EVALUATION OF OPERABILITY OF THE MAIN PIPELINE WITH LOCAL WALL THINNING AT REPAIR BY ARC SURFACING

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Welding surfacing is one of the most rational methods of repairing the main pipelines without taking them out of service, particularly in the case of the need to eliminate typical defects of local metal loss through corrosion. Here welding application on a pipeline, which is at high internal pressure, envisages a thorough optimization of technological parameters of this process in terms of safety and effectiveness of repair-and-renewal operations, in particular, on the base of the results of modeling the occurring physico-mechanical processes kinetics. In this study a package of tools was developed for mathematical modeling of the process of multipass welding surfacing of thinning defects of the main pipeline elements to predict their technological strength and post-repair residual life. For this purpose an integrated approach of numerical analysis of the kinetics of temperatures, stress-strain state and processes of tough fracture of pipeline material has been implemented. A numerical criterion has been proposed, which allows, with a slight conservatism, prediction of formation of structure state, close to the limiting one, as well as guaranteeing the required load-carrying capacity of the pipeline, after repair of the detected defect of discontinuity type. The case of multipass surfacing repair of an inadmissible defect of the main pipeline wall thinning was used to study the characteristic peculiarities of the influence of the main technological parameters on the structure technological strength and its residual life. 17 Ref., 1 Table, 6 Figures.

Keywords: *arc surfacing, main pipeline, defect, local wall thinning, repair under pressure, safety of repair-and-renewal operations, plastic instability, tough fracture*

Maintaining the operability of main pipelines (MP) involves a package of measures on non-destructive testing of their actual state, evaluation of residual life, allowing for the detected service damage, as well as repair-and-renewal operations in the sections with inadmissibly low static strength. MP common defects are external surface local metal losses of corrosion origin, caused by the impact of aggressive media in the region of violation of insulating coating integrity. In view of considerable extent of MP systems, elimination of such defects by capital repair is labour-consuming and requires long downtime in MP operation. One of the techniques, allowing elimination of defects detected by technical diagnostics with minimum reduction of product throughput volumes, is repair by welding, in particular, welding surfacing [1, 2]. Application of local welding heating here involves temporary weakening of pipeline wall that makes the question of the structure technological strength at surfacing urgent in terms of guaranteeing the required level of repair safety.

A number of foreign and national studies [3–5 etc.] are devoted to this problem. In them the questions of technological strength in repair welding of pipelines without shutting them down, are usually divided into two conditional classes: evaluation of development of structural transformations, mechanical stresses and diffusion processes in the structure metal in terms of minimizing the risk of appearance of welding defects (first of all, cold cracks); and analysis of the kinetics of temperature and strain field, in order to determine conservative modes of local welding heating, allowing prevention of burns-through or excess distortion in the repair section.

Influence of welding process on steel susceptibility to cold cracking, has been studied well enough, and a well-established practice of guaranteeing absence of such defects in the surfacing area is preheating up to 100–150 °C that was reflected in currently valid standards and norms [6, 7]. The second problem class is more complicated, as it includes multidimensional analysis of interrelated processes of kinetics of temperature, stress and strain fields in welding, as well as prediction of possible initiation and propagation of micro- and macrofracture of the structural element. At present, two main criteria of technological parameters optimization in defect surfacing in operating MP can be singled out.

1. Battelle criterion [8]

$$T_{\text{in.max}} < T_{\text{in.cr}} = 720 \div 980\ ^\circ\text{C}, \qquad (1)$$

where $T_{\text{in. max}}$ is the maximum temperature on pipeline inner surface during surfacing; $T_{\text{in.cr}}$ is the critical temperature, dependent on the used electrode type.

2. Criterion based on model 46345 [9]

$$dr < dr_{\text{cr}} \sim 1\ \text{mm}, \qquad (2)$$

where dr is the maximum radial distortion of the wall in the heating area as a result of internal pressure impact; dr_{cr} is the critical strain value.

There also exist a number of alternative criteria, in particular, the approach earlier proposed by PWI specialists, which consists in tracing the evolution of isothermal surface $T_{\text{def}} = 1000$ °C, and evaluation of admissibility of such an area as a thinning defect [5], similar to CRC/CSIRO model [10]. All the above-mentioned procedures allow realization of simple in practical application, but maximum conservative engineering criteria, not allowing for a number of important aspects of welding surfacing, for instance, pipeline internal pressure and geometry for condition (1), degree of melting and temperature dependencies of mechanical properties of a specific steel for (2). This is related, in particular, to the problem of selection of criterial parameters ($T_{\text{in.cr}}$, dr_{cr}, T_{def}), which are not fracture resistance characteristics of structure material and require either experimental precising for each specific case of service damage, or significant conservatism for sufficiently wide applicability.

Within the bounds of this study, with the purpose of further development of methodological fundamentals of analysis of the safety and effectiveness of multipass surfacing in operating MP, a package of kinetic models of interrelated physico-mechanical processes characteristic for this technology have been developed, and respective criteria of structure integrity preservation have been proposed. Peculiarities of pipeline condition, determining both its technological strength during repair welding, and its performance in subsequent operation, have been analyzed in the case of multipass surfacing of an external defect of MP wall thinning under internal pressure.

Numerical analysis was based on calculated kinetics of the temperature field, determined by solving the equation of heat conductivity with temperature-dependent thermophysical characteristics of the material [11]. Subsequent tracing of elasto-plastic strains within the bounds of finite-element solution of boundary problem of nonstationary thermoplasticity was used to calculate the kinetics of the structure stress-strain state [12]. At each tracing step the relationship between the components of tensors of stresses σ_{ij} and strains ε_{ij} was defined by generalized Hooke's law and associated plastic flow rule, proceeding from the following relationships:

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

where $K = (1 - 2\nu)/E^*$; $G = E/(2(1 + \nu))$; E is the Young's modulus; ν is the Poisson's ratio; δ_{ij} is the Kronecker symbol; ψ is the material state function, determined by iteration to satisfy the plastic flow condition; f is the volume concentration of microdiscontinuity, initiating during material fracture; $\sigma_m = \sigma_{ij}/3$ is the membrane stress; $i, j = \{r, \beta, z\}$ according to Figure 1; here summation is performed by repeated symbols.

Optimization of repair technological parameters is based on the ability of MP defective section to take complex load from internal hydrostatic pressure P_r at the moment of performance of repair-and-renewal operations, alongside temporary welding stresses in the surfacing area. Therefore, an important step is selection of rational criteria, which guarantee the integrity of pipeline wall for the considered case. As violation of material continuity in arc surfacing repair of local thinning of pipeline wall occurs at high temperatures in the absence of sharp-angled geometrical raisers, the prevailing fracture mechanism is the tough fracture, which consists in initiation and propagation of material micropores at intensive plastic deformation [13]. This, eventually, leads to formation of macrodefects and violation of structure integrity. As demonstrated by the authors in [14], change of load-carrying net-section of the material after it has reached limit loads, should be additionally taken into account

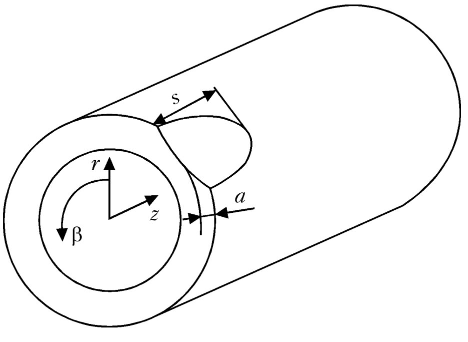


Figure 1. Schematic of pipeline section with local wall thinning (in cylindrical system of coordinates)

at definition of the problem of nonstationary thermoplasticity for correct evaluation of the structure limiting state. One of the recognized approaches is use of material yield surface, allowing for uniformly distributed discontinuity within the bounds of Gurson–Tvergaard–Needleman model [15]:

$$\begin{cases} \psi = \dfrac{1}{2G}, \text{ if } \sigma_i < \sigma_s = \sigma_y \times \\ \times \sqrt{1 + (q_3 f)^2 - 2q_i f \cosh\left(q_2 \dfrac{3\sigma_m}{2\sigma_y}\right)}, \\ \psi > \dfrac{1}{2G}, \text{ if } \sigma_i = \sigma_s, \end{cases} \qquad (4)$$

where $q_1 = 1.5$, $q_2 = 1$, $q_3 = 1.5$ are the constants; $\sigma_i = \sqrt{\sigma_{ij}\sigma_{ij}/2}$ is the stress intensity.

Thus, the criterion of pipeline wall integrity preservation at surfacing is absence of plastic instability of porous material that is mathematically expressed by the following condition:

$$\psi < \frac{1}{2G} + \frac{\varepsilon_f - \kappa^*}{1.5\sigma_i(\kappa, T)(1 - 2f/3)}, \qquad (5)$$

where κ^* is the Odqvist parameter, referred to the previous step of tracing the elastoplastic strains; ε_f is the ultimate strain of metal dependent on the stressed state rigidity, according to [12].

Moreover, considerable development of material porosity by the tough mechanism causes an essential increase of true stresses in the structure metal, and its fracture as a result of it. Therefore, a further condition can be added to (5) with the purpose of definition of a criterion of MP integrity preservation, which is correct and convenient for numerical analysis, as follows:

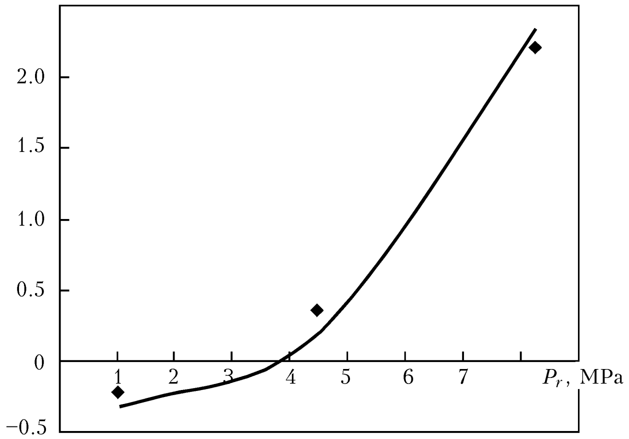


Figure 2. Comparison of calculated values of pipeline wall residual radial distortions after surfacing with experimental data [11]

$$(q_3 f)^2 - 2q_1 f \cosh\left(q_2 \frac{3\sigma_m}{2\sigma_y}\right) \to 0. \qquad (6)$$

Models of pore initiation and propagation right up to fracture in pipeline elements with geometrical anomalies, are given, in particular, in [14].

An important factor of effectiveness of the considered repair procedure, which is not allowed for in its optimization criteria (1) and (2), is residual postweld deformed state of the structure. During local heating, the defect area acquires excess radial displacement dr_{res} under the impact of internal pressure. In fact, the detected defect of pipe wall local thinning is transformed into a shape defect after surfacing under pressure, the admissibility of which is determined by pipeline analysis for static strength. Here, the position of shape defect coincides with the deposited beads that makes higher requirements to the quality of welding operation performance and to subsequent nondestructive testing in terms of guarantee of welding defect absence.

Admissibility of shape defect is determined, in particular, by national standard [16], according to the requirements of which the safety factor of a pipe with defect n should be not smaller than the admissible value of k [17]:

$$n \geq k = \frac{0.9 k_1 k_{\text{p}}}{m}, \qquad (7)$$

where k_1, k_{p} are the safety factors by material and purpose, respectively; m is the coefficient of pipeline operation conditions.

Thus, simultaneous fulfillment of conditions (5)–(7) is a complex numerical criterion of optimization of welding surfacing technological parameters. Proposed complex models were verified proceeding from the data on stress-strain state of model pipeline samples (diameter $D = 219$ mm, wall thickness $t = 3.2$ mm, material — API 5L steel) at different values of internal pressure ($P_r = 1.03$–8.47 MPa) at deposition of two circumferential beads on them [9]. Figure 2 gives comparison of calculation results with experimental data. It should be also noted that in keeping with the developed procedure of evaluation of pipeline limiting state at surfacing, plastic instability for the considered case is found at the pressure of about 8.6 MPa. Studying the microstructure of an experimental sample deposited at the pressure of 8.47 MPa, revealed initiation of material discontinuities in the region of maximum deformation that corresponds to the ingress of its limiting state. The above-said leads to the conclusion that the results of numerical studies within the bounds of the proposed numerical analysis procedure, describe with sufficient accuracy the behaviour of pipeline elements in welding surfacing.

Characteristic features of the limiting state and the effectiveness of this approach, in particular, its conservatism, compared to criteria (1) and (2) were studied in the case of welding surfacing repair of thinning defect of length $2s = 140$ mm and depth $a = 10$ mm on external surface of pipeline of $D = 1420$ mm with wall thickness $t = 20$ mm from steel 17G1S ($\sigma_y = 490$ MPa, $\sigma_t = 560$ MPa) with maximum operating pressure $P = 7.4$ MPa. An isolated defect of local thinning of MP wall was considered as a semi-elliptical surface geometrical anomaly, which was surfaced in two layers by the following schematic, given in Figure 3. It was assumed that pipeline section with the detected defect was preheated up to temperature T_{pr} to avoid cold cracking. Accordingly, repair parameters are welding current I, internal pressure in the pipeline at surfacing P_r, as well as the time between deposition of each of the beads, ensuring maintenance of maximum metal temperature, not lower than the required $T_{min} \geq T_{pr}$.

To illustrate the relationship of conservatism of criteria (1) and (2) and numerical criterion (5)–(7), Figure 4 gives the result of calculation of the dependence between value of pipeline wall maximum radial distortion dr in the area of welding heating and maximum temperature of the inner surface for deposition of one bead (in the defect center) at repair parameters, recommended by the currently valid standards: $I = 80$ A, $P_r = 4$ MPa, $T_{pr} = 100$ °C. As is seen from this dependence, maximum compliance of the wall to internal pressure ($dr_{max} = 1.17$ mm) is observed not at maximum temperatures of heating the pipeline metal or its inner surface, but at certain heat propagation to the periphery of surfacing area. Therefore, monitoring the extent of wall distortion during welding according to (2) is not rational, as the process of heated area cooling is difficult to monitor after deposition of a specific bead. Moreover, the balance between the increasing strength of cooling metal and growing stresses in the area of local bending of the pipe wall, determining the pipeline limiting state, is difficult to predict without the respective multidimensional analysis of thermomechanical processes. This confirms the rationality of the proposed approach to evaluation of the limiting state in terms of minimizing its conservatism. Moreover, bead deposition in the center of a rather deep defect causes local overheating, excess distortion of the wall and non-fulfillment of criterion (2), whereas criteria (1) and (5)–(7) confirm the pipe integrity at such repair parameters that leads to the conclusion about their lower conservatism.

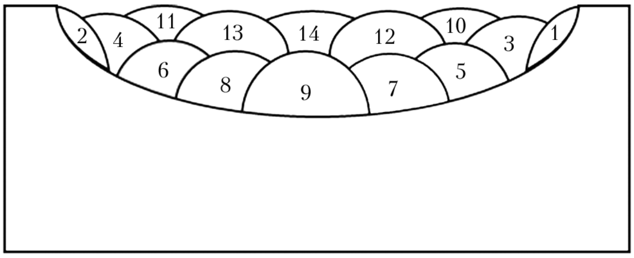


Figure 3. Schematic of surfacing repair of thinning defect on pipeline external surface

Change of the stress-strain state during multipass surfacing is of a complex nature, determined both by different bead location relative to the thinning defect, and by the change of profile of the pipeline damaged part as the deposited metal solidifies (Figure 5). This, in its turn, predetermines the essentially nonlinear dependencies between surfacing parameters in terms of ensuring repair safety and pipeline operability after repair of thinning defect. As an example, the Table gives the results of evaluation of admissibility of some modes of surfacing repair of the above MP defect. Admissibility of residual deformed state according to [16] is based on the distribution of residual radial displacement dr_{res}, derived through mathematical simulation by numerical tracing of the structure state. In particular, the specific value of maximum radial buckling dr_{max} is determined by the degree of development of pipeline metal plastic strains under the joint impact of welding heating and internal pressure: surfaced defect area becomes more compliant to external force impact that intensifies

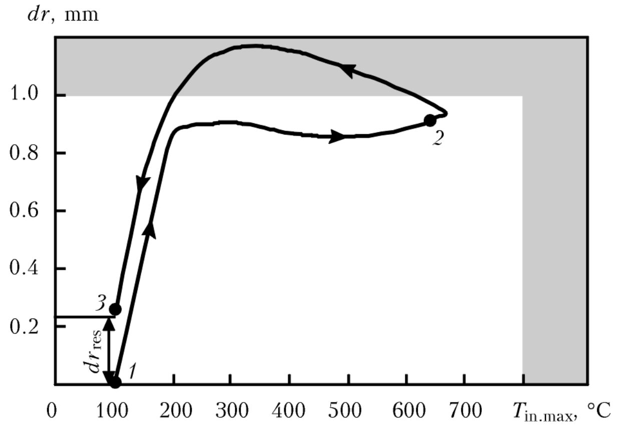


Figure 4. Dependence of excess radial displacement of pipeline external wall on maximum temperature on inner surface at bead deposition on thinning defect (gray colour marks the region of inadmissible states by criteria (1) and (2): *1* — start of defect surfacing; *2* — end of heat source action; *3* — complete cooling of repair area)

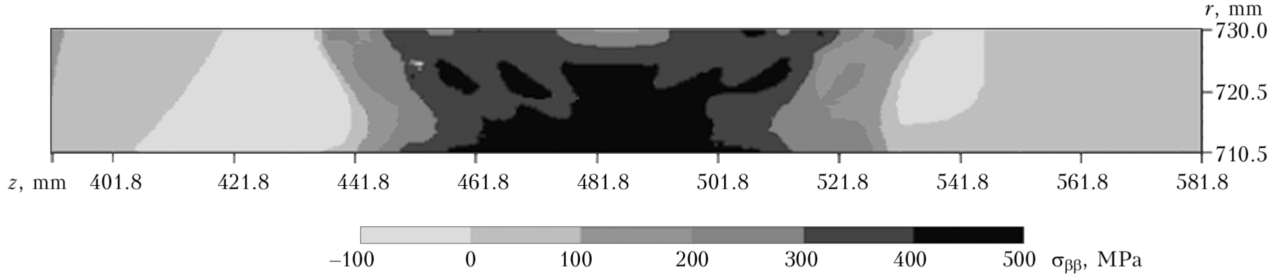
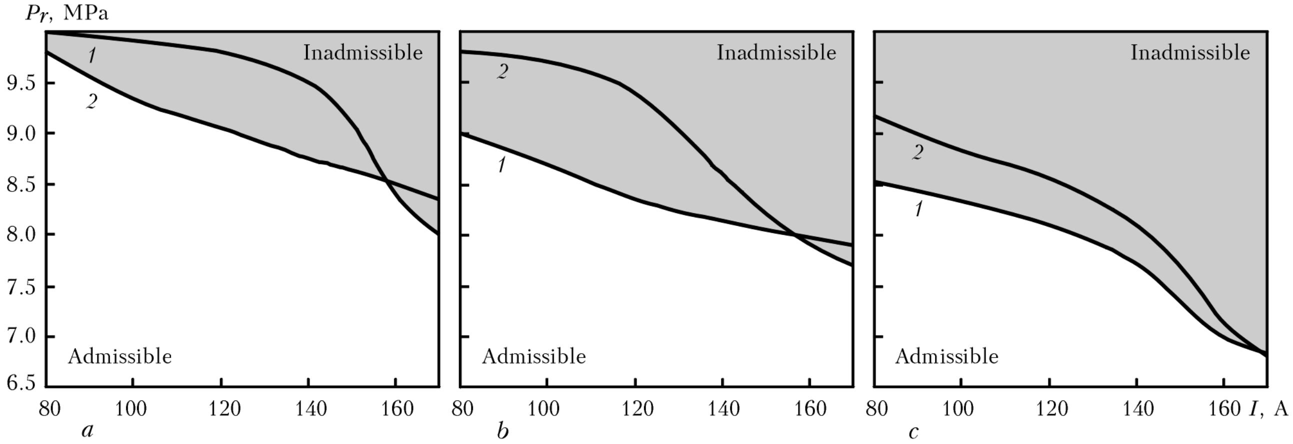


Figure 5. Distribution of residual circumferential stresses in the area of pipeline wall thinning defect after its repair by mutlipass welding surfacing



a *b* *c*

Figure 6. *I*–*P* diagram of applicability of multipass surfacing modes allowing for admissibility of residual shape defect *1* and plastic instability criteria *2*: *a* — T_{pr} = 100; *b* — 300; *c* — 500 °C

Influence of some technological parameters of surfacing on pipeline limiting and residual states

P_r, MPa	I, A	T_{min}, °C	Conclusion on admissibility
4.0	100	300	Surfacing is allowed
4.0	100	500	Same
7.5	150	500	Shape defect, formed as a result of surfacing, is medium according to [16], $1.593 = n < k = 1.617$
7.5	170	500	Plastic instability $\psi \sim 1$

the local accumulation of irreversible plastic strains.

These data can be presented more completely in the form of 2D diagrams, in particular, in the repair pressure–welding current coordinates, an example of which for the considered case (pipeline properties and geometry, extent and nature of damage) is given in Figure 6. These data lead to the conclusion that at significant heat input the prevailing mechanism limiting the application of surfacing, is the risk of plastic instability, whereas at relatively low powers of local heating and high pressures excess residual distortion of the structure becomes dangerous. Curves in the given diagrams mark the boundary separating the regions of pipeline admissible and inadmissible states in multipass surfacing and subsequent operation: parameter region, located below curves *1*, corresponds to fulfillment of criterion (7), whereas the region under curve *2* corresponds to parameters, guaranteeing fulfillment of criteria (5), (6), according to the results of numerical calculations of MP state kinetics in surfacing.

It should be also noted that at practical application, the engineering recommendations on welding surfacing, in keeping with the described numerical analysis procedures, should further allow for safety factors by individual kinds of input data that can quantitatively change the evaluation of technological parameters admissibility, proceeding from the actual condition of MP specific section with the detected damage.

Conclusions

1. Mathematical models of the kinetics of physico-mechanical processes in multipass arc surfacing of a detected defect of pipeline wall local thinning were developed proceeding from currently available models of stress-strain and limiting states of pipeline elements at complex force and thermal impact. A complex numerical criterion of MP integrity at surfacing was proposed, allowing both for pipeline technological strength and its operability after performance of repair-and-renewal operations.

2. Lower conservatism of the developed numerical criteria of integrity of pipeline element with an external defect of local metal loss, is

shown, compared to the currently available approaches, namely Battelle criterion and 46345 model. Lowering of conservatism of numerical evaluation within the bounds of the proposed methodology is based on additional allowing for the processes of tough fracture, which determine formation of pipeline limiting state at simultaneous impact of internal pressure and local welding heating at surfacing.

3. Characteristic features of the main technological parameters influence on structure technological strength were studied in the case of multipass arc surfacing of an inadmissible defect of MP wall thinning. It is shown, in particular, that at considerable heat input the prevailing mechanism limiting the application of surfacing, is the risk of plastic instability, whereas at relatively low powers of local heating and high pressures the most hazardous is the residual deformation of the structure.

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Received 03.07.2014