MODELLING OF PROCESSES OF NUCLEATION AND DEVELOPMENT OF DUCTILE FRACTURE PORES IN WELDED STRUCTURES

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Evaluation of serviceability and residual life of the critical welded structures with found defect, including pipelines and pressure vessels, assumes a complex analysis of interrelated multidimensional processes, influencing their bearing capacity. At that, grounded reduction of conservatism of such an evaluation is rational that requires description of structure limiting state considering main fracture mechanisms. In particular, ductile fracture is a main mechanism of development of material damage in the main pipelines with typical surface defects of local corrosion wall thinning without accompanying sharp concentrators. Complex methodology for numerical analysis of processes of nucleation and development of ductile fracture pores of metal welded structures as well as criteria for determination of their limiting state was developed in the scope of present work. Thus, a procedure for calculation of stress-strain state in-service structure considering change of load-carrying net-section of structure areas at microporosity growth was build on the basis of Gurson–Tvergaard model. The criteria of pore nucleation as well as mathematical description of different mechanisms of their development depending on character of external force action were proposed for non-isothermal metal state, in particular, in the process of welding heating. Application of the developed approaches was shown on the example of analysis of limiting state of main pipeline element with local wall thinning defect in area of circumferential site weld. It is shown that limiting internal pressure in the pipeline with such service damage is determined by character of interaction of local stresses in zone of the weld and geometrical anomaly, i.e. the lower is the distance between them, the less is the loading necessary for formation of common zone of microdamage in which the macrodefects are formed as a consequence. Similarly, significant effect of pores on the bearing capacity in pipeline site weld is shown. Generality of the developed approaches of numerical analysis of ductile fracture processes allows applying them for evaluation of limiting state and residual life of the welded pressure vessels from high-strength steels. 18 Ref., 1 Table, 3 Figures.

Keywords: *ductile fracture, pore formation, stress-strain state, limit load, welded joint, main pipeline*

Analysis of limiting state of the modern welded structures is an important stage in diagnostics of their real condition and prediction of safe operation residual life. At that, a description of processes resulting in breaking of integrity of the structure material in micro- and macroscale, nucleation and development of the typical defects requires joint application of procedures for modelling of stress-strain state kinetics depending on value and nature of external force effect, basics of fracture mechanics and current interpretations about behavior of crystalline structures under limiting force action. Besides, presence of the welded joints assumes the necessity of additional consideration of structure state in welding area (heat treatment) from point of view of residual stress-strain and structural states of the metal as well as development of scattered damage based on modelling of processes of continuous medium thermoplasticity. As it is shown by experience, the fracture of welded pressure vessels and pipelines from high-strength steels is determined in series of cases by the ductile fracture processes in area of welds and geometric anomalies [1, 2]. At that, most of the existing ductile fracture models consider structurally-homogeneous materials in isothermal case [3–5], whereas in real structures the welds are weak zones and analysis of their limiting state is an important aspect of technical diagnostics of the critical structures. In particular, approaches of Gurson, Tvergaard and Needleman [6–8], which make a basis of the most current models of limiting state of the structures tend to ductile fracture, have found a wide application in description of the development of stress-strain state of the materials with pores. In addition, series of works is dedicated to expansion of these models applicable to the welded structures, but mathematical description of a welding process itself and its influence on peculiarities of the ductile fracture has rather phenomenological character and requires large number of experimental investigations. Numerical procedure for analysis of the ductile fracture was developed and examples of the typical cases of main pipeline damage were considered in the scope of present work in order to study the peculiarities of limiting state of welded pipeline elements under internal pressure.

Studied fracture mechanism in the general case can be divided on several successive stages:

- nucleation of ductile fracture pores in production of structures, including in a zone of local welding heating and at developed plastic flow in area of physical and/or geometry concentrators;
- increase of pore sizes at plastic strain;
- interaction and coalescence of ductile fracture pores;
- nucleation of macrodefect and related with it reduction of bearing capacity of defective area as well as structure in the whole;
- development of macrodefect.

Each of these steps has different physical-mechanical nature, therefore, their description requires construction of the corresponding interrelated models.

It is accepted that the pore nucleation in zone of the structural defects and inhomogeneities (primary pores) is related with significant development of the plastic strains that can be described by Odkvist parameter [9]:

$$\kappa = \int d\varepsilon_i^p, \qquad (1)$$

where $d\varepsilon_i^p = \frac{\sqrt{2}}{3}\sqrt{d\varepsilon_{ij}^p d\varepsilon_{ij}^p}$, $d\varepsilon_{ij}^p$ are the components of tensor of plastic strain increment ($i, j = x, y, z$).

Respectively, if current value of Odkvist parameter exceeds critical value κ_c, it serves as a condition for pore nucleation in the isothermal case.

Appearance of metal structure inhomogeneities, in particular, in area of its solid-liquid state interface (between the liquidus and solidus temperatures) takes place in the process of welding as a result of local welding heating, first order phase transformations and concurrent liquation processes. At that, general sized dependence of Odkvist parameter critical value κ_c on metal state at different temperatures T can be used for description of micropores nucleation:

$$\kappa_c(T) = \kappa_{c0} \exp\left\{\left[\frac{F_0 - F(T)}{B}\right]^{\beta}\right\}, \qquad (2)$$

where $F(T)$ is a function of material resistance to plastic strain; κ_{c0}, B, F_0, β are the constants.

If the expressed temperature embrittlement interval and significant strengthening are not typical for the studied metal, then the yield strength temperature dependence $\sigma_y(T)$ can be taken as $F(T)$ function. Thus, it follows from (2) that κ_{c0} and F_0 are the critical values of Odkvist parameter of the studied metal at room temperature and its normative yield strength σ_y, respectively, and temperature dependence of the Odkvist parameter critical value can be represented in the following way:

$$\kappa_c(T) = \kappa_{c0} \exp\left\{\left[\frac{\sigma_y - \sigma_y(T)}{B}\right]^{\beta}\right\}. \qquad (3)$$

B value for structural steels $\beta \approx 3$ [10] is characterized by material susceptibility to pore formation and lies in $(1.0–1.5)\sigma_y$ ranges.

Criterion of pore nucleation in the metal at variable temperature field with developed kinetics of plastic strain accumulation can be described by following relationship:

$$\chi_\kappa = \int \frac{d\kappa}{\kappa_c(T)} \geq 1. \qquad (4)$$

If condition (4) is fulfilled, it can be assumed that an inhomogeneity in a form of spherical micropores with volume concentration f_{pl} is nucleated in studied area of the structure.

It should be noted that the second typical mechanism of pore nucleation in welding is a formation of impurity bubbles in a welding pool, which do not have enough time to evolve in a gas phase before metal solidification [11]. Modelling of such a process is sufficiently complex and is not included in the scope of present work. Effect of indicated process can be taken into account as a priori either by setting of the spherical macrodefects in the weld area or considering the total volume concentration of nucleated pores f_0 in the specific studied volume:

$$f_0 = f_{pl} + f_{ev}, \qquad (5)$$

where f_{ev} is a volume concentration of pores, nucleated as a result of evaporation processes.

Further growth of ductile fracture pores depends on a rigidity of stressed state and intensity of plastic strain of the metal and is described by Rice–Tracy law [9]:

$$dR = R_0 K_1 \exp\left(K_2 \frac{\sigma_m}{\sigma_i}\right) d\varepsilon_i^p, \qquad (6)$$

where R, R_0 are the current and initial radiuses of pores, respectively; $\sigma_m = (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/3$ is a membrane stress; $\sigma_i = (\sigma_{ij}\sigma_{ij}/2)^{1/2}$ is a stress intensity; σ_m/σ_i is a parameter of stressed state rigidity; $K_1 = 0/28$, $K_2 = 1.5$ are the constants.

If the parameter of stressed state rigidity in studied area of the structure is not enough for intensive growth of pores according to (6), then significant influence of the plastic strains can result in appearance of the secondary discontinuities. Speed of nucleation of the secondary spherical pores depends on concentration of inclusions in the structure metal and development of plastic strains on the following law [9]:

$$f = f_0 + f_i \exp\left(-\frac{\kappa^*}{\kappa - \kappa_c}\right), \qquad (7)$$

where f_i is a volume concentration of the inclusions; κ^* is a metal constant characterizing maximum possible increment of Odkvist parameter.

It should be noted that f_i value in the studied case depends on a structure state of metal in weld area and heat-affected zone (HAZ), in particular, on quantity of cementite (Fe_3C) as well as initial and acquired non-metallic inclusions in the process of welding [12]. Analysis of stress-strain state of the welded structure from point of view of ductile fracture was carried out in the present work from point of view of numerical solution of boundary problem of non-stationary thermoplasticity by means of tracing of elasto-plastic strains from the moment of welding beginning up to complete cooling of the structure and at further loading up to limiting pressure in the scope of finite-element model. Relation of stresses and strains is determined by Hooke's law and associate law of plastic flow, originating from the following relationships:

$$\Delta\varepsilon_{ij} = \Psi(\sigma_{ij} - \delta_{ij}\sigma_m) + \delta_{ij}(K\sigma_m + \Delta\varepsilon_m + \Delta f/3) - \\ - \frac{1}{2G}(\sigma_{ij} - \delta_{ij}\sigma_m)^* + (K\sigma_m)^*, \qquad (8)$$

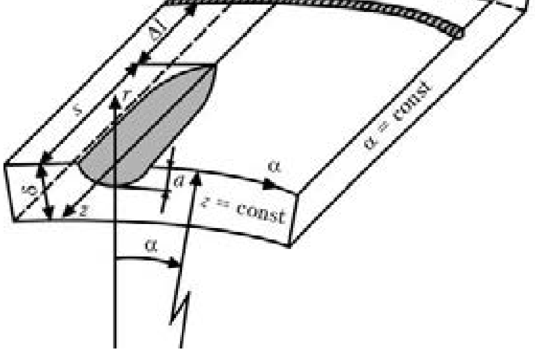

Figure 1. Scheme of pipeline section with local wall thinning and circumferential weld (in cylindrical coordinate system, r, α, z)

where $K = \frac{1 - 2\nu}{E}$; E is an Young modulus; ν is a Poisson ratio; $G = \frac{E}{2(1 + \nu)}$; Ψ is a function of material state. Ψ function is determined by condition of the plastic flow according to Mises criterion with additional consideration of reduction of bearing net-section of the finite element as a result of formation of the discontinuity in scope of Gurson–Tvergaard model, namely:

$$\Psi = \frac{1}{2G}, \text{ if } \sigma_i < \sigma_s, \quad \Psi > \frac{1}{2G}, \text{ if } \sigma_i = \sigma_s, \\ \sigma_s = \sigma_y \sqrt{1 + (q_3 f^*)^2 - 2q_1 \cosh\left(q_2 \frac{3\sigma_m}{2\sigma_y}\right)}, \qquad (9)$$

where $q_1 = 1.5$, $q_2 = 1$; $q_3 = 1.5$ are the constants; f^* is an equivalent volume concentration of pores considering their interaction in the finite element.

Value of equivalent pore concentration, appearing in (9), is determined from a relation, proposed by Gurson and Needleman [7]:

$$f^* = \begin{cases} f, & \text{if } f \le f_c; \\ f_c + \frac{f_u^* - f_c}{f_F - f_c}(f - f_c), & \text{if } f > f_c, \end{cases} \qquad (10)$$

where f_c is a critical concentration of the discontinuities up to which separate pores do not interact (taken as $f_c = 0.15$); f_F is a pore concentration at which fracture of the finite element takes place; $f_u^* = 1/q_1$.

Limiting state of each finite element is determined from two possible fracture mechanisms [15], i.e. plastic instability in $\Psi \to \infty$ case according to McClintock condition and microcleavage.

Limiting state of the pipeline element (diameter 1420 mm, wall thickness 20 mm, material — steel 17G1S, properties of which is given, in particular, in [16]) with circumferential weld and external surface wall thinning of metal loss type (Figure 1) of $2s = 50$, $a = 5$ mm size which is allowable according to [17], was considered as an example of application of the developed complex model for analysis of the welded structures. The following values of parameters and necessary constants were taken as input data of the present numerical investigation, i.e. $f_0 = 0.01$; $f_i = 0.01$; $\kappa^* = 0.1$; $\kappa_{c0} = 0.05$; $B = \sigma_y$; $R_0 = 0.0167$ mm. It should be noted that influence of possible errors in determination of the values of given constants on the results of investigations reduces significantly at approximation of loads to limiting ones (i.e. in the case, if at least one of the finite elements had lost the bearing capacity and macrode-

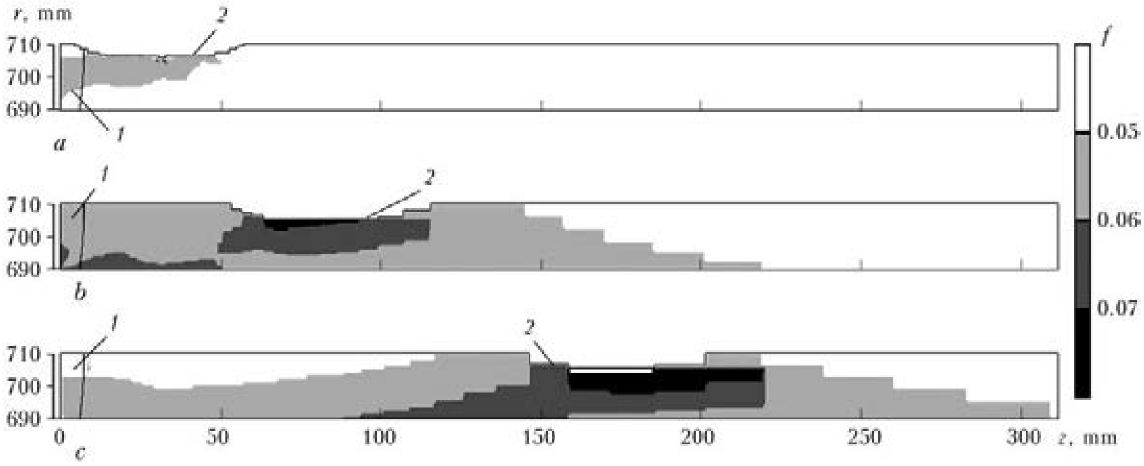

Figure 2. Distribution of volume concentration of micropores f in studied pipeline section at limiting pressure P_{max} depending on Δl distance between weld and wall thinning defect: *a* — Δl = 5 mm, P_{max} = 18.8 MPa; *b* — Δl = 50 mm, P_{max} = 19.8 MPa; *c* — Δl = 150 mm, P_{max} = 20.2 MPa; *1* — half of symmetrical weld; *2* — defect

fect appeared), since at that state of the structure is characterized by plastic strain.

Different mutual location of the weld taking into account residual stress-strain state as well as scattered damage, accumulated in the process of welding, and concentrator in area of geometry anomaly assume different fracture mechanisms [15] as well as different limiting pressure in the pipeline. The results of numerical experiments showed that the appearance of small pore concentration (around 0.05) along the fusion line was promoted by local thermal cycles and corresponding to them kinetics of stress-strain state of the structure metal in area of weld metal and HAZ. Such a damage has insignificant effect on the structure bearing capacity, since rigidity parameter of stress-strain state σ_m/σ_i of the pipeline element does not achieve significant values under internal pressure effect due to absence of sharp concentrators. Therefore, plastic strain in the studied case does not promote significant pore development in welding according to (6) and prevailing mechanism of damage development is the appearance of new pores in area of concentrator and secondary pores from plastic strain on (4) and (7), respectively.

At that, the damage develops independently in area of maximum defect depth and in HAZ of the weld at the initial stages of structure loading by internal pressure. Typical peculiarity of the limiting state is an obvious interaction between two types of studied inhomogeneities from point of view of microporosity formation (Figure 2). At that, the larger is the distance between weld and surface thinning Δl, the more is the force action necessary for formation of volume of metal damage between them, where microfracture (Figure 3) is nucleated at further increase of load. As can be seen from the presented data, close location of allowable thinning defect and site weld can reduce bearing capacity of the pipeline up to 10 %.

As was mentioned above, the possible nucleation of pores in the weld as a result of evaporation of interstitial impurities in a case, when gas bubbles do not have enough time to appear on the surface before complete metal solidification, is one more factor affecting pipeline bearing capacity. This situation was investigated by means of setting of hollows (linear size 1 mm) near the fusion line, i.e. being macrodefects and taking total volume fraction of weld metal around 0.07. Calculation of microporosity development, according to the created procedure, results of which are given in the Table, showed a tangible influence of macropores on the pipeline bearing capacity, namely, reduction of internal limiting pressure from 20.4 up to 17.6 MPa. This result correlates with known experimental investiga-

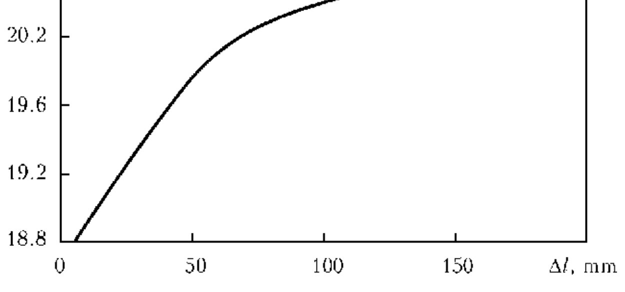

Figure 3. Dependence of limiting pressure in the pipeline from distance between thinning defect and circumferential weld

Concentration of micropores in weld area of pipeline element taking into account presence of macropores at limiting pressure 17.6 MPa

r, mm z, mm	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0
5	0.064	0.052	0	0	1.0	0	0	0	0	0	0
6	0.104	0.063	1.0	1.0	0.05	1.0	0.057	0.051	0	0	0
7	0.102	0.085	0.05	0.05	0.05	0.05	0.058	0.051	0	0	0
8	0.096	0.101	1.0	1.0	1.0	1.0	0.153	0.118	0.089	1.0	1.0
9	0.101	0.123	0	0	0	0	0.13	0.135	0.143	0.05	0.05
10	0.117	0.163	0	0	0	0	0.088	0.115	0.097	1.0	1.0
11	0.079	0	0	0	0	0	0.058	0.063	0.063	0	0
12	0	0	0	0	0	0	0	0	0.086	0.051	0
13	0	0	0	0	0	0	0	0.061	0.056	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0

Cont.

r, mm z, mm	12	13	14	15	16	17	18	19	20	21
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0.05
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0.06	0.057
6	0	0	0	0	0	0	0	0.057	0	0
7	0	0	0	0	0	0	0.063	0	0	0
8	1.0	1.0	1.0	1.0	1.0	1.0	0.086	0.062	0	0
9	0.05	0.05	0.05	0.05	0.05	0.05	0.082	0.062	0.05	0
10	1.0	1.0	1.0	1.0	0.05	0.05	0.067	0.062	0.06	0.059
11	0	0	0	0	1.0	1.0	0.09	0.081	0.07	0.073
12	0	0	0	0	0	0	0.07	0.074	0.08	0.075
13	0	0	0	0	0	0	0.056	0.066	0.07	0.071
14	0	0	0	0	0	0	0	0.059	0.06	0.064
15	0	0	0	0	0	0	0	0.054	0.06	0.059
16	0	0	0	0	0	0	0	0	0.05	0.055

Note. Weld area is marked by grey color.

tions [18] and existing requirements to quality of site welds of the main pipelines.

Conclusions

1. Complex procedure for numerical evaluation of limiting state of the welded structures inclined to ductile fracture under effect of external stresses was developed. A model of nucleation, development and interaction of ductile fracture micropores as well as the criteria of microdefect formation and coming of structural element limiting state were proposed for this based on the finite-element solution of nonstationary thermoplasticity boundary problem.

2. Regularities of the development of damage in metal structure under effect of the internal pressure were considered on the example of main pipeline section with the external defect of local metal loss near the site circumferential weld. It is shown that the limiting state of defective structure is characterized by formation of the general damage area between weld and geometry anomaly. At that, the less is the distance between defect and weld, the lower is the service loading, necessary for showing the mutual effect between them and further appearance of macrodefects. This, in turn, can reduce the pipeline bearing capacity to 10 % in comparison with defect-free structure.

3. Considered are the peculiarities of effect of macropore type weld defects, formed from gas bubbles solidified in the weld metal. Possible significant effect of indicated defects on the structure bearing capacity is shown, i.e. reduction of the pipeline limiting pressure to 17.6 MPa for volume concentration of arbitrary distributed pores 0.07 in the weld metal.

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