

MODELING OF FRACTURE OF STRUCTURAL COMPONENTS WITH ZONES OF CORROSION WEAR UNDER THERMOMECHANICAL LOADING

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Abstract

The paper is devoted to modeling of deformation and fracture of structural elements with zones of local corrosion wear. Corrosion damage is most often occurring type of degradation of the structural material in operation conditions, primarily on oil, and chemical plants. Modeling of corrosion defect growth and possible fracture of the structure implies solving the self-consistent problems on computing the stress-deformation state in the regions with moving boundaries and kinetics of the defect growth in dependence on the loading and material parameters as well as the structure geometry. The criteria of the limit state and fracture of structural elements with the zones of corrosion wear were formulated. Modeling of the corrosion defect growth in dependence on its initial shape and parameters of steady and transient thermomechanical loading was performed.

Introduction

Structural integrity and service conditions for pressurized components containing defects are regulated by a series of national and international Codes (e.g., [1-3]). The Codes determine the tolerant sizes of defects for the given service conditions. Note, that the recommendations of the Codes are related to the stationary service conditions (including the values of operating pressure and temperature). However, transitional technological regimes associated with the planned start and stop of the components are often realized. Recommendations given in the Codes for these cases are too general (see, e.g. [4]), Appendix 17) and do not make provision for the defects presence. Hence, the problem on providing the structural integrity at the transitional regimes needs a special analysis taking into account the service conditions and possible influence of the defects. The appropriate practical recommendations need to be given in the start and stop regulations.

The performed study consists of two parts. In the first part we formulate the criteria of the limit state and fracture of structural elements with the zones of corrosion wear.

Modeling of deformation process and strength computing for an element of the structure surface with a local zone of the corrosion wear was performed under the conditions of a steady and transient thermomechanical loading.

The stress-deformation state of the heated region was computed accounting for the nonuniform and nonstationary temperature distribution. In this case additional thermal stresses occur in the component wall. The boundary value problem was solved by the method suggested in [5]. The criterion of attaining the yield stress that depends on the temperature was used as the criterion of the limit state.

Modeling of the deformation and fracture processes of a structural element without local zones of corrosive wear was performed in [5,6]. Some damage effects were evaluated in [7].

In the second part of the paper we model the growth of a corrosion defect in dependence on its initial shape, loading parameters and temperature. The rate of the corrosion defect growth depends on the spherical part of the stress tensor and is nonuniform along the defect surface [8].

Solving the problem on fracture and modeling the corrosion defect growth implies solving the self-consistent problem on computing a stress-deformation state in the regions with moving boundaries and searching for a rate of the defect growth at each step of the corrosion zone extension. The analysis showed, that the rate field localization is possible at a part of the defect surface where the accelerated growth occurs under certain initial conditions and loading parameters.

Statement of the problem

Let us consider a cylinder of radius R and wall thickness H_0 having a corrosive dimple of rectangular cross-section of length $L = 2\ell$ and depth d at the inner surface. The cylinder represents a model of the cylindrical part of the pressurized component (e.g. pressure vessel or pipe). Multiple experiments show [9,10] that the pipe strength is determined by the maximal depth of the dimple and its size in the longitudinal direction. Assume that the corrosive dimple is located along the whole perimeter of the cylinder.

Denote by T_0 the temperature of cylinder after stopping the component operation. Next start is accompanied by the action of a heated medium of pressure p on the inner surface of the wall. Denote by ΔT the temperature jump at this inner surface. The thermomechanical loading can lead to localization of deformations and fracture in the zone of corrosive wear. The critical regimes and combinations of the parameters are searching for.

To describe the process of deformation of the cylinder with the corrosive dimple one needs to solve a coupled problem on the heat transfer and deformation.

The condition $(H/R) \ll 1$ is assumed later on such that the shell theory can be used for modeling the stress-deformation state of the cylinder. Material deformation is assumed to be elastic up to attaining the limit state.

It is known [11,12] that localization of the corrosion process can occur in the zones of plastic deformation at the component surface (in the places of the dislocation outlet). The physical mechanism of localization is associated with the acceleration of electrochemical reactions at the freshly formed zones of the surface where the oxide film is absent. Stress concentration in such zones also promotes further localization and acceleration of the corrosion process [8]. In this case the criterion of attaining the minimal value of the yield stress depending on the temperature, T , by the maximal equivalent stress can be used [13]

$$\sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \leq \sigma_Y \quad (1)$$

where σ_1 , σ_2 are the main stresses, $\sigma_Y(T)$ is the yield stress with characteristic temperature dependence taken into account [14].

The first criterion is more conservative than the second used criterion that determines the fracture conditions at the zone with the corrosive dimple at the cylinder surface. It is assumed that the fracture process for the steels of low and median strength is determined by attaining the plastic state within the whole section of the component wall. A similar criterion of the limit state is used in the known ASME Code B31G [1] for searching for the critical sizes of the corrosive dimples and is based on the experimental results on fracture of pipes with zones of corrosive damage.

Hence, we used the following criterion of the limit state related to the cylinder fracture

$$\frac{\sigma_\theta}{\sigma_Y} + \left(\frac{M_Z}{M_Y} \right)^2 = 1 \quad (2)$$

where σ_θ is the median circumferential stress in the cylinder, M_Z is the bending moment along its element, $M_Y(T) = (\sigma_Y \Delta^2 / 4)$ is the limit bending moment related to formation of a plastic hinge at bending, $\Delta = H - d$ for the zone of the corrosive dimple and $\Delta = H$ outside of this zone.

Condition (2) determines the critical parameters of the thermomechanical actions at the cylinder fracture in the zone of the corrosive dimple. The critical values of the parameters calculated according to Eq. (2) are compared with ones calculated according to Eq. (1) and used for evaluation of the stock and residual lifetime of the component in further operation.

The nonstationary heat transfer problem will be considered in the 1D–approximation taking into account the nonuniform temperature distribution through the cylinder wall. Hence, the heat fluxes along the cylinder surface are neglected since the maximal nonstationary thermal stresses occur at the time interval when the heat front did not attain the external thermal isolated surface.

The 2D – stress-deformation state occur in the cylinder wall near the corrosive defect (concentrator) is determined by the pressure p and temperature jump ΔT_0 , taking into account the nonstationary heating of the wall. Attaining the limit state in a point of the cylinder is determined by the circumferential stresses and the stresses of longitudinal bending according criteria (1), (2) accounting for the temperature dependence of the yield stress.

Let us consider a model of the defect growth. The rate of the corrosion defect growth at the given temperature is determined by the value of the spherical part of the stress tensor and is nonuniform along the defect surface [8].

Assume that the structure was in service during the period of τ years. Then one can evaluate the corrosion rate in each point of the defect at the moment of its detection as follows

$$V_0(x) = \frac{W(x)}{\tau}, \quad |x| \leq \ell \quad (3)$$

The rate $V_0(x)$ is considered as the initial rate of the defect growth under subsequent loading.

An influence of the stresses on acceleration of the corrosion processes is determined by the following formula [8]:

$$V(x, t) = V_0 \cdot F(x) \cdot K_{y.K.}; K_{y.K.} = \exp(\sigma V / 3RT) \quad (4)$$

where $V=7 \text{ cm}^3/\text{mole}$ is the steel molar volume, $R=8.31 \text{ J/mole K}$, T is the temperature, $^{\circ}\text{K}$, $\sigma = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3$ is the spherical part of the stress tensor at the surface of the corrosion defect (the value σ is determined numerically during modeling the defect growth), $F(x)=(1-x^2/\ell^2)$ at $|x| \leq \ell$ for the defect of the parabolic shape and $W(x)=d$ at $|x| \leq \ell$ for the defect of the rectangular shape (the shape function).

The variation of the defect shape is determined as follows

$$W(x, t) = W(x) + V(x, y) \cdot t \quad (5)$$

where t is the time interval such that the rate of the defect can be considered as constant during this interval.

Hence, we formulated the self-consistent statement of the problem on the corrosion defect growth.

The stresses during the defect growth process are determined from the solution of the 2D-problem on deformation of a cylinder with a zone of a corrosion defect. The variations of the defect growth rate and its shape are determined by relations (4) and (5), respectively.

Analysis of the results of the numerical modeling

The stress-deformation state and critical parameters (pressure and temperature jump) for the cylinder with the corrosive defect were computed for the following material and initial parameters typical for carbon low-alloy steels: $\alpha = 5 \cdot 10^{-6} \text{ K}^{-1}$, $\lambda = 40 \text{ wt/m grad}$ (coefficient of thermal conductivity), $C_p = 460 \text{ Joule/kg grad}$ (the heat capacity), $\rho = 7800 \text{ kg/m}^3$ (density), $R = 0.01 \text{ m}$, $E = 200 \text{ GPa}$, $H_0 = 0.008 \text{ m}$, $L = 0.08 \text{ m}$, $T_0 = 0^{\circ}\text{C}$ (initial temperature). The values of the yield stress were taken according to the data given in Fig. 2 for the maximal temperature ($T_0 + \Delta T$) to provide a conservative estimate of the critical parameters determined by criteria (1), (2) of the limit state. The computations were performed for different values of the pressure, temperature and residual wall thickness, H , in the zone of the corrosive defect.

The interrelation between the critical pressure and temperature jump determined by criterion (1) is given in Fig. 1 for the cylinder of the nominal wall thickness $H_0 = 0.008 \text{ m}$ and the residual wall thickness in the zone of the corrosive defect $H = H_0 - d = 0.003 \text{ m}$ (the lower curve) and $H = 0.005$ (the upper curve). The combinations of the parameters which provide save operation of the component are associated with the regions located under the limit curves of Fig. 1. Note, that plastic deformations do not occur in these regions under the nonstationary loading regimes.

Similar limit dependences determined by criterion (2) are given in Fig. 2. The limit curves in this case are located over the appropriate curves for criterion (1) (see Fig. 1). However, the

difference between the critical parameters determined by two criteria is not large. Just this difference determines the margin of safety. Hence, the development of the transient regimes regulation requires introducing additional margins of safety accounting for possible variations of the loading parameters as well as geometric and material parameters such that the appropriate calculations of the safe parameters for the transient regimes need using the probabilistic models of the structural strength and the defect statistics (see, e.g. [1,15]).

Two preceding examples were related to the case of the search for the critical pressure within the framework of criteria which do not admit attaining the limit state in no one section.

Now let us consider the case of loading where the limit state is attained. Assume that fracture of low and mean strength steels is described by a model taking account of plastic buckling (collapse), i.e. occurring large deformations and displacements on a certain part of the structural element being deformed. In turn, formation of the plastic buckling zone on a tube with an axisymmetric corrosion defect will be related to formation of a tube zone restricted by plastic hinges. Then the large section rotations (and as a consequence large displacements) occur at the boundary of this zone. Plastic hinge formation within the tube wall is determined by the criterion given by Eq. (2).

The computed values of the critical pressure at the stationary temperature we will compare with the results of computations on the basis of known Code B31G [1]. Remind, that this Code is based on the experimental data on tube rupture related to the conditions of stationary loading. Hence, we will compare the values of the maximal allowable operation pressure – MAOP obtained according to the suggested model and Code B31G.

An example of the results of the critical pressure computing in dependence on the corrosion defect length are given in Fig. 3 for a tube of wall thickness $H = 0.01$ m and diameter $D = 0.2$ m, at the $T = 50^{\circ}\text{C}$ and the yield stress of the tube material

$\sigma_Y(50^{\circ}\text{C})=270$ MPa. One can see a good fitting of the pressure values obtained by both methods in the case of the stationary loading.

The computed results of the defect depth, $W(x,t)$, variation in dependence on time are given in Fig. 4 (for a rectangular defect) and in Fig. 5 (for a parabolic defect) for a half-length of the defect. In both cases one can see localization of the defect growth rate on a certain part of its surface followed by an increasing acceleration up to the defect intergrowth through the whole thickness of the structure wall. But the defect of a rectangular shape grows almost uniformly up to the instant of formation of the defect localization zone. It is the zone where the abrupt increase of the defect growth rate subsequently occurs. The regime of progressive formation of the localization zone (without any abrupt acceleration of the defect growth rate) is realized for a defect of a smooth variation of the defect shape. The characteristic size of the breaking through zone is not larger than 10 mm. This size correlates with the observed one for the leaks on the pipelines. The time interval of the localization zone growth up to its breaking through is of order 10% of the full computed time of the defect growth and depends on the defect length and pressure value.

In conclusion note that the suggested model and method for computing fracture characteristics of structural components with zones of corrosion wear is applicable in cases of transient and stationary thermomechanical loading.

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References

1. *ASME B31G-1991*. Manual for Determining the Remaining Strength of Corroded Pipelines. ASME, New YORK, US, 1991.
2. *CAN/CSA-Z184-M186* "GAS Pipelines Systems", Canadian Standards Associations, 178 Rexdate Blvd., Rexdate, Ontario, Canada, 1986.
3. *Methodical recommendation for the check rating of boilers and their elements*, Publ. "AOZT "DIEKS"", Moscow, Russia, 1996.
4. *Code "OST 26 291-94"*. Vessels and apparatus, steel welded, Publ. "NPO OBT", Moscow, Russia, 1996.
5. Goldstein, R.V., Zhitnikov, YU.V., Kadochnikov, I.V., *Mechanics of Solids*, vol. **35**, N 6, 89-96, 2000.
6. Shesterikov, S.A., *Structure and strength of materials subjected to laser radiation*, Publ. "Izd. MGU", Moscow, Russia, 1988.
7. Zainulin, R.S., Gumerov, A.G., Morozov, E.M., Galyuk, V.Kh., *Hydraulic measurements of operating oil pipelines*, Publ. "Nedra", Moscow, Russia, 1990.
8. Steklov, O.I., *Materials and structures resistance to corrosion under stress*, Publ. "Machinostroenie", Moscow, Russia, 1990.
9. Kiefner, J.F., Vieth, P.H., *Oil and Gas J.*, vol. **88**, No.32, 56-59, 1990.
10. Kiefner, J.F., Vieth, P.H., Eiler, R.J., Duffy A.R., In *ASTM STP 536*, 461-481, 1973.
11. Popov, Yu.A., *Theory of metals and alloys interaction with the corrosion-active medium*, Publ. "Nauka", Moscow, Russia, 1995.
12. Leis, B.N., Parkins, R.N., *Fatigue & Fracture of Engineering Materials & Structure*, vol. 21, 583-601, 1998.
13. Vinokurov, V.A., Kurkin, S.A., Nikolaev, G.A., *Welded construction. Fracture mechanics and workability criteria's*, Publ. "Mashinostroenie", Moscow, Russia, 1996.
14. Gudkov, S.I., *Mechanical properties of steels at low temperatures*, Publ. "Metallurgija", Moscow, Russia, 1967.
15. Bolotin, V.V., *Application of the methods of the probability theory and reliability theory in construction computing*, Publ. "Stroiizdat", Moscow, Russia, 1971.

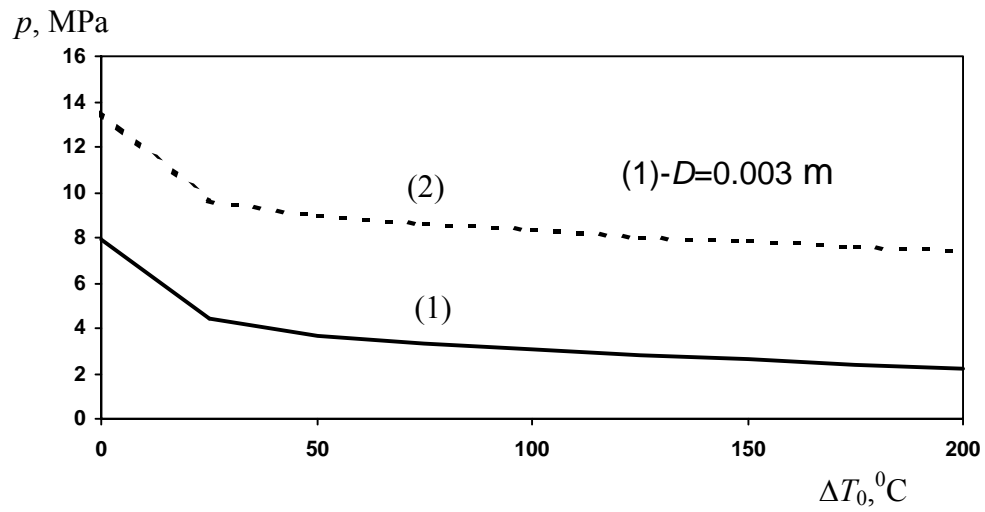


FIGURE 1: Limit curves of critical pressure dependence vs temperature jump according to criterion 1 (Eq. 1)

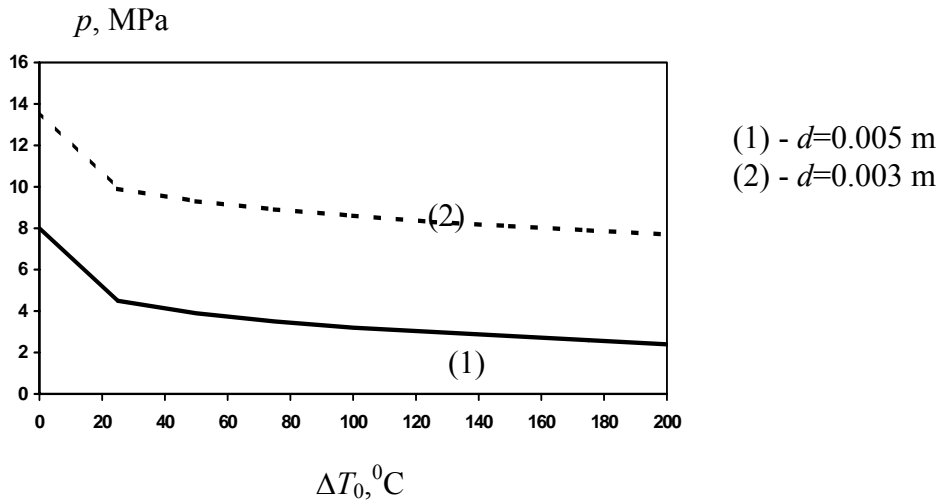


FIGURE 2: Limit curves of critical pressure dependence vs temperature jump in according to criterion 2 (Eq. 2)

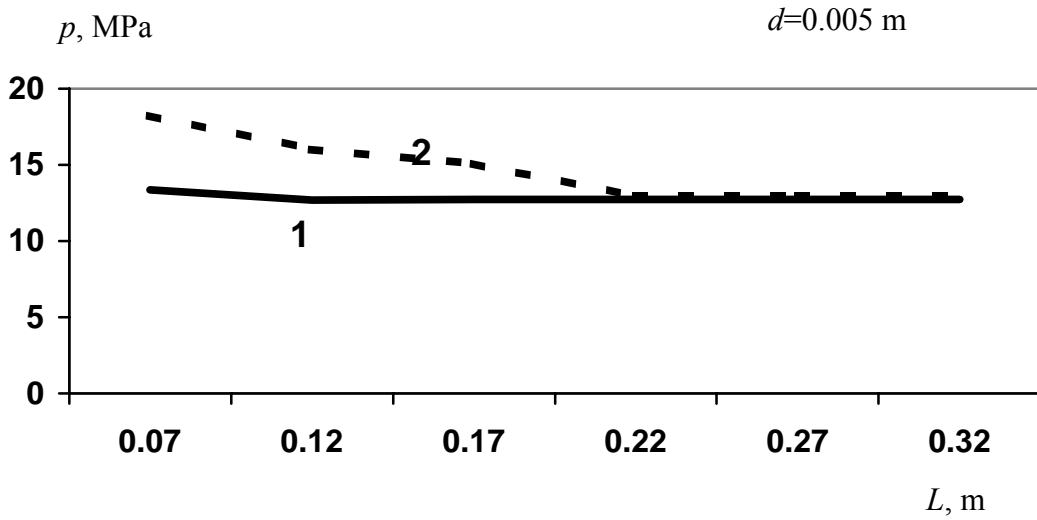


FIGURE 3: Limit curves of critical pressure dependence vs temperature $T=T_0+\Delta T$ ($T_0=0^{\circ}\text{C}$) at the uniform and stationary temperature distribution $T=T_0+\Delta T$. Limit curve 1 are in according to criterion 2 (Eq.2). Limit curves 2 are in according to ASME B31G [1].

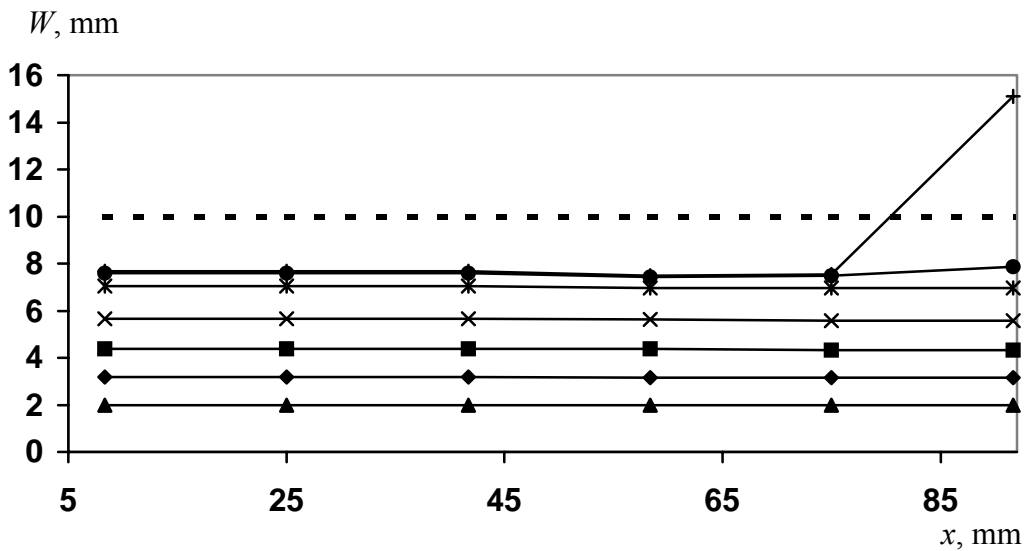


FIGURE.4: Dependence of the shape variation for a rectangular defect at corrosion wear ($d=0.002$ m – initial defect depth, $p = 12$ MPa - pressure, $V_0=0.5$ mm/year – initial defect growth rate).

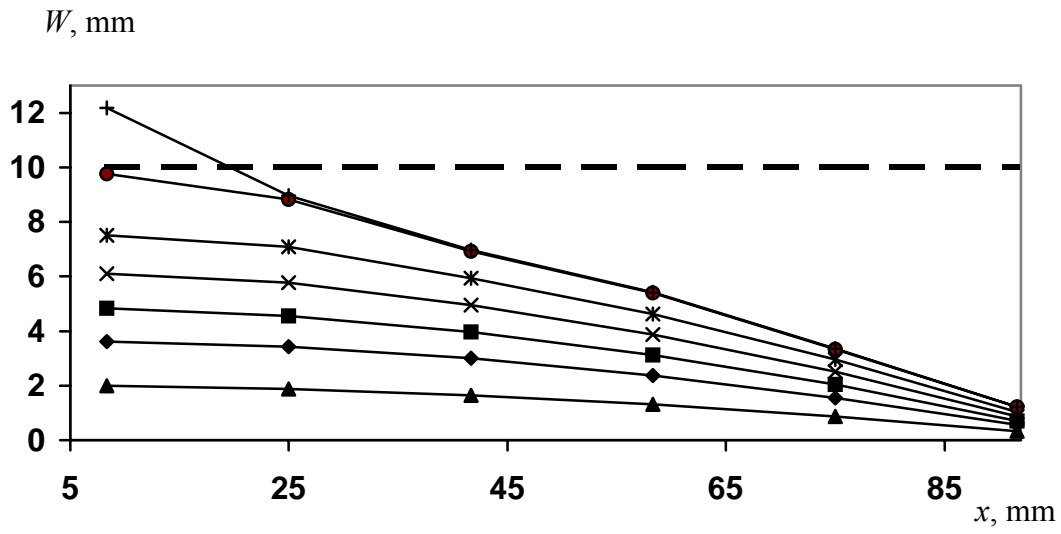


FIGURE 5: Dependence of the shape variation for a parabolic defect at corrosion wear ($d=0.002$ m – initial defect depth, $p = 12$ MPa - pressure, $V_0=0,5$ mm/year – initial defect growth rate)