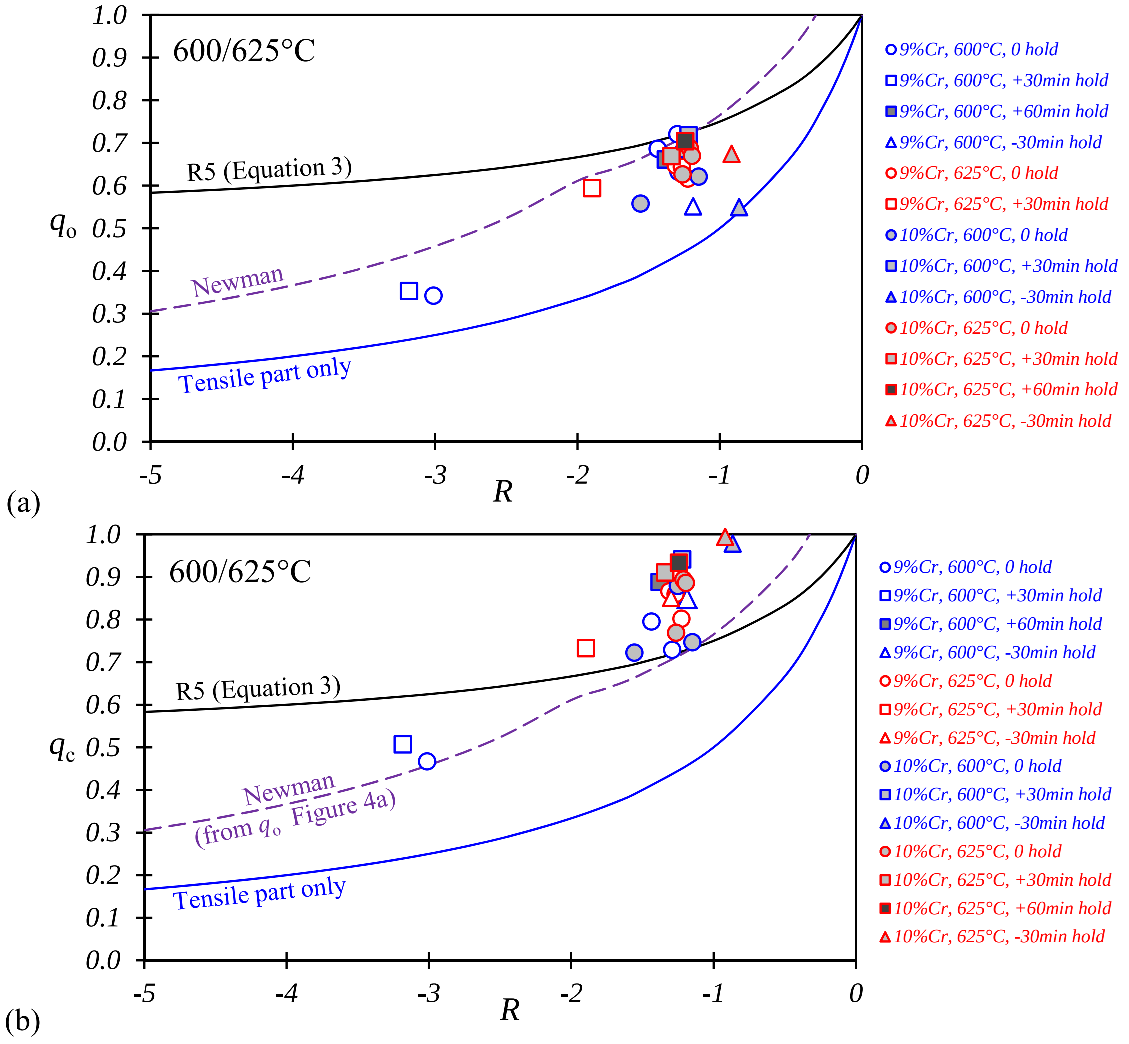

Figure 4. Variation of (a) q_o and (b) q_c with *R* for Q+T 9%Cr and 10%Cr turbine steels at 600/625°C

Notes: Open symbols are for 9%Cr steel, shaded symbols are for 10%Cr steel, blue outlined symbols are for 600°C, red outlined symbols are for 625°C. Applied Newman parameters: α, *3;* σ_{max}/R_F, *2.5*

SHORT CREEP-FATIGUE CRACK GROWTH MEASUREMENTS FOR 9/10%CR STEELS

New observations for advanced martensitic power plant steels originate from short creep-fatigue crack growth tests conducted on 9/10%Cr alloys at 600 and 625°C, in strain-control, using 8mm diameter single edge notched tension (SENT) specimens with initial crack starters which were 0.2mm deep, Yan (2014). The results from these tests indicated that σ_c was typically lower than σ_o, and therefore that q_c was higher than q_o, Figure 4.

Focusing on Figure 4a, the evidence indicates that q_o tends to be lower for the 9/10%Cr steels at 600-625°C than for low alloy ferritic steels at 538-565°C, in particular at low R (i.e. R <~-2).

The data for CrMo(V) steels in Figure 3 were entirely from tests involving a 30 minute hold time at peak load point displacement in tension. The results for the 9/10%Cr steels in Figure 4a indicate that q_o values for cycles involving a 30 minute hold time in compression tend to be lower than those for cycles without and with a hold time in tension.

CRACK CLOSURE

Practical Considerations

Since the concept of crack closure was first introduced by Elber (1970), there have been many studies involving the measurement of crack opening and closure stresses involving techniques such as cross-crack displacement gauging, ultrasonics, electrical potential drop and laser interferometry, as well as the use of crack mouth opening displacement extensometry, Kemp (1990). Despite the sophistication of some of these techniques, care is required in response interpretation because of their respective sensitivities to the influence of local closure relative to global closure. While recognising resolution limitations, the least subjective indicator of global closure is that involving the measurement of crack mouth opening displacement by means of a mechanical device of the type adopted by Holdsworth (1993), Figure 2, and Yan (2014).

Effective Crack Opening Ratio

The evidence suggests that crack opening ratios for the 9/10%Cr steels at 600-625°C can be significantly lower than those for low alloy ferritic steels at 538-565°C for R <~2 (cf. Figures 3 and 4). This should not really be surprising. The main factors influencing $q_o(R)$ at high temperature are plasticity-induced and oxidation-induced closure (where the oxide scale responsible for premature closure is the consequence of environmentally-generated surface degradation at high temperatures). Oxidation-induced closure (due to crack face fretting debris) and crack face roughness-induced closure are also influential, but not to the same level, in the circumstances under consideration.

Plasticity-Induced Closure. The monotonic yield strengths of the low alloy ferritic turbine casing steels covered by Figure 3 (at 538-565°C) are ~200MPa compared with those for the advanced martensitic 9/10%Cr turbine rotor steels of ~450/420-420/370MPa (at 600-625°C). The magnitudes of the cyclic plastic zones and consequent plasticity induced closure components are therefore likely to be significantly lower for the higher strength 9/10%Cr steels. Even assuming cyclic softening ratios of ~0.55 for the 9/10%Cr steels compared with ~0.8 for the CrMo(V) steels, Holdsworth (2014), cyclic plastic zone sizes in 9/10%Cr steels at 600-625°C are estimated to be lower than 0.6 of those for CrMo(V) steels at 538-565°C.

Oxidation-Induced Closure. While for a given high temperature, the oxidation resistance of CrMo(V) steels in air is lower than that of 9/10%Cr steels, the indicated oxidation resistances of the two alloy classes at the respective temperatures of interest in this paper (i.e. 538-565°C and 600-625°C) are apparently nominally the same (cf. the elliptical regions highlighted in Figure 5). In Figure 5, k_p is the parabolic oxide growth rate constant in the expression:

$$x^2 = k_p t \tag{6}$$

where x is the overall oxide thickness and t is the exposure time. In practice, the interpretation of such diagrams should be made with due consideration of the respective oxidation mechanisms (schematically represented as insets in Figure 5). For example, whereas the oxide layer in CrMo(V) steels is broad-front and forms entirely above the original metal surface at temperatures in the range 538-565°C, the oxide layer in 9/10%Cr steels at 600-625°C tends to form in a discontinuous way (as nodules) with components both above and below the original metal surface. For this reason, the contribution to crack face closure of oxide product formation above the original metal surface is in reality lower for 9/10%Cr steels at 600-625°C than for CrMo(V) steels at 538-565°C.

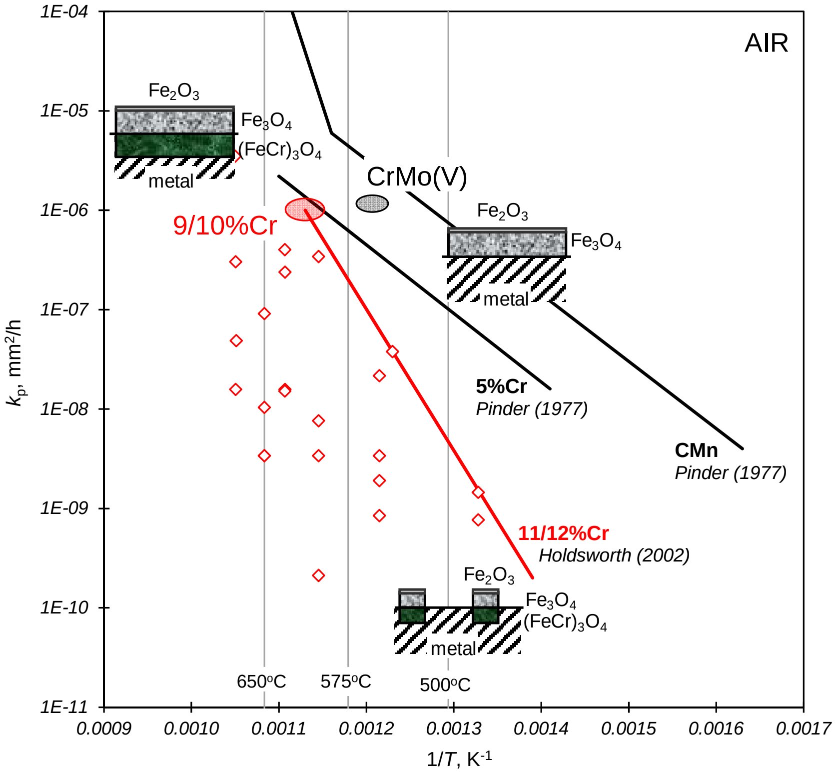

Figure 5. The influence of chromium content on oxidation kinetics for a range of power plant steels in air
Notes: Data lines represent $k_p(T)$ upper-bounds for CMn, 5%Cr and 11/12%Cr steels. Insets indicate oxidation mechanisms for the low and high alloy steels, Holdsworth (2002)

There are therefore good reasons why effective crack opening stress ratio $q_o(R)$ relationships can vary with material and temperature, and why they should be specifically determined to avoid unnecessary levels of conservatism in defect integrity assessment.

CONCLUDING REMARKS

New evidence for the effect of stress ratio (R) on the effective crack opening stress ratio (q_o) for 9/10%Cr steels at 600-625°C has been reviewed with reference to existing results for CrMo(V) steels at 538-565°C to highlight the fact that $q_o(R)$ is not unique for all alloy classes, in particular at high temperatures and negative R values involving high loading fractions in compression.

For these cases, an explanation for the different crack opening responses is provided by examination of the respective cyclic yield and oxidation properties and their influence on plasticity and oxidation induced closure.

While for some applications it is convenient to universally adopt a potentially excessively conservative upper-bound $q_o(R)$ relationship assuming a crack to be open for all of the tensile stress range and half of the compressive stress range, there are practical circumstances when it is commercially and technically more appropriate to be only just conservative by employing more alloy representative effective crack opening stress ratios.

NOMENCLATURE

A_0, A_1, A_2, A_3	Constants in Newman equation;
$\mathrm{d}a/\mathrm{d}N$	Fatigue crack growth rate;
f	Newman factor;
k_p	Parabolic constant in oxidation law;
K, ΔK,	Stress intensity factor; Stress intensity factor range;
ΔK_{eff}	Effective stress intensity factor ($q_o.\Delta K$);
N+T	Normalised and tempered;
q_c, q_o	Crack closure ratio; Crack opening ratio;
Q+T	Quenched and tempered;
R	Stress ratio ($\sigma_{min}/\sigma_{max}$);
SENB	Single edge notched bend (specimen);
SENT	Single edge notched tension (specimen);
t	Time;
V_L	Load line displacement;
x	Oxide thickness;
α	Parameter in Newman equation (formally: $\alpha = 1$, plane stress; $\alpha = 3$, plane strain);
σ, $\Delta\sigma$	Stress; Stress range (σ_{max} - σ_{min});
σ_c, σ_o	Stress at crack closure; Stress at crack opening;
σ_{max}, σ_{min}	Maximum stress; Minimum stress;
σ_{max}/R_F	Maximum stress to flow strength ratio

REFERENCES

Elber, W. (1970). "Fatigue crack closure under cyclic tension," *Eng. Fract. Mech.*, 2, 1, 37-45

Holdsworth, S. R. (1993). "Factors influencing high temperature HSF crack growth rates in turbine casting steels," *Proc., Conf. on Behaviour of Defects at High Temperatures*, ESIS 15, Sheffield, UK, 327-349.

Holdsworth, S. R. (2002). "Oxide scale spallation in 9-12%Cr steels," *unpublished*.

Holdsworth, S.R. (2014). "Creep-fatigue interaction in steam power plant materials," *Proc. 10th Liège Conf. on Materials for Advanced Power Engineering*, Liège, ISBN 978-3-95806-000-5, 19-28.

Kemp, P. M. (1990). "Fatigue crack closure - A review," *Technical Report TR90046*, RAE Farnborough, UK.

Newman, J. C. (1984). "A crack opening stress equation for fatigue crack growth," *Int. J. Fracture*, 24, R131-5.

Paris, P. C. and Erdogan, F. (1963). "A critical analysis of crack propagation laws," *J. Basic Eng. (Trans ASME)*, 85, 528-534.

Pinder, L. W. (1977). "Oxidation kinetics and scale morphology of mild steel and low chromium alloy steels in N2/20%O2 between 500 and 850," *CEGB Report SSD/MID/R58/77.*

R5 (2012). *Assessment Procedure for the High Temperature Response of Structures, Issue 3, Rev. 001*, EDF Energy Nuclear Generation Ltd.

Skelton, R. P., Beech, S. M., Holdsworth, S. R., Neate, G. J., Miller, D. A. and Priest, R. H. (1993). "Round robin tests on creep-fatigue crack growth in a ferritic steel at 550°C," *Proc., Conf. on Behaviour of Defects at High Temperatures*, ESIS 15, Sheffield, UK, 299-325.

Yan, W., Holdsworth, S.R., Kühn, I. and Mazza, E. (2014). "Creep-fatigue crack development from short crack starter", *Materials at High Temperatures*, 31(4), 305-314.