REMAINING LIFE ASSESSMENT OF POWER PLANT COMPONENTS EXPOSED TO HIGH TEMPERATURE STATIONARY CREEP

by

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Remaining life of high temperature cracked components has been analysed, using time dependent fracture mechanics parameters. As the most efficient parameter for stationary creep problems and simple component geometry, the C integral has been used, taking advantage of its complete analogy with the J integral, well established fracture mechanics parameter for elastic-plastic problems. In other cases, the importance of detailed thermal analysis, including numerical evaluation of temperature fields based on accurately determined boundary and initial condition, is emphasized. Three-step assessment procedure has been applied in order to evaluate the influence of material damage and initial crack length on steamline remaining life. The C* integral, as a crucial parameter in this procedure, has been evaluated using EPRI procedure, developed for elastic-plastic problems, but applied here to stationary creep problem. The results indicate significant influence of material damage and initial crack length.*

Introduction

Components operating at high temperature and internal pressure for a long period of time may fail by slow and stable crack growth. They tend to develop cracks due to different damage mechanisms, and some of them may have initial crack-like defects. Some typical examples of major failures involving high temperature conditions, include turbine rotors and steamlines. There are two main mechanisms of damage in high temperature components. The first one corresponds to the unsteady regime (starting – shutting down, *i. e.* heating – cooling) and it is called low cycle thermal fatigue. The main concern in this case is to have as few as possible cycles of temperature change (heating - cooling) and to have as slow as possible change in temperature history in one cycle. The second one corresponds to the steady regime, called stationary creep. In this case the main concern is steady temperature field, which must not overcome certain maximum value, in order to avoid excessive creep damage. Typical situation is when low cycle thermal fatigue acts as mechanism for crack initiation and steady creep acts as mechanism for crack propagation, as described and analysed in detail for high and intermediate turbine rotors [1]. Creep crack growth in high temperature component under prolong constant stress is the main concern of this paper. These are typical conditions for steamlines and they can be classified as stationary creep. Time dependent fracture mechanics approach is required when creep failure is controlled by a crack growth mechanism.

Figure 1 illustrates the typical creep response of an uncracked material subjected to constant stress at high temperature, indicating four regimes of deformation: instantaneous (elastic) strain, primary (unsteady) creep, secondary (steady) creep and tertiary (final) creep. The elastic strain occurs immediately upon load has been applied. Primary creep dominates short time afterwards, whereas secondary creep with strain rate being constant covers most of high temperature component life. Tertiary creep, as the final stage of process, is not relevant to the analysis performed here, and primary creep will be neglected too, as explained later.

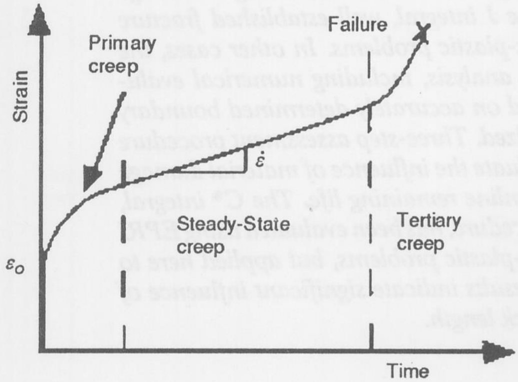

Figure 1. Creep behaviour of material subjected to constant stress

For the secondary creep the Norton's law applies:

$$\dot{\varepsilon}_{ij} = A\sigma_{ij}^n \tag{1}$$

where $\dot{\varepsilon}_{ij}$ is strain rate tensor, σ_{ij} stress tensor, A and n material parameters.

In order to reduce number of component failure, one should be able to assess their remaining life. Toward this end, fracture mechanics parameters are applicable, presenting material properties on one side, and cracked component geometry and loading, on the other side. When creep problems are considered, path independent integrals are the most efficient parameters, because of their sound physical basis and simplicity of evaluation (analytical, numerical or experimental).

There are a large number of papers dealing with time dependent fracture mechanics problem [2], and path independent integrals, in particular. Not long after J integral had been introduced, its counterpart C^* integral, valid for stationary creep problems, was formulated [3] and applied in a manner of strict analogy with plasticity problems. Having in mind the analogy between J and C^* integrals, it is clear that the latter one is path independent, equal to the energy rate (power) release rate and represent the amplitude of stress and strain rate fields around crack tip, under certain limits, such as steady creep dominance.

Creep zones in front of crack tip

In order to define parameters characterizing creep crack growth, one should consider deformation zones ahead of crack tip, caused by constant (in time) load. Immediately after loading is applied, plastic strain zone develops in front of crack tip, surrounded by elastic strains (*K* zone). If plastic zone size is of the same order of magnitude as the elastic one, than stress intensity factor loses its dominance and *J* integral becomes the appropriate measure of stresses and strains ahead of crack tip.

During creep process, stresses in front of crack tip relax, whereas strain zone increases. As long as the creep zone stays small (*SSC* – small scale creep), *K* and *J* are valid fracture parameters out of it. Anyhow, even then new parameters are needed to describe creep crack growth. Figure 2 shows three basic cases regarding creep zone size: the first one, when creep zone size is small comparing to the crack length (SSC), Fig. 2a, the second one, when creep zone is not negligible (transition region), Fig. 2b, and the third one, when creep zone becomes extensive (stationary creep), Fig. 2c. First two cases are defined by unstationary stress state, whereas in the third one stationary stress state allows complete analogy with plastic strains to be applied.

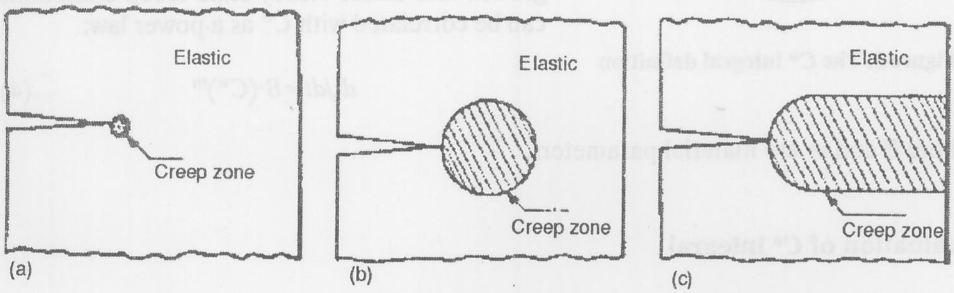

Figure 2. Different creep zone sizes
(a) small creep zone size, SSC, (b) creep zone not negligible, transition region, (c) extensive creep zone, stationary creep

Time dependent fracture mechanics parameters

Landes and Begley [3] introduced C^*- integral, in complete analogy to *J*-integral, to characterize crack growth in a material undergoing steady state creep:

$$C^* = \int_{\Gamma} \left[W^* \, dy - T_i \left(\frac{\partial \dot{u}_i}{\partial x} \right) ds \right] \qquad (2)$$

where $W^* = \int \sigma_{ij} d\dot{\varepsilon}_{ij}$ is the stress work rate (power) density, Γ contour encompassing crack tip, ds element along Γ, $\dot{u}_i$ displacement rate vector, x coordinate in the crack direction, y coordinate normal to the crack, T_i traction force vector, defined by outer normal n_i, Fig. 3.

Having in mind the analogy with J integral, it is clear that C^* integral can be interpreted as energy rate (power) release rate due to unit crack growth. It is also path independent integral providing that the basic conditions, as defined for J integral, are fulfilled [2]. Furthermore, C^* characterizes stress and strain rate distribution near the crack tip as follows:

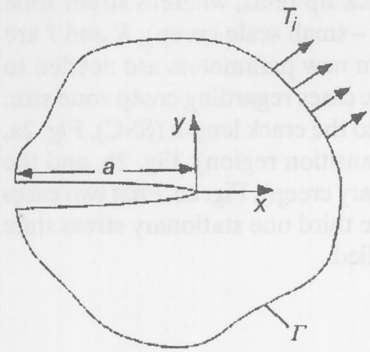

Figure 3. The C^* integral definition

$$\sigma_{ij} = \left(\frac{C^*}{AI_n r}\right)^{\frac{1}{n+1}} \tilde{\sigma}_{ij}(\theta, n);$$

$$\dot{\varepsilon}_{ij} = \left(\frac{C^*}{AI_n r}\right)^{\frac{1}{n+1}} \tilde{\varepsilon}_{ij}(\theta, n) \qquad (3)$$

where $\tilde{\sigma}_{ij}(\theta, n)$ and $\tilde{\varepsilon}_{ij}(\theta, n)$ are the same functions as for J integral, I_n nondimensional constant depending on n, and r distance from the crack tip. Experimental evidence has shown that crack growth rate under steady state creep conditions can be correlated with C^* as a power law:

$$d_a/dt = B \cdot (C^*)^m \qquad (4)$$

where B and m are material parameters.

Evaluation of C^* integral

As already explained, remaining life estimation of stationary creeping components with a crack is possible by using time dependent fracture mechanics parameters, such as C^* integral. Its value depends on component geometry, including crack length, loading conditions and material properties. While C^* integral can be evaluated using different analytical, experimental and numerical methods, here only EPRI procedure will be applied [4]. This procedure covers several simple geometries (CT specimen, edge or centre cracked plate, cylinder with axial or circumferential crack) which can approximate engineering components with relatively simple shape. In this paper such a component will be analysed as an illustration of EPRI procedure – a steam pipe under internal pressure, with an axial crack, Fig. 4. The relevant data for this problem is as follows: outer radius R_o, inner radius R_i, wall thickness b, ligament $c = b - a$ and internal pressure p.

The cylinder is analysed under plane strain conditions, Fig. 4, with internal pressure acting on cylinder wall and crack faces. In the linear elastic region the stress intensity factor K_I, crack mouth opening displacement δ and J integral can be written as follows:

$$K_I = \frac{2pR_o^2\sqrt{\pi a}}{R_o^2 - R_i^2} F(a/b, R_i/R_o) \qquad (5a)$$

$$\delta = \frac{8pR_o^2 a}{(R_o^2 - R_i^2)E'} V_1(a/b, R_i/R_o) \qquad (5b)$$

$$J = K_I^2 / E' \qquad (5c)$$

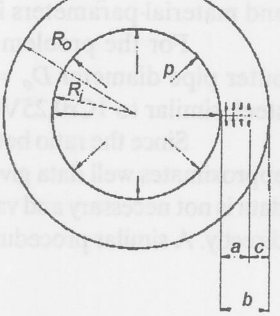

Figure 4. Radial section of cylinder with axial crack

where $E' = E/(1-\nu^2)$. The dimensionless functions F and V_1, depending on two parameters, a/b and b/R_i are given in [4] for certain values of parameters (b/R_o = 1/5, 1/10 and 1/20; a/b = 1/8, 1/4, 1/2 and 3/4). Numerical error for these solutions, obtained by the finite element method, is 1–4%. The fully plastic solutions for J and δ are expressed as:

$$J = \alpha \cdot R_e \cdot \varepsilon_e \cdot c(a/b) \cdot h_1(a/b, n, R_i/R_o) \cdot (p/p_o)^{n+1} \qquad (6a)$$

$$\delta = \alpha \cdot \varepsilon_e \cdot a \cdot h_2(a/b, n, R_i/R_o) \cdot (p/p_o)^n \qquad (6b)$$

where p_o is the limit pressure, which is given:

$$p_o = \frac{2}{\sqrt{3}} \frac{cR_e}{R_c} \qquad (7)$$

where $R_c = R_i + a$.

The dimensionless functions h_1 and h_2, depending on three parameters, a/b, n and b/R_i, are also given in [4], for the same values of a/b and b/R_i as in the case of functions V and F, and for the following values of n: 1, 2, 3, 5, 7 and 10.

Solutions for crack tip opening displacement (CTOD or δ_t) are not given here because the relation between J i δ_t has not been verified for the loading acting on crack faces.

As already explained, time dependent fracture mechanics is complete analogous to the plastic fracture mechanics in the case of stationary problems. If instead of displacement and strains their rates are used, and parameters of Ramberg-Osgood law are replaced by:

$$A = \alpha \cdot \varepsilon_e / R_e^n \qquad (8)$$

then the following expression for C^* is obtained:

$$C^* = A \cdot c \cdot a/b \cdot h_1(a/b, n) \left(\frac{\sqrt{3}\, pR_c}{2c} \right)^{n+1} \qquad (9)$$

All quantities in (9) are defined if pipe geometry, crack length, internal pressure and material parameters in Norton's law (A, n) are known.

For the problem of old pipes, analyzed here, the following data is known [5]: outer pipe diameter D_o = 219 mm; pipe thickness b = 18 mm; produced of 12H1MØ steel, similar to 1Cr0,25V0,25Mo.

Since the ratio between pipe thickness and inner radius $b/R_i = 18/91{,}5 = 0{,}197(\approx 0{,}2)$ approximates well data given in tab. 8.4 of handbook [4] for b/R_i = 1/5, the interpolation of data is not necessary and values for 'h' functions given in tab. 8.4 of handbook [4] can be used directly. A similar procedure is also applied for new pipes.

Remaining life evaluation

Three-step procedure for remaining life evaluation is shown in Fig. 5. The first step takes care about material properties, both the creep deformation law Eq. (1), using standard smooth specimens [4], and creep crack growth law Eq. (4), using standard pre-cracked specimens [4]. The second step defines C_t as the parameter depending on component geometry, including crack length, loading and material parameters (creep deformation law), valid for non-stationary creep, which reduces to C^* for steady state creep. Taking into account creep crack growth law (step 1) and C_t or C^* value (step 2), it is possible to calculate remaining life for different initial crack length (step 3), as shown in Fig. 5.

The second step in this procedure usually requires detailed thermal analysis, including evaluation of temperature fields, both in time and space. Time distribution of temperature is needed for non-stationary problems, where primary creep is not negligible, and for low cycle thermal fatigue analysis. Space distribution of temperature is needed for components of complex shape such as turbine rotors. In both cases, initial and boundary conditions for the appropriate heat transfer problem are necessary. Numerical methods are often the only choice to solve this problem and obtain temperature fields, as described in Report [1], where the high and intermediate turbine rotors were analysed in detail by the finite difference method and finite element method. One should notice that correct evaluation of initial and boundary conditions are of essential importance, and that this presents rather difficult task for thermal engineer.

Results and discussion

Described procedure is applied to 12H1MØ steel [6]. In order to get more insight in service condition effect specimens taken from new pipes Ø 273×22 of this steel (new material) and from pipes Ø 219×18, of the same steel, after 175.000 service hours under maximum temperature 540 °C and inner pressure 100 bar are compared.

The remaining life will be estimated for 3 different values of initial crack length, chosen according to available data in [4]:

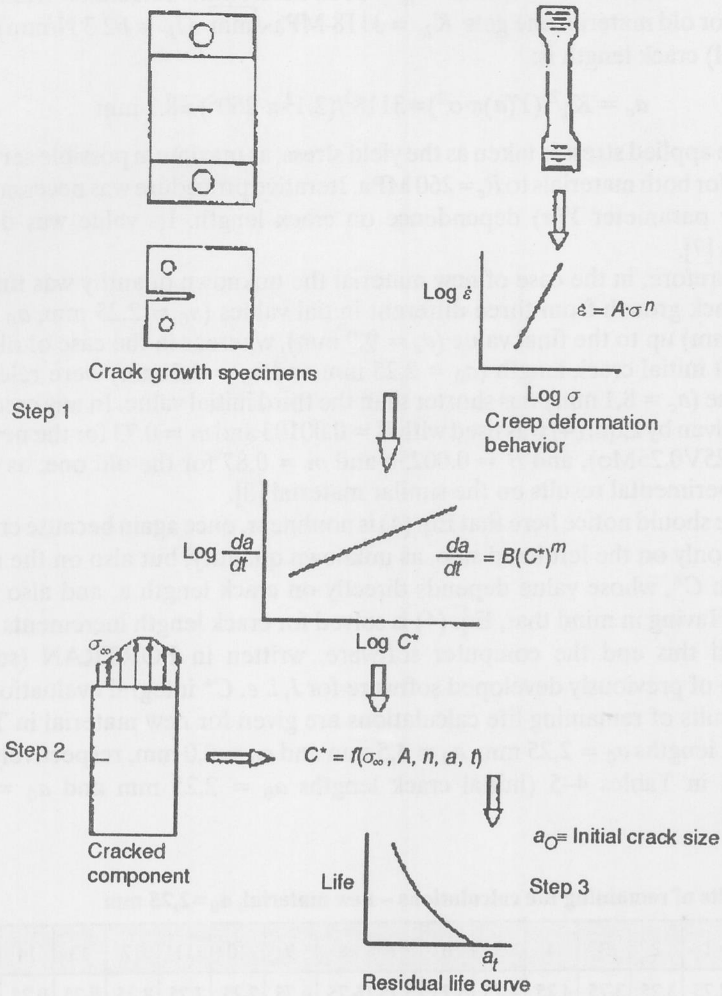

Figure 5. Three step procedure for remaining life evaluation

$$a_0 = 2{,}25 \text{ mm } (a_0/b = 1/8);\ a_0 = 4{,}5 \text{ mm } (a_0/b = 1/4);\ a_0 = 9 \text{ mm } (a_0/b = 1/2)$$

while the final crack length is determined as the critical crack length from the basic linear elastic fracture mechanics relation, using iterative procedure:

$$a_c = K_{Ic}^2 \,/\, (Y(a)\pi \cdot \sigma^2) = 3368^2 \,/\, (2.35^2 \cdot \pi \cdot 260^2) \approx 9.9 \text{ mm}$$

which applies for new material, with $K_{Ic} = 3368 \text{ MPa}\sqrt{\text{mm}}$ calculated from $J_{Ic} = 72.7$ N/mm [5]. For old material one gets $K_{Ic} = 3118 \text{ MPa}\sqrt{\text{mm}}$ ($J_{Ic} = 62.3$ N/mm) [5], so the critical (final) crack length is:

$$a_c = K_{Ic}^2/(Y(a)\pi\cdot\sigma^2)=3118^2/(2.1^2\cdot\pi\cdot260^2) \approx 8.1 \text{ mm}$$

The applied stress is taken as the yield stress, as maximum possible service stress, being equal for both materials to R_e=260 MPa. Iterative procedure was necessary because of geometry parameter $Y(a)$ dependence on crack length. Its value was determined according to [7].

Therefore, in the case of new material the unknown quantity was time needed for creep crack growth from three different initial values (a_0 = 2,25 mm, a_0 = 4,5 mm and a_0 = 9 mm) up to the final value (a_c = 9,9 mm), whereas in the case of old material two different initial crack length (a_0 = 2,25 mm and a_0 = 4.5 mm) were relevant since the final value (a_c = 8,1 mm) was shorter than the third initial value. In any case the crack growth law given by Eqn. (4) was used with B = 0.00103 and m = 0.73 for the new material (steel 1Cr0,25V0,25Mo), and B = 0.00256 and m = 0.87 for the old one, as calculated from the experimental results on the similar material [8].

One should notice here that Eq. (4) is nonlinear, once again because crack length appears not only on the left hand side, as unknown quantity, but also on the right hand side, through C^*, whose value depends directly on crack length a, and also indirectly, through h_1. Having in mind that, Eq. (4) is solved for crack length increments of *e. g.* 0.5 mm. Toward this end the computer software, written in FORTRAN (see [5]), as modification of previously developed software for J, *i. e.* C^* integral evaluation [9].

Results of remaining life calculations are given for new material in Tables 1–3 (initial crack lengths a_0 = 2,25 mm, a_0 = 4,5 mm and a_0 = 9,0 mm, respectively), and for old material in Tables 4–5 (initial crack lengths a_0 = 2,25 mm and a_0 = 4,5 mm, respectively).

Table 1. Results of remaining life calculations – new material, a_0=2,25 mm

Step	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
a [mm]	2.75	3.25	3.75	4.25	4.75	5.25	5.75	6.75	6.75	7.25	7.75	8.25	8.75	9.25	9.75	10.25
Δt [h]	1335	1090	931	794	688	599	512	444	390	343	305	273	246	222	198	175
C^*[N/mm/h]	0.25	0.33	0.41	0.51	0.62	0.75	0.93	1.13	1.35	1.61	1.89	2.20	2.54	2.92	3.41	4.05

Table 2. Results of remaining life calculations – new material, a_0=4,5 mm

Step	1	2	3	4	5	6	7	8	9	10	11
a [mm]	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
Δt [h]	650	551	478	415	365	324	288	259	234	211	186
C^*[N/mm/h]	0.67	0.84	1.02	1.24	1.48	1.74	2.04	2.36	2.72	3.12	3.72

Table 3. Results of remaining life calculations new material, a_0 = 9,0 mm

Step	1	2
a [mm]	9.5	10.0
Δt [h]	211	186
C^*[N/mm/h]	2.72	3.12

Table 4. Results of remaining life calculations – old material, a_0=2,25 mm

Step	1	2	3	4	5	6	7	8	9	10	11	12
a [mm]	2.75	3.25	3.75	4.25	4.75	5.25	5.75	6.25	6.75	7.25	7.75	8.25
Δt [h]	652	512	424	351	296	251	208	176	150	129	112	98
C^*[N/mm/h]	0.25	0.33	0.41	0.51	0.62	0.75	0.93	1.13	1.35	1.61	1.89	2.20

Table 5. Results of remaining life calculations – old material, a_0 = 4,5 mm

Step	1	2	3	4	5	6	7	8
a [mm]	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
Δt [h]	276	227	192	162	139	121	105	93
C^*[N/mm/h]	0.67	0.84	1.02	1.24	1.48	1.74	2.04	2.36

On the basis of calculations presented in Tables 1–5, the time needed for creep crack growth from different initial values up to the final value can be reviewed for both materials, as presented in Table 6.

Table 6. Time needed for creep crack growth from different initial values

Initial crack length a_0 [mm]	2.25	4.5	9.0
New material (a_c = 9.9 mm) – time [h]	8545	3963	397
Old material (a_c = 9.9 mm) – time [h]	3360	1315	

By comparing the results for crack growth times for used and new material one can notice that creep damage significantly reduces remaining life of steamline. The same effect is noticeable for the initial crack length. One should be aware of the conservatism built in into EPRI procedure, mostly due to simplification of crack shape, as shown in this example where large, length through crack had to be assumed instead of short surface crack which are most likely to appear in reality.

Conclusions

Based on theoretical analysis and numerical results presented in the paper, one can conclude the following:

- Remaining life of high temperature components depends strongly on initial crack length and degree of material damage. Anyhow, even with a large crack, both new and exposed steamlines can withhold considerable time before failing.
- EPRI procedure is efficient engineering tool for conservative remaining life prediction of high temperature components of relatively simple shape, such as steamlines. It can replace other more complicated procedures, like the finite element method, at least as the first approximation for problem solution.
- Experimental verification of EPRI procedure is needed, but it should be noticed that high temperature experiments in steady state creep conditions are extremely time consuming and long.
- Components with more complex geometry than pipes and/or non-stationary creep conditions require more complex evaluation of fracture mechanics parameters based on numerical analysis of temperature fields and stress fields caused by time and space temperature distribution. The essential part of such analysis is correct evaluation of initial and boundary conditions, what requires detailed thermal analysis, including measurements on components during steady operating regime and at starting and shutting down procedures.

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