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ESTIMATION OF SAFETY OF STRAIGHT SEGMENTS OF PIPELINES FOR HEAT AND POWER GENERATING PLANTS ACCORDING TO SINTAP PROCEDURES

In the paper, the assessment of safety of the pipelines elements from the heat and power generating plants of Ukraine made of 12Kh1MF steel has been presented. The SINTAP procedures for failure assessment have been performed assuming two shapes of hypothetical cracks along the straight segments of pipeline. The thermal stresses during the cooling process have been taken into account in the analysis. The analysis has been performed at the first level of SINTAP procedures. Two stages: a) before pipeline operation and b) after 156000 hours of service work have been analyzed. The comparison of results obtained by other assessment method has been made.

1. Introduction

At the moment, more than 10 different fitness-for-service (FFS) procedures exist all over the world. We will mention only those most important: R6 [1], BS 7910 [2], API 579 [3], SINTAP [4], ETM [5], [6]. Globalisation in the industry requires widely accepted standards or recommendations to be used uniformly in most countries, at least in Europe. Among the others SINTAP seems to be the most comprehensive. The SINTAP procedure serves as a basis for further developments in the European Commission Project FITNET aiming at a unified European FFS procedure. The SINTAP procedure has the following underlying principles: a) a hierarchical structure based on the quality of available data inputs; b) decreasing conservatism with increasing data quality including detailed guidance on determination of characteristic input values such as fracture toughness; c) the choice of representation of

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results in terms of a Failure Assessment Diagram (FAD) or Crack Driving Force (CDF); d) specific methods incorporating the effect of weld strength mismatch.

In this paper, the SINTAP procedure has been applied to assess safety of pipelines in heat and power generating plants after 160000 hours (more than 18 years) of operation. The pipeline is made of the 12Kh1MF steel. The first level of analysis has been performed for a uniform material. However, the secondary thermal stresses due to the cooling process have been taken into account. Both FAD and CDF options have been used for crack initiation. In the process of computation, results presented in the earlier author's papers [11], [12], [13], [14], [15] have been utilized.

2. Materials and elements tested

In the heat and power generating plants, the pipelines are used to transport superheated steam at the temperature range 500–550°C and under the pressure, P = 10 – 14 MPa. The steam-gas is also a source of hydrogen [7]. Under the synergetic action of temperature and stresses, the structure of steel (ferrite – pearlite or ferrite – bainite) changes in time. The results obtained by the author and other authors, reported in the literature [8], [9], [10], [11], [12], [13], [14], [15] suggest, that mechanical properties *Re* (yield strength) and *Rm* (ultimate strength) weakly reflect the changes in the steel structure. The weak decrease of *Re* and *Rm* can only be observed during the first 40000 hours of operation (Fig. 1.1), afterwards no changes of these quantities were observed.

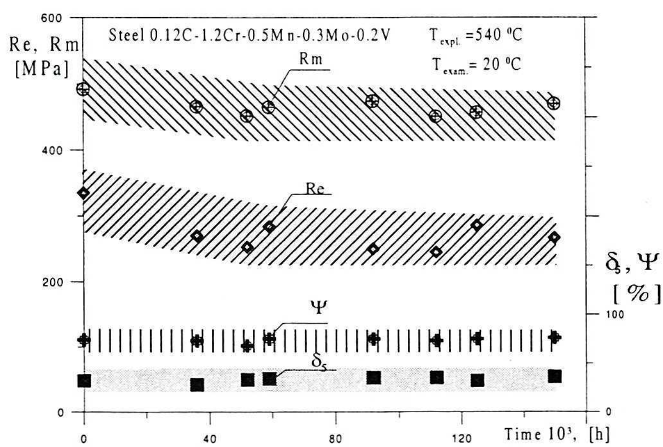


Fig. 1.1. The hange of the mechanical properties of the 12Kh1MF steel during operation time

However, the fracture toughness quantities are sensitive to the evolution of microstructure during the whole period of pipeline operation [11], [12],

[13], [14], [15]. It was shown that fracture toughness values under monotonic loading J_{IC}, were reduced during the time of pipeline operation from the value 187-318 kN/m recorded before pipeline operation to the value 48-98 kN/m after 156000 hours of service (Fig. 1.2). Similarly, the fracture toughness characterizing the stable crack growth, here defined as dJ/da, was even more reduced from 398-480 MPa to 0-56 MPa at 156000 hours of operation (Fig 1.2). Higher values of dJ/da correspond to ductile mechanism of fracture due to the void nucleation growth and coalescence (NGC) (Fig. 1.3a). However, when $dJ/da = 0$, the fracture mechanism is cleavage [14] (Fig. 1.3c).

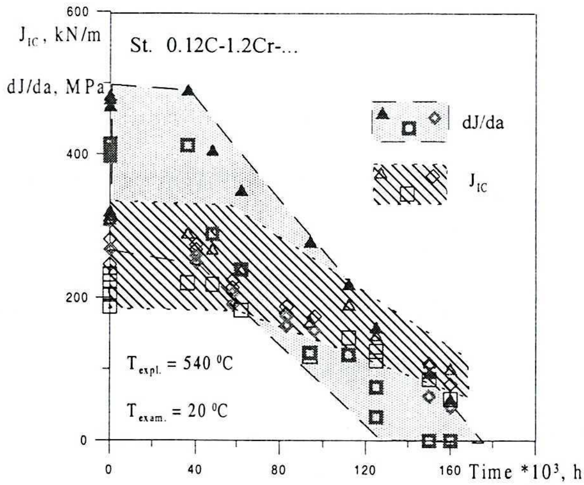
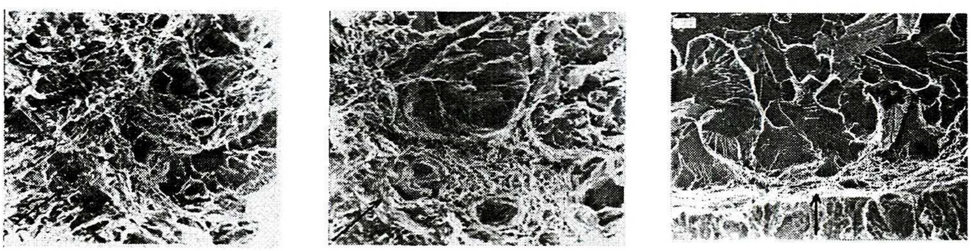


Fig. 1.2. The change of the facture toughness parameters J_{1c} and dJ/da during operation time



(*a*) (*b*) (*c*)

Fig. 1.3. Fracture mechanisms at the initial stage of crack propagation for 12Kh1MF steel at various period of service: (*a*) ductile – before service; (*b*) mixed, the regions of ductile fracture are followed by the regions of cleavage fracture – after 125000 hours of operation; (*c*) cleavage – after 156000 hours of operation. The arrows indicate direction of the crack propagation

The scatter of results, shown in Figs 1.1 and 1.2, is due to the fact that specimens were cut off from different pipes in different power plants. Scatter of results depends on many factors both technological and operational.

Among them are: different original structure, different internal pressure, temperature, and numbers of cooling-heating processes during pipeline operation in different power plants [11], [13], [14].

Regardless of mechanism of subcritical crack growth (fatigue, creep, stress-corrosion), the final act of failure is due to the macro-crack propagation. Thus, the parameters of static linear or non-linear fracture mechanics seems to be the appropriate to predict the moment of unstable crack growth. These parameters are easiest and cheapest to obtain.

In the present article, the fitness for service analysis of straight segments of pipelines operated in heat and power generating plants over the long period (up to 160000 hours) are presented. The pipelines were made of 12Kh1MF steel (GOST 5520, 1979) equivalent to 13HMF (Polish Standard), or 14CrMo4-5 (ISO 9328-2, 1991), or 13CrMo4-5 (EN 10028-2, 1992), or ~F12C1.1 (ASTM A182-96). The chemical composition of this steel is as follows: 0.12%C, 1,1%Cr, 0.54%Mn, 0.26%Mo, 0.26%Si, 0.17%V, 0.019%S, 0.015%P.

The original structure of 12Kh1MF steel, before the working period, was ferrite – pearlite. This steel is considered as ductile material. The lower yield plateau is observed during uniaxial tensile test. Thus, the fracture toughness was measured according to ASTM-E813-88 (since all tests were made before the new standard was published). Then, the K_{IC} was computed from the well-known formula using the measured J_{IC} values. The J_{IC} was measured using three point bent (SEN(B)) specimens of B (thickness) = W (width) = 15 mm. The tested specimens were cut off from pipeline straight segments in such a manner that crack growth direction corresponded to C-R orientation. The yield and ultimate (R_e and R_m) tensile stresses were measured using specimens of 8 mm diameter and 40 mm length. Measured mechanical properties and fracture toughness for the whole time of pipeline operation (from 0 to 156000 hours) are shown in Table 1. Minimum, maximum as well as the mean values are listed.

Table 1

Mechanical properties and fracture toughness of the 12Kh1MF steel

Time operation (h)	Re (MPa)	Rm (MPa)	J_{IC} (kN/m)	K_{IC} (MPa · m$^{1/2}$)	K_{mat_25}** (MPa · m$^{1/2}$)
0	300–330 (320)*	460–500 (480)*	187–232	207.74	185.23
54000	287–315 (301)*	454–492 (473)*	170–218	198.07	
94000	275–310 (298)*	410–485 (470)*	144–167	182.29	
156000	250–320 (303)*	475–490 (477)*	48–56	105.25	95.03

* mean values

** computed by eq. (2.4)

It was assumed, for the purpose of analysis, that the pipelines contain semi-elliptical (Fig. 1.4a) or infinite length cracks (Fig. 1.4b) located along the pipe axis at the inner surface. Cracks can penetrate part of the pipe wall thickness or they can breakthrough (Fig. 1.4c).

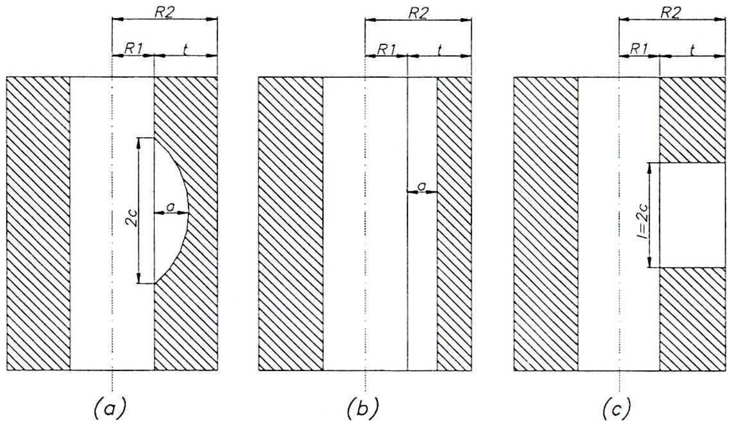


Fig. 1.4. Cracks analysed in the paper: (*a*) – finite-axial-internal surface semi-elliptic crack; (*b*) – infinite-axial-internal surface crack; (*c*) – axial-through-thickness crack

Following the observations reported in the literature, the most critical situation is usually observed during the cooling process of the pipeline [8], [9]. Therefore, the experimental results, concerning mechanical properties obtained at the ambient temperature (20°C) were utilised in the analysis.

An example computations were performed for two states of the pipeline: for the state before operation and after 156000 hours of service.

3. Application of SINTAP procedures

SINTAP procedure [4] allows using one of two equivalent approaches: FAD approach or CDF approach. In both cases, one must determine L_r function (the ratio of the applied stress to the stress to cause yielding of the cracked structure).

According to FAD approach, it is necessary to plot an assessment point or set of assessment points, of co-ordinates (K_r, L_r), where K_r is the ratio of the applied linear elastic stress intensity factor, K_I, to the materials fracture toughness, K_{mat}, calculated under the loading conditions applicable and these are then compared with the Failure Assessment Line, $f(L_r)$. Assessment Line defines the envelope for achievement of limiting condition for the loading of the cracked structure, and assessment points lying on or within this envelope indicate that the structure, as assessed, is acceptable against this limiting condition. The Assessment Line depends on the selected level of analysis and can be computed from the formulas listed in [4].

The CDF approach requires calculation of the crack driving force on the cracked structure as a function of L_r. The crack driving force may be calculated in terms of J – integral or crack opening displacement. To use the CDF approach, for the basic level of analysis, the CDF should be plotted as a function of L_r, to values of $L_r \leq L_r^{max}$, and a horizontal line drawn at the value of CDF equivalent to the material's fracture toughness. The point where this line intersects the CDF curve defines the limiting conditions.

In both approaches, the determination of L_r and $f(L_r)$ functions is based on the mechanical properties of a tested material. In fact, selection of the level of analysis depends on the quality and details of the material's data available (yield or proof strength, ultimate tensile strength or full stress – strain curve).

The first level of analysis requires minimum (to compute L_r) and mean (to compute $f(L_r)$) values of yield or proof strength and ultimate tensile strength and fracture toughness determined for at least three specimens. One should also know whether the stress strain curve is continuos or it contains lower yield plateau.

For materials with lower yield plateau, the $f(L_r)$ function can be determined from Eqs (2.1a), (2.1b), (2.1c).

$$f(L_r) = [1 + 0.5 \cdot (L_r)^2]^{-1/2} \qquad for \qquad L_r \leq 1 \qquad (2.1a)$$

$$f(1) = \left(\lambda + \frac{1}{2\lambda}\right)^{-1/2} \qquad for \qquad L_r = 1 \qquad (2.1b)$$

$$f(L_r) = f(1) \cdot L_r^{(N-1)/2N} \qquad for \qquad 1 \leq L_r \leq L_r^{\max} \qquad (2.1c)$$

Work hardening power exponent N in (2.1c) can be determined experimentally, or can be computed from approximate formula (2.2a) [4]:

$$N = 0.3 \cdot (1 - R_{el} / R_m) \qquad (2.2a)$$

$$L_r^{\max} = 0.5 \cdot (1 + R_m / R_{el}) \qquad (2.2b)$$

$$\lambda = (1 + E \cdot \Delta\varepsilon / R_e) \qquad (2.3a)$$

$$\Delta\varepsilon = 0.0375 \cdot (1 - R_e / 1000) \qquad (2.3b)$$

In the equations (2.2-2.3), R_{el} is lower yield strength, or $R_{el}=0.95 \cdot R_{eH}$. If the stress – strain curve is known $\Delta\varepsilon$ should be measured as a length of a lower yield plateau.

In Figs 2.1 and 2.2 the FAD's, $K_r=f(L_r)$, are shown for material before operation and after 156000 hours of service. The curves are practically identical. Slightly different are the values of L^r_{max}. $L^r_{max}=1.25$ for the material before operation and $L^r_{max}=1{,}287$ after 156000 hours of operation.

Function K_r is defined as: $K_r = K_I/K_{mat\_25}$, where K_{mat_25} is fracture toughness related to the specimen thickness $B=25$ mm. Depending on fracture mechanism: cleavage or ductile SINTAP procedure defines different methods to determine fracture toughness. For cleavage fracture K_{mat} is determined after censoring procedure and application of Maximum Likelihood Method. For ductile mechanism of fracture K_{mat} is computed for minimum value from the series of $\{J_{IC}\}_i$ values from the well known formula $K=\sqrt{JE/(1-\nu^2)}$. K_{mat_25} is computed from the formula [4]:

$$K_{mat\_25} = 20 + (K_{mat} - 20) \cdot (B/25)^{1/4} \tag{2.4}$$

Next step in the SINTAP procedure is to determine primary stresses within tested element. In our case, for the straight segment of the pipeline, the primary stresses can easily be computed from the Lame' formula. Since the axial cracks are considered in this paper only the formula for hoop stresses is given:

$$\sigma_\theta = \frac{P \cdot k^2}{1-k^2}\left(1+\frac{1}{\rho^2}\right) \tag{2.5}$$

where $k = R_1/R_2$ – the ratio of the inner to outer radius of a tube;

$\rho = r/R_2$ – the ratio of the actual to outer pipe radius.

The Stress Intensity Factor (SIF) can be computed from one of the available in the literature formulas. For the inner axial semi-elliptical crack the following formula was adopted [16], [17], [18]:

$$K_I = \sqrt{\pi a}\sum_{i=0}^{3}\sigma_i f_i\left(\frac{a}{t}, \frac{2c}{a}, \frac{R_1}{t}\right) \tag{2.6}$$

where σ_i is a polynomial approximation of the stress distribution in the plane of a crack for the defect free element.

For the axial inner surface crack of infinite length [16], [17], [18]:

$$K_I = \frac{1}{\sqrt{2\pi a}} \int_0^a \sigma(u) \sum_{i=1}^{3} f_i\left(\frac{a}{t}, \frac{R_1}{t}\right)\left(1 - \frac{u}{a}\right)^{i-\frac{3}{2}} du \tag{2.7}$$

Coefficients f_i in Eqs (2.6) and (2.7) should be chosen from a proper literature [16], [17], [18], [19].

To compute P_L (in order to determine L_r), the following formula is adopted for the axial inner surface crack of infinite length [20]:

$$P_L = \sigma_y\left(\frac{R_1}{R_1 + a}\right) \ln\left(\frac{R_2}{R_1 + a}\right) \tag{2.8}$$

For inner axial semi-elliptic crack and assuming global yielding [1], the appropriate formula is as follows [20]:

$$P_L = \sigma_y\left(\frac{a}{R_1 M} + \left(\frac{R_1}{R_1 + a}\right) \ln\left(\frac{R_2}{R_1 + a}\right)\right) \tag{2.9}$$

where

$$M = \left(1 + \frac{1.61 \cdot c^2}{R_1 a}\right) \tag{2.9a}$$

For inner axial semi-elliptic crack and assuming local yielding we have [20]:

$$P_L = \frac{\sigma_y}{2(s + c)}\left(s \cdot \ln\left(\frac{R_2}{R_1}\right) + 2b \cdot \ln\left(\frac{R_2}{R_1 + a}\right)\right) \tag{2.10}$$

where

$$s = \frac{ac(1 - a/t)}{MR_1\left(\ln\left(\frac{R_2}{R_1}\right) - \ln\left(\frac{R_2}{R_1 + a}\right)\right) - a} \tag{2.10a}$$

σ_y is a minimum value from the set of Re values reduced by 5%

In Figs (2.1 and 2.2) the results of computations for a straight segment of the pipeline ($R_1 = 0.12$ m, $R_2 = 0.14$ m, $t = R_2 - R_1 = 0.02$ m) under inner pressure $P = 10$ MPa and containing hypothetical axial inner cracks (Fig. 1.4) are shown. It was assumed that depth of the crack changed from 0 to $1.0t$. For semi – elliptic crack the ratio $c/a = 5$ and it was assumed to be constant during crack growth.

[1] The global yielding is understood as a yielding of the whole element crossetion contai ing crack in contrast to the local yielding of the uncracked ligament.

The results of FFS analysis depend strongly on the selection of a type of yielding (local or global) adopted in the computations. For semi–elliptic crack and global yielding (solid lines), the operation of the pipeline is safe even for $a = t$ both for virgin material and after 156000 hours of operation (Fig. 2.1). The sensitivity coefficient ($F_L = OB/OA$; Fig. 2.1) is greater than 1 in the whole range of potential crack growth propagation; for $c/a = 5$ (Fig. 2.3). If the local yielding is assumed in computation process (dashed lines), the critical moment is observed at $a = 0.8t$ (Fig. 2.1). The sensitivity coefficient F_L is smaller than 1 for $a/t > 0.8$ (Fig. 2.3).

For the axial inner surface crack of infinite length (Fig. 2.2), the critical state is reached both for virgin material and after 156000 hours of operation. In the former case it can happen for $a > 0.74t$ in the later case for $a > 0.69t$ (Fig. 2.2).

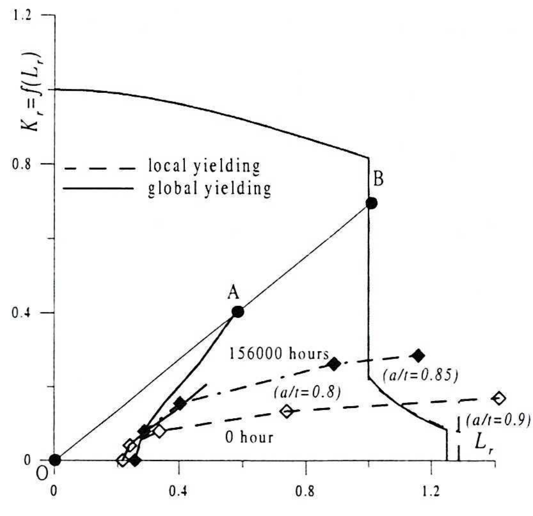


Fig. 2.1. FAD's for finite-axial-internal surface, semi-elliptic crack

In Fig. 2.4, the results of FFS analysis for the axial inner surface crack of infinite length, using the CDF concept are shown. Besides L_r and $f(L_r)$ one should determine the J – integral or crack opening displacement, δ. SINTAP procedure provides simplified analytical formulas to compute these two quantities. J – integral can be found from the equation [4]:

$$J = J_e \cdot [f(L_r)]^{-2} \quad \text{where } J_e = (1 - \nu^2) K_I^2 / E \tag{2.11}$$

According to the data shown in Fig. 2.4, for virgin material failure is likely not to happen for $a < 0.74t$ (empty rhombus). For the pipeline after 156000 hours of operation it can be considered as being in the critical state for $a \geq 0.69t$ (solid rhombus). Thus, both FAD and CDF approaches provide similar results (to compare look at Figs 2.2 and 2.4).

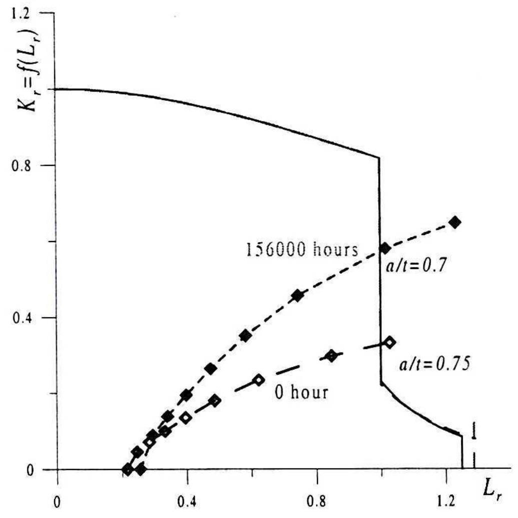


Fig. 2.2. FAD's for infinite-axial-internal surface crack

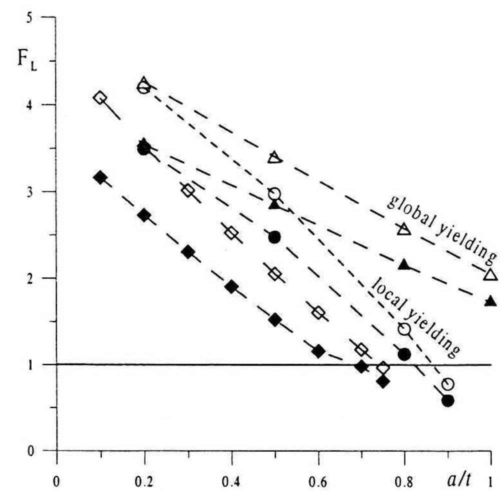


Fig. 2.3. Reduction of the sensitivity coefficient F_L for various crack shapes (semi-elliptic surface crack: virgin material – ○, Δ and material after 156000 hours operation – •, ▲; infinite surface crack: virgin material – ◊ and material after 156000 hours operation – ♦)

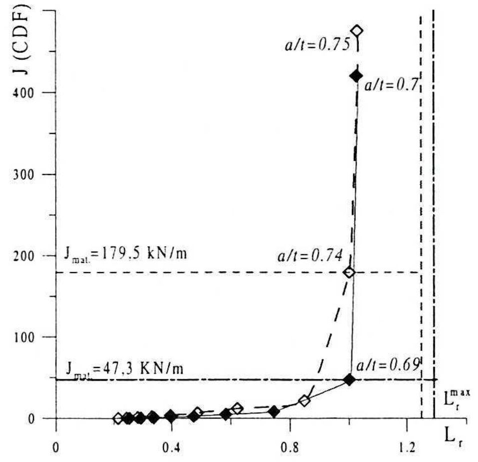


Fig. 2.4. CDF diagrams for axial-inner surface crack of infinite length

Since inner axial semi-elliptic crack is "safe" for $a = t$, the through the thickness crack (Fig. 2.1) should be analysed in addition. The formulas to compute K_r and L_r were adopted from SINTAP document [4]:

$$K_I = \sigma_h \sqrt{\frac{\pi l}{2}(1 + 0.52\chi + 1.29\chi^2 - 0.074\chi^3)} \tag{2.12}$$

$$L_r = \frac{\sigma_m}{\sigma_y}\sqrt{1 + 1.05\chi^2} \tag{2.13}$$

where $\chi = \dfrac{l}{2\sqrt{R_1 t}}$; $\sigma_h = \dfrac{P(R_1 + u)}{t}$; $\sigma_m = \sigma(u)$ *for* $0 < u \le t$

In Fig. 2.5, the FAD along with assessment points is shown for the straight segment of the pipeline with a through the thickness crack. For virgin material the pipeline can be in the critical state ($F_L \le 1$) when $l \ge 220$ mm (Figs. 2.5 and 2.6). After 156000 hours of operation the situation becomes critical for $l \ge 130$ mm (Figs 2.5 and 2.6). According to SINTAP procedures, the semielliptic crack penetrating the element thickness should be replaced by through the thickness crack of $l = 2c + t$ length. Since it was assumed that $c/a = 5$, thus the length of the equivalent crack for $a = t = 20$ is $l = 220$ mm. It means that the pipeline that has operated for 156000 hours with a crack of this size is already in a critical state.

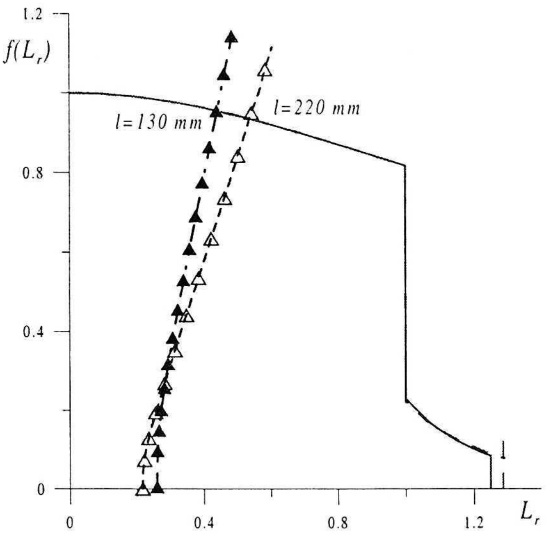


Fig. 2.5. FAD's for the straight segment with a through-the-thickness crack for virgin material (Δ) and after 156000 hours of service (▲)

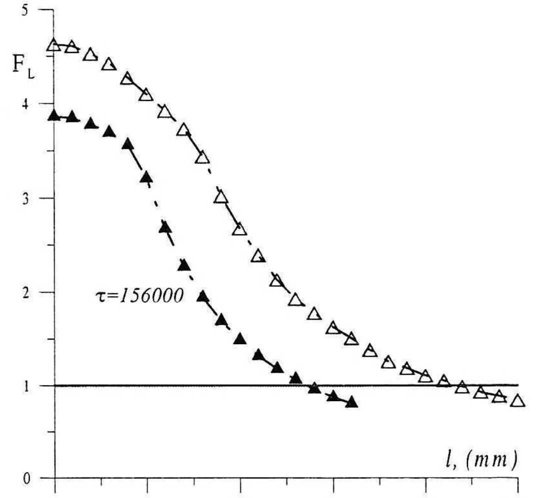


Fig. 2.6. The plot of the sensitivity coefficient F_L v.s. crack length l. (Δ – virgin material, ▲ – after 156000 hours of service)

4. Secondary stress field due to the temperature change

Sintrap procedures classify stresses within the structural element as *primary* and *secondary* stresses. External loading is a source of the primary stress field. The primary stress field can cause the plastic collapse of a structural element alone. The secondary stresses are not able to generate a plastic collapse alone. However, they can influence the evolution of the plastic deformation. To compute L_r, the primary stresses are taken into account only. However, when K_r is computed both primary and secondary stresses should be taken into account.

During the whole period of operation, the pipelines are often cooled down and heated. During these processes, the temperature gradients generate the secondary stress fields – σ^S. The level of stresses during the cooling down — heating processes can be computed from the equations listed in [21]:

$$\sigma_{\theta T} = \frac{\alpha_T \cdot E_T \cdot \omega^{\pm} \cdot (R_2 - R_1)^2}{\lambda_T \cdot (1 - v^2)} S_\theta \tag{3.1}$$

where $S_\theta = \frac{1}{16}(5 + k^2 + \frac{4k^2 \cdot \ln k}{1 - k^2} + 4 \ln \rho - 3\rho^2 + (\frac{4k^2 \cdot \ln k}{1 - k^2} + k^2) \cdot \frac{1}{\rho^2})$ (3.1.1)

In equation (3.1): E_T – is Young modulus for temperature T, v – is Poison's ratio, $\omega^{\pm}$ – is a speed of the temperature change, α_T – is lineal coefficient of thermal expansion, λ_T – is coefficient of heat transfer.

In Fig. 3.1 the hoop stress distribution through the thickness of the pipeline wall is shown for various rates of cooling and heating. $\omega = 0$ denotes stationary regime (no temperature gradients), $\omega = 2$ or ω = -2 are associated with the heating or cooling rates 2 °C/min, respectively. One can notice that during the heating process compressive stresses arise in a pipeline wall. During the cooling process the situation is opposite, and tensile stresses are generated. The level of these stresses at high rates of cooling (ω = -4°C/min) is comparable to the primary stresses.

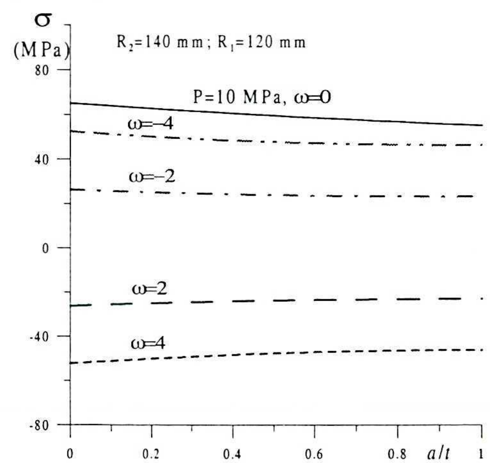


Fig. 3.1. The hoop stress distribution in the wall of pipeline due to the temperature gradients for various rates ω of cooling or heating (dashed lines) and stationary regime $\omega = 0$ (solid line)

The computations of the SIF, K_I^S generated by secondary stress, σ^S were made according to Eq. (2.7). The total, normalised SIF, K_r that includes correction function $\rho(a)$ can be computed from the formula [4]:

$$K_r = K_I^P / K_{mat} + K_I^S / K_{mat} + \rho(a) \tag{3.2}$$

where K_I^P, K_I^S are SIFs for primary, σ^S and secondary, σ^S stresses respectively and function $\rho(a)$ represents interaction between σ^P and σ^S.

In order to compute $\rho(a)$ function, the plastically corrected SIF, K_P^S is necessary. We have selected one of the four procedures suggested by SINTAP to compute K_P^S that is based on effective crack length – a_{eff}.

$$K_P^S(a) = \left(\frac{a_{eff}}{a}\right)^{1/2} K_I^S(a);$$

$$where \quad a_{eff} = a + \frac{1}{2\pi\beta}\,[K_I^S(a)/\mathrm{Re}]^2; \tag{3.3}$$

$$\beta = 1 \ \textit{for plane stress,} \qquad \beta = 3 \ \textit{for plane strain}$$

Next, the function $K_P^S/(K_I^S / L_r)$ should be computed in order to select (from Tables III.2.2 and III.2.3 in SINTAP procedure [4]) proper coefficients ψ and ϕ, that are necessary to find $\rho(a)$.

$$\rho = \psi - \phi\left[\frac{K_I^S}{K_P^S} - 1\right] \tag{3.4}$$

In Fig. 3.2, the FAD's (along with the assessment points) are shown for axial inner infinite crack for the straight element of the pipeline with cooling rate $\omega = -4$ $^{\mathrm{O}}$/min for material, which has operated for 156000 hours. Results are shown for two cases: stationary (triangles) and cooling (rhombus) stages of the operation. Also, results are shown with and without taking into account correction function $\rho(a)$.

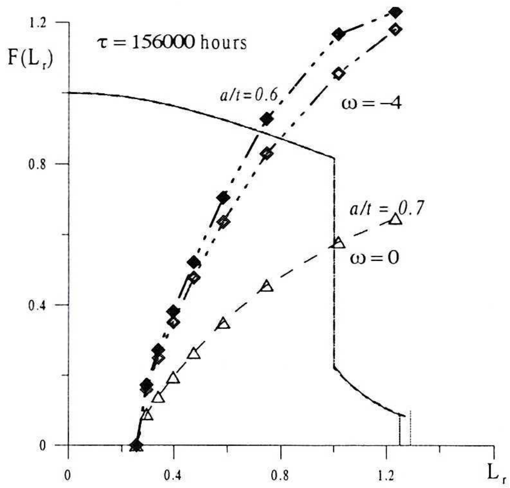


Fig. 3.2. The FAD's for straight pipeline element with axial inner infinite crack for cooling process (ω= -4, (◆,◊)) and stationary regime (△) (◆ – with correction function $\rho(a)$, ◊ – without correction function $\rho(a)$)

5. Discussion

In Fig. 4.1, the results of failure assessment analysis for a straight segment of a pipeline from the heat and power generating plants are shown for inner axial infinite crack. The analysis was performed according to the methodology proposed in [14]. This methodology was based on classical fracture mechanics analysis. The moment of crack growth initiation was predicted by fracture criterion $J_I = J_{IC}$. The level of the dJ/da ratio was used to predict fracture mechanisms, cleavage or ductile.

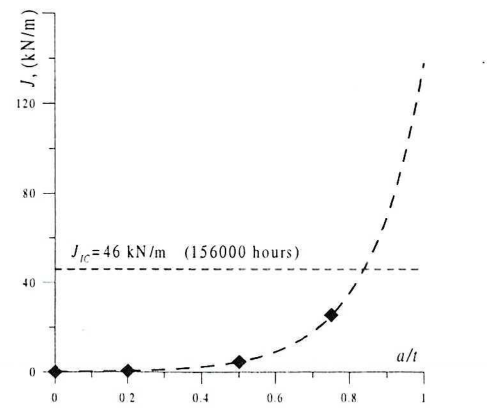


Fig. 4.1. Estimation of safety of the straight pipeline element with inner-axial-infinite crack according to procedure in [14]

It was shown that the critical state could be observed for a crack depth of ~0.85t. According to SINTAP procedure, the critical state can occur for a crack depth of ~0.7t (Figs 2.2, 2.4). Difference observed is due to more conservative assumptions associated with the first level of SINTAP procedure. Results shown in Fig. 4.1 were obtained without assuming any safety factors. One may expect that for higher level of analysis in SINTAP the results could be closer each other.

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Ocena bezpieczeństwa prostoliniowych elementów rurociągów ciepłowniczych wg procedur SINTAP

Streszczenie

W pracy przeprowadzono ocenę bezpieczeństwa prostoliniowych elementów rurociągów ciepłowniczych wykonanych ze stali 12Kh1MF. Obliczenia wykonano według metodyki SINTAP dla prostoliniowych odcinków rurociągów, zawierających hipotetyczne szczeliny powierzchniowe półeliptyczne i o nieskończonej długości, ulokowane na wewnętrznej ściance rury oraz szczeliny przechodzące na wskroś przez ściankę rury. W artykule analizowano sytuacje podczas stacjonarnego okresu eksploatacji, a także dla przypadku niestacjonarnej eksploatacji – rozgrzewania oraz chłodzenia rurociągu. Analizę przeprowadzono dla materiału w stanie nie eksploatowanym i dla materiału po 156000 godzinach pracy rurociągu. Pokazano, że rezultaty obliczeń dobrze zgadzają się z wynikami uzyskanymi wg innej wcześniej zaproponowanej metodyki.