Internal Elliptic Surface Creep Crack Growth Analysis in Pressure Vessels for 2.25Cr Steel

NWE NI TUN[1], ZAR CHI THAUNG[2]
[1] *Mechanical Engineering Department, Mandalay Technological University*
[2] *Mechanical Engineering Department, Technological University (Maubin)*

Abstract-* Nonlinear fracture mechanics-based methodologies is common practice to model an elliptic axial surface crack located at the internal or external surface of a cylindrical pressure vessel as an infinitely long axial crack. This simplification considerably reduces the amount of computation needed for evaluating high temperature fracture parameters such as $C^*$and C_t and for determining crack growth life. This simplification on the estimated component life have never been systematically assessed in detail except stating that the assumption leads to a conservative estimate of life. In this study, an analysis method is developed that does not require any assumption. Using this developed method, a procedure for life assessment was demonstrated for an elliptic axial surface crack located on the internal surface of a pressurized vessel at high temperature. Equations are proposed for estimating C_t at both the deepest point along the crack front and also at the crack tip on the surface. Using these equations, the aspect ratios of the surface crack were updated for every time step of crack growth calculation and were reflected in determining C_t value of the next step. Changes of crack depth, crack size and C_t values at the deepest point and surface point of the crack tip are estimated and used to predict the evolution of crack shape during creep crack growth.

***Index Terms-* Life Assessments; Pressurized Vessel; Surface Cracks; C^*; C_t**

I. INTRODUCTION

Remaining life assessment based on time dependent fracture mechanics has been developed and applied successfully to many structural components in power generating industry and process industry such as steam pipes, super-heater headers, turbine rotors, casings and pressure vessels when they have cracks and are operated at elevated temperature [1–6]. The accuracy of predicted life has been improved by considering various aspects such as better material creep constitutive law, existence of weld, various operation conditions and crack geometry. However, frequently the geometry of a crack uncovered during on-site inspection is a surface crack of finite size. Due to lack of accurate expressions for determining high temperature fracture parameters such as C^* and C_t for surface cracks under various loading conditions, the crack geometry is usually simplified considerably and represented as infinitely long crack for which reliable C^* and C_t expressions are available [2,5]. The elliptic axial surface crack located at the internal surface of a pressure vessel is very often simplified as an infinitely long axial crack. This simplification results in considerable reduction in computational effort for determining crack growth life. Using the proposed equations for estimating C_t; life assessment is conducted for an elliptic axial surface crack located on the internal surface of a 2.25Cr steel pressure vessel at high temperature. The aspect ratios of the surface crack were updated for every time step of crack growth calculation and were reflected in determining C_t value of the next step. Changes of crack depth, crack size and C_t values at the deepest point and surface point of the crack tip are shown. In this study, the life assessment of internal surface creep crack growth methodology is extended, and an analysis method is proposed that does not require simplifying assumptions regarding the crack geometry.

II. DESIGN METHODOLOGY

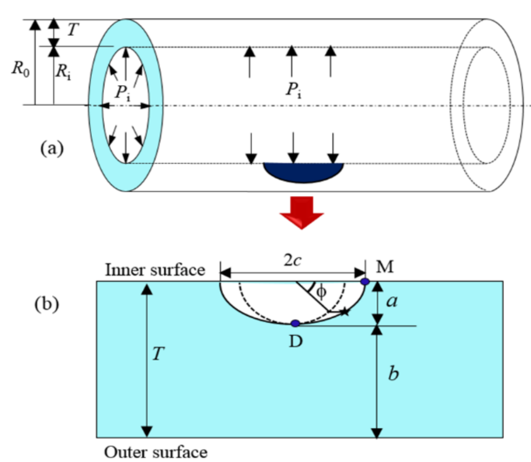


Figure1. Geometry of an elliptic surface crack located in the radial-axial plane on the internal surface of a vessel (a) a vessel containing a surface crack and subjected to uniform internal pressure; (b) the sketch of a semi-elliptical axial surface crack

An elliptic surface crack located in the radial–axial plane on the internal surface of a thick wall pressure vessel is shown in Figure 1. Notations for cylinder and crack dimension are shown in Figure 1(a) and definition of crack front as a function of angle, ϕ; is shown in Figure 1(b). R_i and R_o is inner and outer radius respectively, T is thickness, a is crack depth, c is half crack length and P_i is internal pressure. The deepest point along the crack front is denoted as crack front location D and the crack tip location on the surface is denoted as location M.

A. Equations for K

Stress intensity factor equations for a wide range of surface cracks on the inside of a pressurized vessel were derived by Newman and Raju [7, 8]

$$K = \frac{P_i R_i}{T}\sqrt{\pi \frac{a}{Q}} F\left(\frac{a}{c}, \frac{a}{T}, \frac{R_i}{T}, \phi\right) \quad (1)$$

$$F = 0.97\left(m_1 + m_2\left(\frac{a}{T}\right)^2 + m_3\left(\frac{a}{T}\right)^4\right) f_\phi . g . f_c \quad (2)$$

$$Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65} \quad (3)$$

$$m_1 = 1.13 - 0.09\left(\frac{a}{c}\right) \quad (4)$$

$$m_2 = 0.54 + \frac{0.89}{0.2 + \frac{a}{c}} \quad (5)$$

$$m_3 = 0.5 + \frac{1}{0.65 + \frac{a}{c}} + 14\left(1 - \frac{a}{c}\right)^{24} \quad (6)$$

$$f_\phi = \left(\left(\frac{a}{c}\right)^2 \cos^2\phi + \sin^2\phi\right) \quad (7)$$

$$g = 1 + \left(0.1 + 0.35\left(\frac{a}{T}\right)^2\right)\left(1 - \sin\phi\right)^2 \quad (8)$$

$$f_c = \left(\frac{R_0^2 + R_i^2}{R_0^2 - R_i^2} + 1 - 0.5\sqrt{\frac{a}{T}}\right)\frac{T}{R_i} \quad (9)$$

B. Equations for C^* and C_t

$$C^* = A.T.\left(1 - \frac{a}{T}\right)\sigma^{n+1} q_A\left(\frac{a}{T}, \frac{a}{c}, n\right) \quad (10)$$

$$\sigma = \frac{P_i R_i}{T - \frac{\pi . a}{4}} \quad (11)$$

$$q_A\left(\frac{a}{T}, \frac{a}{c}, n\right) = [\xi].[q].[n]^T \quad (12)$$

In order to characterize the crack growth rate from small-scale to extensive steady-state creep conditions, a parameter of C_t for elastic-plastic-secondary creeping material is as follows [29];

$$C_t = \frac{4\alpha\beta\tilde{r}_c(\theta, n)}{E(n-1)} \frac{(1-\nu^2)K^4}{t} \frac{F'}{F}(EA)^{2/(n-1)}\left(t + t_{pl}\right)^{-(n-3)/(n-1)} + C^* \quad (13)$$

At D,

$$\frac{F'}{F} = \frac{n_1 - \sqrt{\frac{a}{T}}}{2n_1 . \left(\frac{a}{T}\right) - \left(\frac{a}{T}\right)^{3/2}} + \frac{2m_2 . \left(\frac{a}{T}\right) + 4m_3 . \left(\frac{a}{T}\right)^3}{m_1 + m_2 . \left(\frac{a}{T}\right)^2 + m_3 . \left(\frac{a}{T}\right)^4} \quad (14)$$

At M,

$$\frac{F'}{F} = \frac{2m_2 . \left(\frac{a}{T}\right) + 4m_3 . \left(\frac{a}{T}\right)^3}{m_1 + m_2 . \left(\frac{a}{T}\right)^2 + m_3 . \left(\frac{a}{T}\right)^4} + \frac{\frac{n_1}{2}\left(\frac{a}{T}\right)^{-1/2} - \frac{1}{2}}{n_1 . \sqrt{\frac{a}{T}} - \frac{1}{2}\left(\frac{a}{T}\right)} + \frac{0.7\left(\frac{a}{T}\right)}{1.1 + 0.35\left(\frac{a}{T}\right)^2} \quad (15)$$

$$n_1 = \frac{2R_0^2}{R_0^2 - R_i^2} \quad (16)$$

where, β is a scaling factor, E is the Young's modulus, ν is the Poisson's ratio, K is the stress intensity factor and θ is the angle measured from the crack plane ahead of the crack tip. And t is the elapsed time after loading, t_{pl} is the time for crack tip creep zone development retardation due to crack tip plastic zone and α is a dimensionless function of n. β

is 1/3 determined by finite dimensionless function dependent on n. At $\theta = 90^\circ$, a non-dimensional constant $\tilde{r}_c(90^\circ, n)$ for plane strain condition varies approximately from element calculations and $\tilde{r}_c(\theta, n)$ is a 0.2 to 0.5 when n varies from 3 to 13. F and F' are K- calibration function and derivative of F with respect to a/T in this analysis.

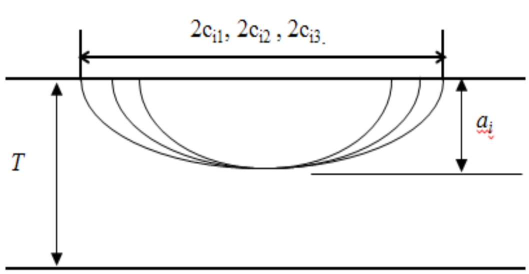
The creep crack growth rate under small scale to transient creep conditions can be characterized by the Equation. (17);

$$\frac{da}{dt} = H(C_t)^q \tag{17}$$

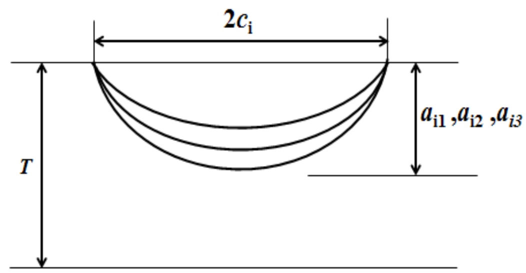
where, da/dt is the creep crack growth rate, H and q are material constants and C_t is a crack tip parameter that is valid from small-scale to extensive creep conditions [19].

C. Life Assessment for Creep Crack Growth

A pressurized cylinder with 330 mm outer radius, R_0, and 292 mm inner radius, R_i, is chosen for life assessment. The thickness of the cylinder (T) is 38 mm and R_i/T is 10. It is assumed that the internal pressure to be 6.2 MPa. The material properties are also assumed as follows: creep coefficient, A, is 7.04×10^{-25} MPa^{-n}, creep exponent ,n, is 9.9, creep crack growth coefficient, H, is 5.903×10^{-2}, creep crack growth exponent, q, is 0.714 and the time for crack tip creep zone development retardation due to crack tip plastic zone, t_{pl}, is 4×10^{-3} h.



(a)



(b)

Figure2. Initial crack geometries for two sets of crack growth: (a) when the initial crack depth is fixed; (b) when the initial surface half crack length is fixed

The two sets of analysis were carried out for the initial crack geometry shown in Figure 2. The remaining life assessment for creep crack growth analyses was conducted by developing the conventional code in MATLAB software, a structured program, based on the procedure of the algorithm as shown in Figure 3.

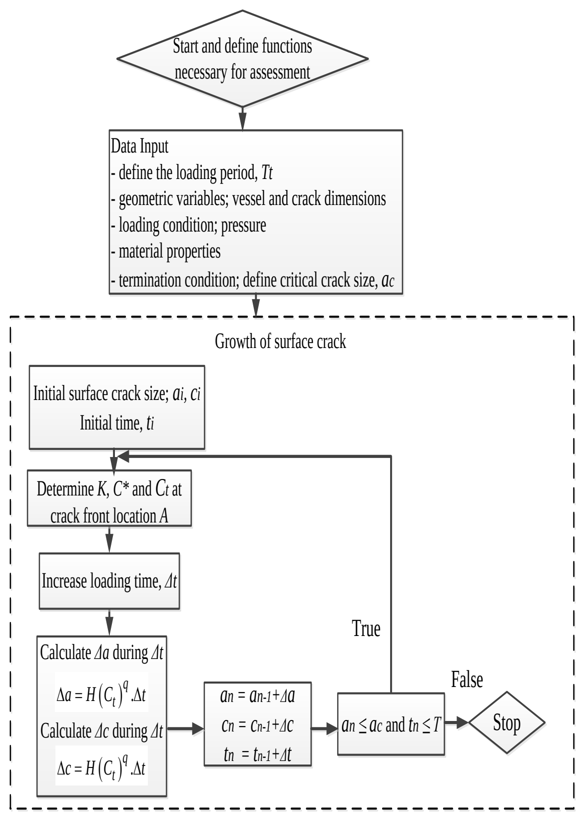
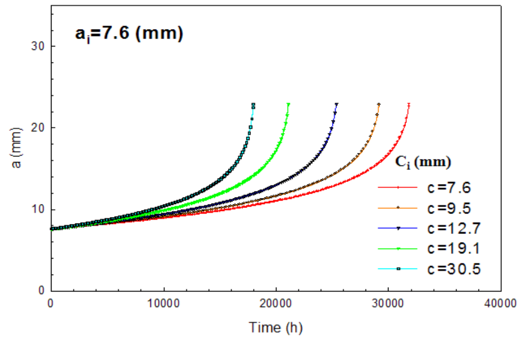
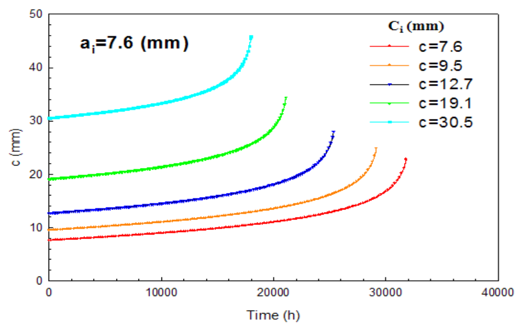


Figure3. Simulation algorithm for life assessment of surface creep crack growth analysis

III. RESULTS AND DISCUSSIONS

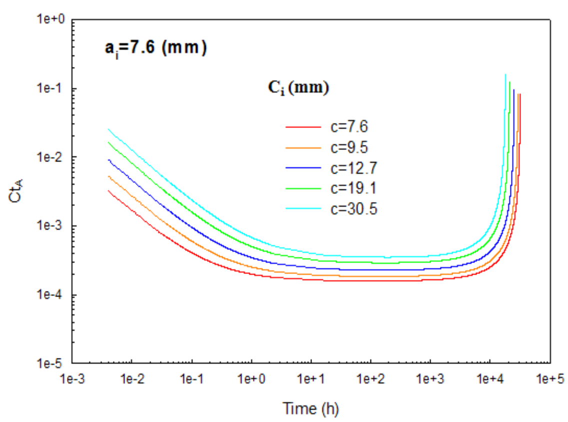


(a)

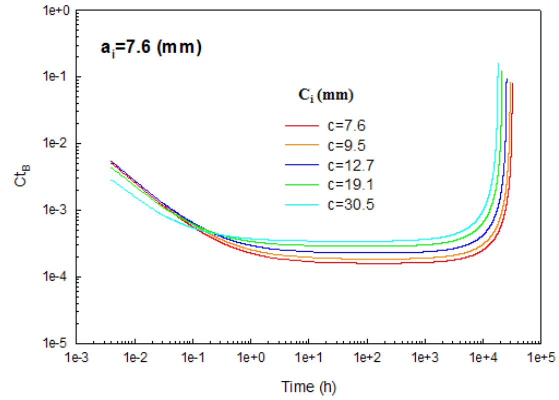


(b)

Figure4. (a) Crack depth growth and (b) surface crack length behaviors



(a)



(b)

Figure5. Variation of C_t during the crack growth at the crack front location D and crack tip location M

The analyses were terminated when the crack depth exceeds 60% of the thickness. Figure 10(a) shows crack depth growth behavior as a function of the loading time and figure 10(b) shows surface crack length growth behavior. The crack growth rates were determined from the C_t values at each location of D and M of the surface crack using the creep crack growth model expressed as equation (17).

Variations of the C_t values with time are shown in Figure 5 (a) for the crack front location D and Figure 5 (b) for the location M. During the initial period after the internal pressure is applied, the contribution of the first term in equation (13) is significant since the small scale creep is dominant

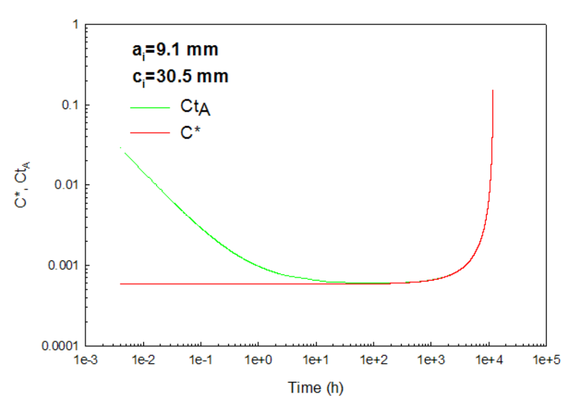


Figure6. Variations of C_t and C^* for the case of creep crack growth analysis

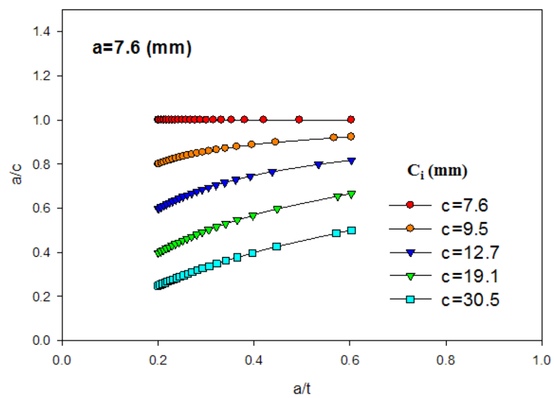
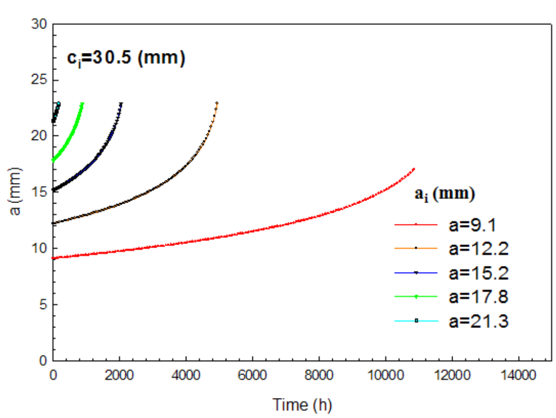
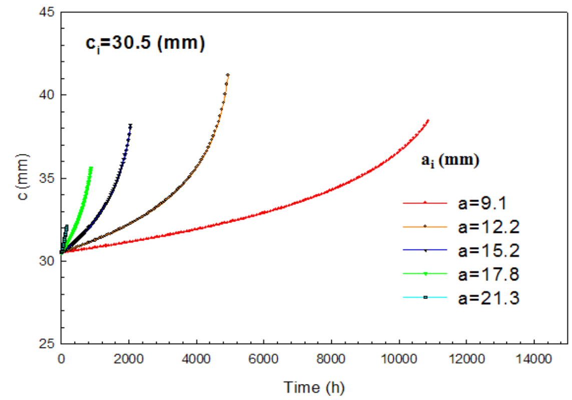


Figure7. Change of aspect ratio of the surface cracks during creep crack growth when initial a is fixed

and the C_t value during this period is much higher than the value of C^*. As extensive creep condition is achieved C_t value approaches to C^* since the first term in equation (13) vanishes and the second C^* term becomes dominant. This trend is shown in Figure 6 in which C_t and $C^*$are shown together for the case of the analysis. Figure 7 shows change of aspect ratio for the surface crack over the creep crack growth life. It is shown that as the crack grows the aspect ratio is approaching to an asymptotic value whatever the initial aspect ratio would be. Figure 8(a) and 8(b) show crack depth growth and surface crack length growth as a function of time and variations of the C_t corresponding to the crack growth data.

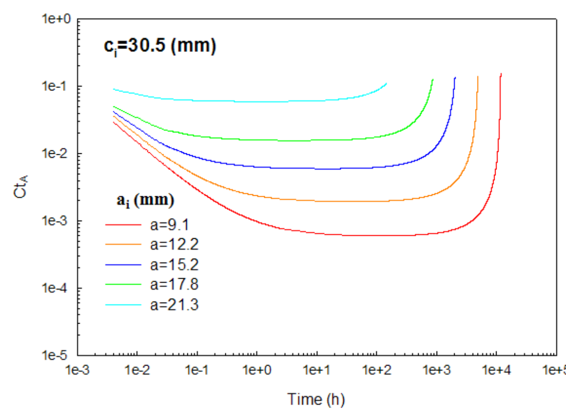


(a)

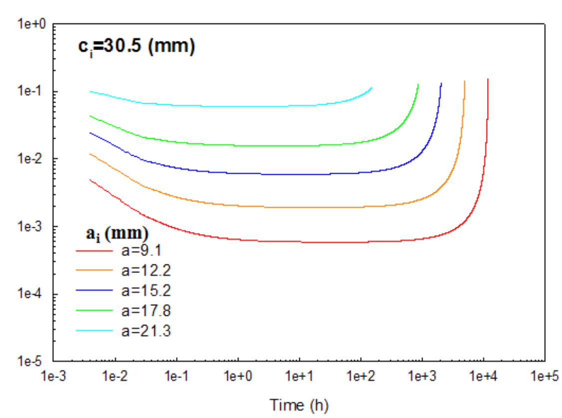


(b)

Figure8. (a) Crack depth growth and (b) surface crack length growth behaviors as a function of time when initial c is fixed



(a)



(b)

Figure9. Variation of C_t during the crack growth at the crack front locations D and M when initial c is fixed

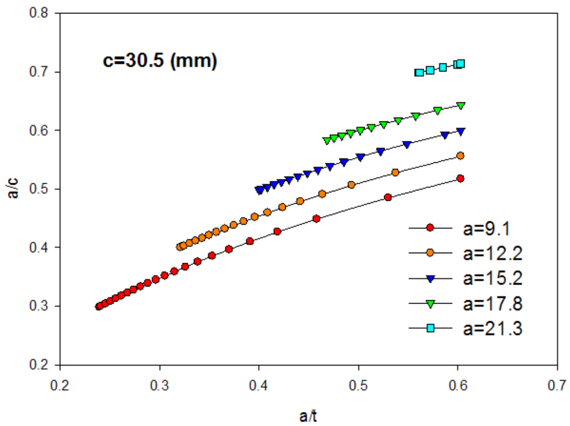


Figure10.Change of aspect ratio of the surface cracks during creep crack growth when initial c is fixed

Figure 9 showing variations of C_t during the overall crack growth life period, the transition time appears to be approximately several hundred hours. Changes of the aspect ratio during the whole creep crack growth life is shown in Figure 10. The approach developed in this study can be used reliably for practical purpose. Most of the creep crack growth life is consumed when a = T is less than 0.4. A mushroom type of crack growth is not probable until the last stage of crack growth when the crack depth is approaching the pressure vessel thickness.

IV. CONCLUSIONS

A creep crack growth life prediction procedure is developed for the case of surface crack located in the radial axial plane and on the internal surface of a pressurized cylinder. This method does not require simplifying assumptions regarding the crack geometry used in earlier studies. A procedure is proposed for estimating C^* along the entire surface crack front using the C^* equation derived for the case of surface crack in a flat plate under uniform tension. Equations are also proposed for calculating C_t at both the deepest point along the crack front and at the crack tip on the surface.

Using the newly proposed equations for estimating C_t; creep crack growth analysis is conducted for an internal surface crack of a pressure vessel at high temperature. The aspect ratios of the surface crack were updated for every time step of crack growth calculation and were reflected in determining the C_t value of the next step. Changes of crack depth, crack size and C_t values at the deepest point and surface point of the crack tip are presented. Finally, limitations of the current approach are discussed. It is argued that the approach developed in this study can be used reliably for practical purpose despite of these limitations.

ACKNOWLEDGMENT

The first author wishes to acknowledge her deepest gratitude to her parents, professors, teachers, relatives and friends to carry out this paper.

REFERENCES

[1] Viswanathan R. Damage mechanisms and life assessment of high temperature components. ASM Int; 1989.

[2] Saxena A. Nonlinear fracture mechanics for engineers. Boca Raton: CRC Press; 1998.

[3] Bloom JM, Lee DR. Determination of piping acceptance requirements based on state of the art creep crack growth methodology. Proc Fifth Int Conf Creep Mater; 1992; 203–8.

[4] Liaw PK, Saxena A, Schaefer J. Estimating remaining life of elevated temperature steam pipes-part I materials properties. Engng Fract Mech; 1989; 675–708.

[5] Liaw PK, Saxena A, Schaefer J. Estimating remaining life of elevated temperature steam pipes—part II fracture mechanics analysis. Engng Fract Mech; 1989; 32(5): 709–22.

[6] Liaw PK, Saxena A, Schaefer J. Creep crack growth behavior of steam pipe steels-effects of inclusion content and primary creep. Engng Fract Mech; 1997; 57(1):105–30.

[7] Newman JC, Raju IS. Stress intensity factors for internal surface cracks in cylindrical pressure vessels. J Pressure Vessel Technol Trans ASME; 1980; 102: 342–6.

[8] Raju IS, Newman JC. Stress intensity factors for internal and external surface cracks in cylindrical vessels. J Pressure Vessel Technol Trans ASME; 1982; 104: 293–8.

[9] Raju IS, Newman JC. Stress intensity factors for a wide range of semi-elliptical surface cracks in finite-thickness plates. Engng Fract Mech; 1979; 11: 817–29.

[10] Newman JC, Raju IS. An empirical stress-intensity factor equation for the surface crack. Engng Fract Mech; 1981; 15(1):185–92.

[11] DeLorenzi HG. Elastic-plastic analysis of the maximum postulated flaw in the beltline region of a reactor vessel. J Pressure Vessel Technol Trans ASME; 1982;104: 278–86.

[12] Killian DE, Yoon KK. Elastic-plastic analysis of reactor vessel longitudinal flaws. ASTM STP; 1992; 1131:248–67.

[13] Yoon KK, Killian DE. J estimation method for a semi-elliptical surface flaw in a cylinder. J Pressure Vessel Technol Trans ASME; 1995;117:66–70.

[14] Zahoor A. Ductile fracture handbook. Research project 1757-69, vol.3. Electric Power Research Institute; 1991.

[15] Kumar V, German MD, Shih DF. An engineering approach for elastic-plastic fracture analysis. EPRI Topical Report NP-1931; Research Project 1237-1; Electric Power Research Institute; 1981.

[16] Yagawa G, Kitajima Y, Ueda H. Three-dimensional fully plastic solutions for semi-elliptical surface cracks. Int J Pressures Vessel Piping; 1993; 53: 457–510.

[17] Yagawa G, Kitajima Y, Ueda H, Erratum H. Int J Pressures Vessel Piping; 1997;74:77–80.

[18] He MY, Hutchinson JW. Bounds for fully plastic crack problems for infinite bodies. ASTM STP; 1983; 803:I277–90.

[19] Saxena A. Creep crack growth under nonsteady state conditions. ASTM STP; 1986; 905:185–201.

[20] Saxena A, Han J, Banerji K. Creep crack growth behavior in power plant boiler and steam pipe steels. J Pressure Vessel Technol Trans ASME; 1988;110:137–46.

[21] Yoon KB, Saxena A, Liaw PK. Characterization of creep fatigue crack growth behavior under trapezoidal waveshape using C_t -parameter. Int J Fracture; 1993; 59:95–114.

[22] Norris RH, Saxena A. Creep crack growth behavior in chromium molybdenum steel weldments. Mater Ageing Component Life Extension; 1995; 713–23.

[23] Tabuchi M, Kubo K, Yagi K. Effect of specimen size on creep crack growth rate using ultra-large CT specimens for 1Cr–Mo–V steel. Engng Fract Mech; 1991; 40(2):311–21.

[24] Saxena A, Yagi K, Tabuchi M. Crack growth under small scale and transition creep conditions in creep-ductile materials. ASTM STP; 1994; 1207: 381–497.

[25] Grover PS, Saxena A. Characterization of creep fatigue crack growth behavior in 2.25Cr–1Mo steel using $(C_t)_{avg}$. Int J Fracture; 1995; 73: 273–86.

[26] Saxena A. Creep fatigue crack growth in power plant materials and components. Adv Fracture Res, ICF9; 1997;1:51–62.

[27] Grover PS, Saxena A. Modelling the effects of creep fatigue interaction on crack growth. Fatigue Fract Engng Mater Struct; 1999; 22:111–22.

[28] Yoon KB, Saxena A, McDowell DL. Influence of crack-tip cyclic plasticity on creep fatigue crack growth. ASTM STP; 1992; 1131: 267–392.

[29] Lee DR, Bloom JM. Assessment of fully plastic J and C^*-integral solutions for application to elastic-plastic fracture and creep crack growth. J Pressure Vessel Technol Trans ASME; 1993; 115:228–34.

[30] Bloom JM. Validation of creep crack growth life estimation methodology/hot reheat steam pipes. J Pressure Vessel Technol Trans ASME; 1994;116: 331–5.

[31] Brocks W, Krafka H, Kunecke G, Wobst K. Stable crack growth of axial flaws in pressure vessels. Nucl Engng Des; 1992;135:151–60.

[32] Ohtani R, Kitamura T, Sakanoue Y, Wakabayashi M. Surface crack propagation in plate specimens of 1Cr–1Mo–1/4V turbine rotor steel under creep-fatigue condition. ISIJ Int; 1990; 30(10): 838–46.

[33] Watashi K, Furuhashi I, Yoshida H. Analytical crack growth evaluation of a plate with a surface crack. Nucl Engng Des; 1992;133(3): 489–503.