CRACKS IN WELDED JOINTS OF LARGE DIAMETER PIPES AND MEASURES FOR THEIR PREVENTION

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Considered are the cases of failure of main gas pipelines, including after long-term operation, caused by presence of crack-like defects in the welded joints of pipes which were formed at their manufacture. Analysis of main reasons of appearance of such defects in weld metal and heat-affected zone is provided considering the peculiarities of technological processes of manufacture and welding of pipes. It is shown that cracks can have different orientation and origin, being formed immediately in the process of welding or at later stages of manufacture during performance of adjacent operations, for example, pipe expanding. Their formation is caused by series of technological reasons, for example, movement of welded edges of pipe in process of assembly, incorrect selection of consumables (welding wire, flux), local change of weld metal chemical composition or its structural inhomogeniety due to entering of exogenous particles in weld, increased flux humidity etc. Measures for prevention of appearance of crack-like defects in welded joints of pipes are described. Research results can be used in tube-welding production for improvement of welding technology and control of tubular products, as well as inspection of pipelines in process of their operation. 9 Ref., 1 Table, 9 Figures.

Keywords: *arc welding, main oil-gas pipelines, welded joints, failure, cracks, reasons of formation, prevention*

Main reasons of accidents of linear part of main oil-gas pipelines, as shown by statistical data [1, 2], are such called constructional (formed during construction-assembly works) and service (mainly, corrosion, including stress-corrosion) defects. It is assumed that failures of pipelines caused by construction reasons are the most often in the initial period of their operation [2]. In contrast, increase of pipeline operation significantly raises amount of failures due to corrosion damages.

At the same time, as study of series of failures on main pipeline indicates, their failure, including after long-term operation, can be related with defects formed in the process of pipe manufacture, in particular, with presence of crack-like defects in the welded joints.

Thus, main zone of failure at accident on gas pipeline of 820 mm diameter, the consequences of which are shown in Figure 1, became an extended crack in a mill longitudinal weld of the pipe. Crack length made 850 mm, depth was 4–6 mm (Figure 2). Defect propagation lied in the limits of outside weld along the whole length. Crack surface is damaged by surface corrosion, whereas, out of defect, i.e. zone of failure devel-

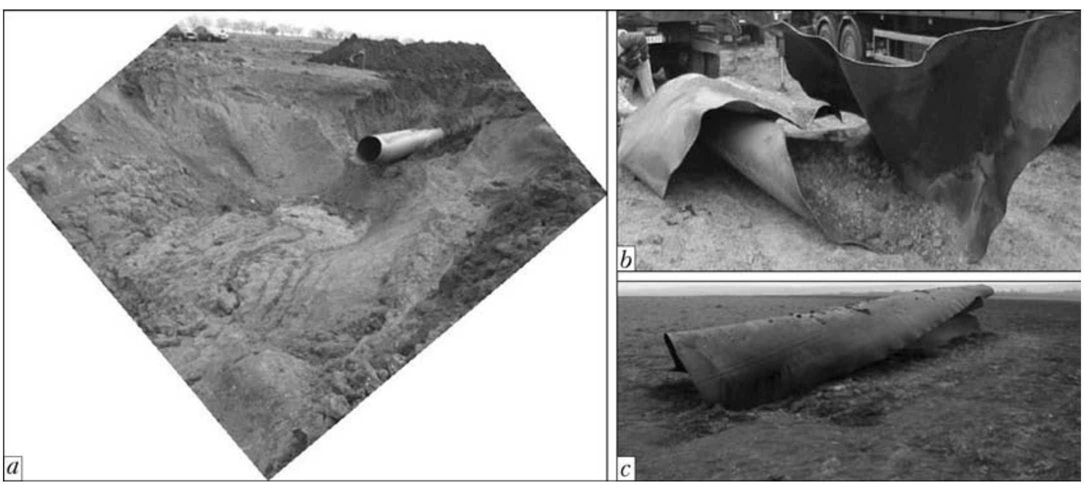

Figure 1. Pipeline failure (*a*), and fragments of failed pipes (*b*, *c*)

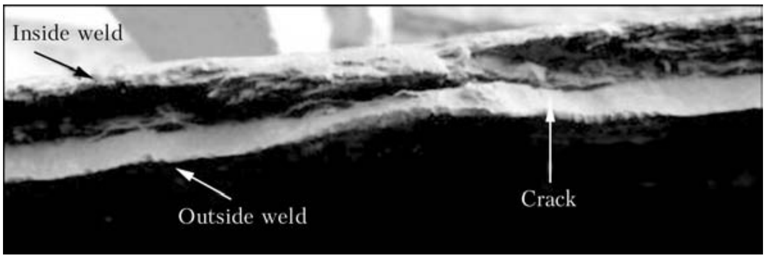

Figure 2. Crack in outside longitudinal weld on failed pipe of 820 mm diameter

opment (final break), there are no fracture corrosion damages, that is additional confirmation of crack formation during the pipe manufacture. Failure of pipeline took place after 35 years of its operation at 4.5 MPa pressure (operating pressure of the pipeline was 5.4 MPa). The pipes are manufactured from 17GS steel of 9 mm thickness.

Defect, classified as «metal loss», was found in the welded joint of main gas pipeline of 1420 mm diameter, constructed in 1983 from pipes of 15.7 mm wall thickness (X70 type steel) during in-tube diagnostics. Through crack in which transported gas leaked out (Figure 3) was detected in longitudinal weld of the pipe at test probing. Gas leakage started at pressure more than 3 MPa, the crack was closed at lower pressure. Additional non-destructive testing of this weld detected one more crack which reached the surface of only inside weld. Fractographic examinations of surface of these defects allow stating that they were also formed in the process of pipe manufacture.

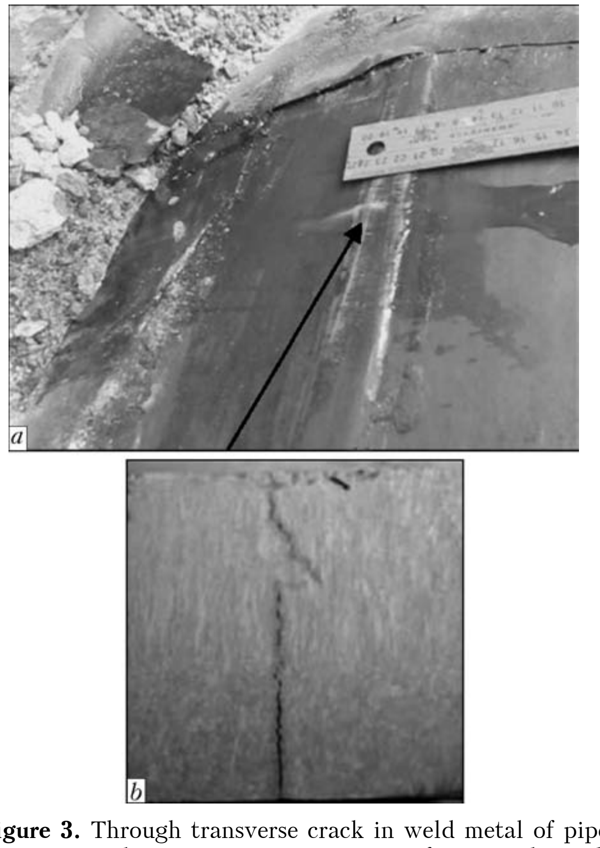

Figure 3. Through transverse crack in weld metal of pipe of 1420 mm diameter: *a* — appearance of pipe with crack in weld from side of external surface; *b* — marcosection of weld metal with crack (arrow indicates gas outflow from crack in longitudinal weld)

Failure of series of pipes of 1220 × 19 mm size from steel K60 (Figure 4) took place at hydraulic testing of newly constructed oil pipeline. At that, 12.4 MPa pressure was registered (mill testing pressure was 13.3 MPa). The pipes fractured along the near-weld zone of longitudinal mill weld on length, approximately, 1.6 m. Examination of fracture pattern in zone of failure on scanning microscope allowed determining that it propagated from external surface of the pipe to internal one, and, mainly, by toughness mechanism. It was determined that lamellar tearing along the HAZ of longitudinal weld became the reason of pipe failures (Figure 4, *b*).

Thus, described cases of pipeline failure were caused by presence in the welded joints of crack-like defects which had been already formed at stage of manufacture. Analysis of conditions and reasons of appearance of indicated defects in the welded joints of pipes is given below considering applied technological processes of their manufacture (in this case longitudinally welded pipes of

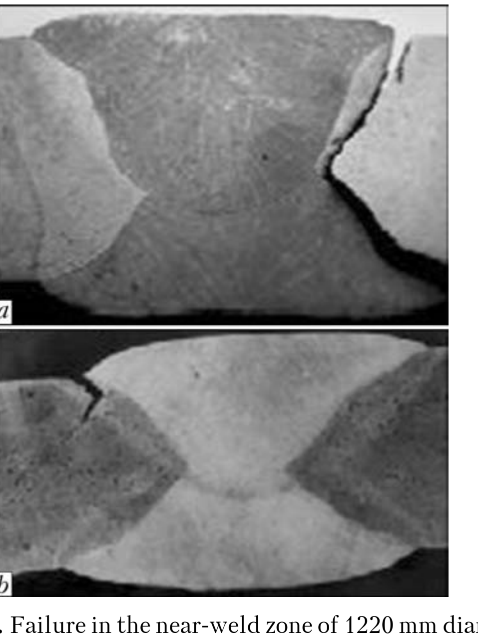

Figure 4. Failure in the near-weld zone of 1220 mm diameter pipe: *a* — failure character; *b* — lamellar tearing in HAZ metal

large diameter made using submerged arc welding are analyzed). Studied defects were conditionally joined in separate groups based on general characteristics and main reasons of their formation for convenient representation of material.

Longitudinal solidification cracks. Cases of formation of this type of cracks, similar to crack which became a reason of described above failure of 820 mm diameter gas pipeline, have been already known at the early stage of development of large diameter welded pipe production [3]. They mostly appeared in application of outdated two-layer welding technology. Using this technology, longitudinal weld of longitudinally welded pipe was made successively in two layers from external and internal surfaces of the pipe. At that, the first one, as a rule external layer was performed in assembly-welding mill in a process of assembly of edges of tubular billet that under excessive deformations of these edges provides the conditions for formation of hot solidification cracks. In 1960s longitudinally welded pipes of up to 1220 mm diameter were manufactured applying such a welding technology and in great number used for construction of main pipelines. Figure 5 shows longitudinal cracks by example of welds of 820 mm diameter pipes from 14KhGS steel. Coarse columnar crystallites can be seen on the surface of crack that verify their hot origin.

Figure 5. Longitudinal crack in outside weld of pipe from 14KhGS steel caused mainly by force factor: *a* — appearance from side of outside weld; *b* — fracture surface

Three-layer welding technology was developed and realized at the beginning of 1970s in tube-welding production, firstly for spirally-welded pipes and then for longitudinally welded pipes of large diameter, during which the edges of tubular billets in the moment of their matching are welded in shielding gas by assembly (technological) weld [4]. The latter then completely re-welded by external and internal working layer made under the flux. Such a technology allowed eliminating formation of longitudinal cracks in welds related with movement of welded edges.

It should be noted that current normative documents provide for obligatory application of pipes being welded using three-layer technology with preliminary edge joining by technological weld in construction of critical oil-gas pipelines. In our opinion, this requirement is to be stipulated in contracts for pipe supplying. As for old pipelines, the possibility of presence of such defects in them is not eliminated, including due to absence of sufficient means of non-destructive testing of pipe welded joints in period of their construction.

Longitudinal crack-like defects related with shrinkage porosity in welds. Defects of this type (Figure 6) are formed in submerged multiarc welding with increased speed due to, as indicated in work [5], isolation of tail part of the weld pool and solidification of remaining portions of liquid metal under conditions of complicated shrinkage. Depth of shrinkage porosity (shown by arrow in Figure 6, *a*) is usually not significant (0.3–0.4 mm). However, cracks, which sometimes accompany porosity, can have large depth. Such cracks are located along the weld center and have, as in previous case, intercrystalline character. Work [5] shows that possibility of formation of shrinkage porosity rises with in-

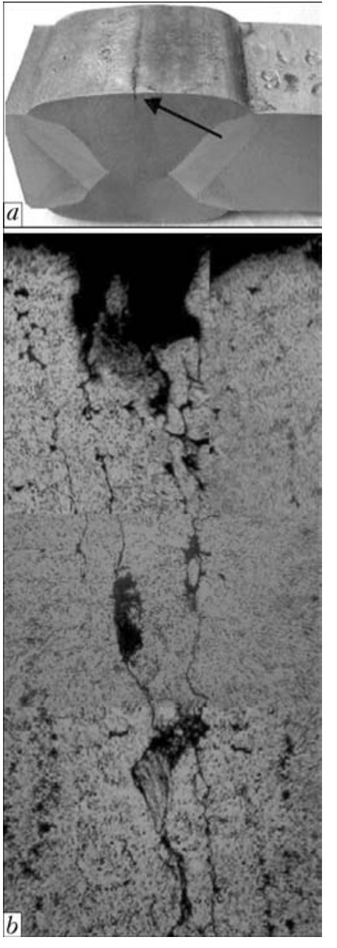

Figure 6. Macrosection with shrinkage porosity along the weld center (*a*), and microstructure (×250) of this zone (*b*)

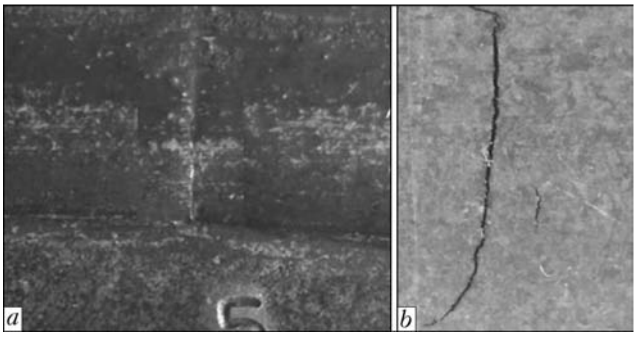

Figure 7. Cold transverse cracks formed in welds with hardening type structures: *a* — transverse crack on external weld surface; *b* — longitudinal macrosection

crease of speed of multiarc welding and application of fused flux of average and coarse grain size. If agglomerated flux is used for pipe welding, no shrinkage porosity is observed, as a rule.

Cold transverse cracks can be formed in welds as a result of effect of two main factors [6–8], i.e. formation of hardening structures in weld metal, and/or presence of excessive hydrogen. Figure 7 shows appearance of cold transverse crack in the longitudinal pipe weld caused, mainly, by structural factor. It is determined, that cracks of this type in weld metal of pipes from typical microalloying steel of K56–K65 strength class appear due to its increased alloying, first of all, by manganese, molybdenum, niobium and vanadium, that promotes formation of hardening type structures of high strength *HV*49-280–350. Such cracks in double-sided welded joint of pipes, nucleate, mostly, in metal of local brittle zones of the first weld with increased strength, which are formed in reheating during performance of the second weld. The failure, preferably, has intecrystalline character.

Peculiarities of formation of *cold transverse hydrogen cracks* were studied by example of welded joints of 914 mm diameter pipe from X65 steel (Figure 8). Cracks reached the surface of outside, inside or both welds. No specific differences of structure in metal of crack formation zone from usual one were found. Hardening structures in the welds were absent. No polyganizational boundaries, which could testify increased weld microalloying, were also detected. Vickers hardness of the weld metal did not exceed critical level from point of view of crack formation (*HV*49-260). At the same time, investigations using scanning microscope showed accumulation of small pores in the crack zone, that is indicative of its hydrogen origin (see Figure 8). Similar pores were found in area of the through crack which became the reason of failure of gas pipeline of 1420 mm diameter mentioned above.

Data of work [8] confirm an idea of delayed character of formation of hydrogen transverse cracks in metal of pipe welds. Therefore, their detection immediately in the process of pipe manufacture is difficult.

Application of increased humidity flux as well as accelerated cooling of welded joint before ultrasonic testing is the possible source of increase concentration of diffusible hydrogen in weld metal at pipe manufacture.

Different orientation cracks of metallurgical origin, caused by local change of chemical composition of weld metal of pipes, can be formed by different reasons, mainly, due to entering of exogenic particles in the weld metal. There are cases, for example, of crack appearance in the weld due to its local enrichment by carbon and manganese and formation of structural constituents with high hardness. Such cracks, in particular, were found in the pipe welds in application of fused flux AN-60 and AN-67B due to its contamination by particles of furnace lining in the process of manufacture [9]. Cracks of this type of different orientation were located in outside as well as inside weld, have filament character and, mainly, small sizes. However, in series of cases, they were propagated along the whole weld

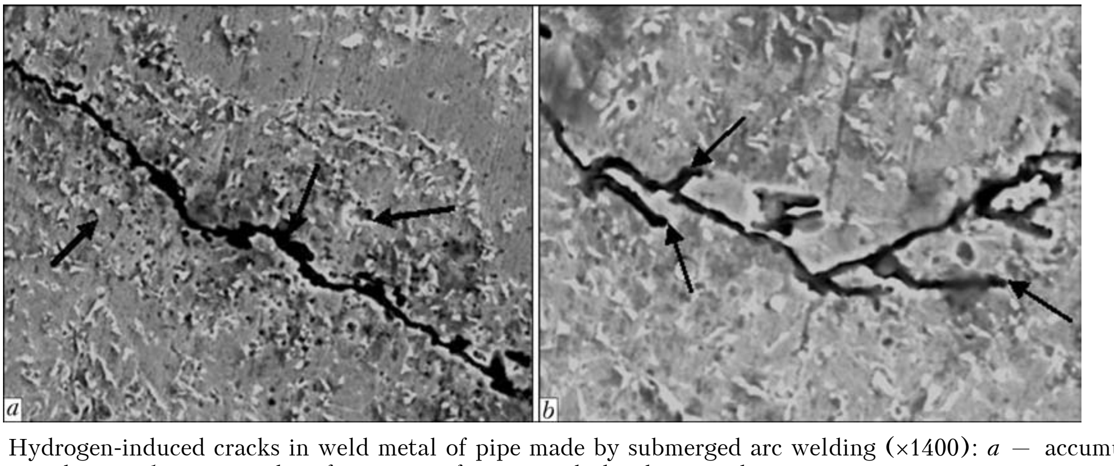

Figure 8. Hydrogen-induced cracks in weld metal of pipe made by submerged arc welding (×1400): *a* — accumulation of pores in crack zone; *b* — examples of stopping of microcrack development by pores

section. Crack formation in the weld metal of pipes can also be caused by coarse nonmetallic (slag) inclusions of exogenic character from contaminated flux in its re-usage and inequality separation.

Cases of crack formation in places of local enrichment of weld metal of pipes by copper and sometimes zinc (Figure 9) were registered. Cracks were nucleated in the surface layers of welds and propagated normal to its axis up to 15 mm depth. Contamination of the weld metal by specified elements can be related with fusion of tips and contact dies of welding machines including due to breaking of stability of submerged multiarc welding process, for example, at increased arc voltage that results in shunting of arcs by slag crust. Cracks formed at that have relatively small dimensions, that make difficult their detection using non-destructive methods.

Cracks in repaired sections of pipe weld, where correction of found defects (pores, slag inclusions, lacks of penetration etc.) was performed with their preliminary removal and further multipass mechanized submerged multilayer welding, are formed, as a rule, due to unfavorable structural characteristics of metal of «repair» weld. Cracks, mainly, develop in longitudinal direction and nucleate, as a rule, in the last layer of «repair» weld and then propagate in metal of previous layers of this weld and HAZ.

It is determined that studied cracks can be related to cold ones and their formation is caused by progressive increase of weight fraction of alloying elements (manganese, silicon, molybdenum, chromium etc.) from layer to layer during performance multipass welds using consumables applied, usually, for these purposed in pipe production. For example, application of flux AN-60 and Sv-08G1NMA wire for repair of defective area of the longitudinal weld of pipe from 10G2FB steel resulted in increase of content of manganese in the last (fourth) layer of «repair» weld up to 1.97 %, silicon — up to 0.98 and molybdenum — up to 0.53 % (in the first layer of this weld quantity of indicated elements was in the level of 1.96, 0.45 and 0.16 %, respectively). Excessive level of alloying of metal of the last weld layers resulted in formation of areas of upper bainite structure with high hardness, reduced ductility and toughness, enrichment of ferrite matrix by silicon, also reducing its ductility, and formation of developed system of polygonization boundaries with microcracks. Issues on optimizing of chemical composition and structure of metal in sections of pipe welds subjected to repair will be considered in detail in our next publications.

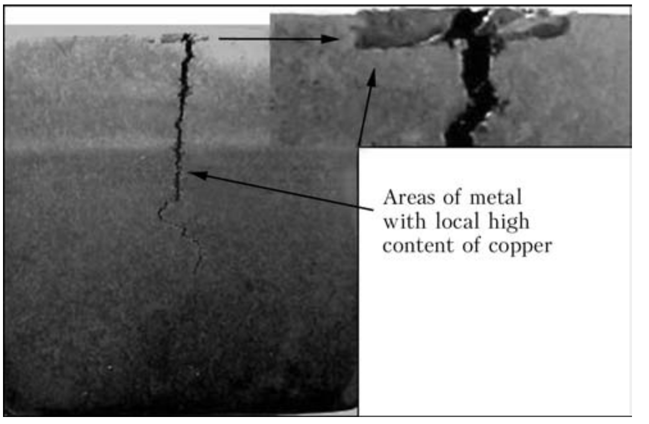

Figure 9. Cracks in weld metal in areas of local enrichment by copper (fragment of crack (×6) is shown in right upper angle)

Cracks-tears in the near-weld zone, similar to shown in Figure 4, can be formed during performance of expanding operation of pipes, necessary for providing their required dimensions. Appearance of such cracks is a result of effect of series of factors, i.e. excessive deviations of pipe profile in area of welded joint from circularity before expanding, non-smooth transfer of weld reinforcement to base metal, and unfavorable structural characteristics of metal in areas adjacent to weld caused by welding heating. Cases of formation of cracks-tears are mostly observed in a period of mastering of production of new grade pipes or pipes of higher level strength. Small dimensions of these defects and location in area of geometry concentrator complicate their detection using non-destructive testing methods. Namely, cracks-tears formed in expanding of pipes at the near-weld zone became a reason of considered earlier failures of main pipeline of 1220 mm diameter.

Therefore, study of reasons of failures of main pipelines and investigations of technological welding and allied processes performed at tube-welding plants allowed determining peculiarities of location, reasons and mechanisms of formation of crack-like defects in welds on the pipes designed for application in construction of main pipelines. System of measures on reduction of possibility of appearance of such defects and increase of reliability of testing methods was developed considering these data and partially realized in acting tube-welding productions. For example, as was previously mentioned, three-layer welding technology (with preliminary performance of assembly weld) is virtually everywhere used in manufacture of pipes of critical designation instead of outdated two-layer welding. Welding of pipes is performed only using ceramic flux instead of fused one, in which presence of separated particles of furnace lining and other foreign particles is possible. Accelerated

Recommended measures for prevention of appearance of crack-like defects in welds on large diameter pipes made by submerged arc welding

Cracks	Measures for prevention of crack formation
Longitudinal solidification cracks in outside welds caused mainly by effect of force factor	Application of three-layer welding technology with preliminary joining of pipe edges by assembly (technological) weld Forming of pipe billets eliminating excessive deformations of edges in assembly
Longitudinal cracks in metal of pipe welds related with shrinkage porosity	Improvement of pipe shape (elimination of «saddle», limitation of weld width) Limitation of slope angle «downhill» of a mill for welding of inside pipe welds in the range not more than 20 min Application of ceramic flux Control of flux quality
Cold transverse cracks of hydrogen origin or caused by formation of hardening structures in weld metal	Control of flux humidity (flux humidity should be not more than 0.03 %) Limitation of weld metal alloying (first of all, not more than 0.3 % Mo and not more than 0.03 % Nb) Elimination of operation of accelerated cooling of welded joints before US testing (if this operation is necessary, time between finish of welding and start of cooling should be not less than 1 h, and weld temperature — not more than 80 °C) Control of hardness of metal of the first weld for new grades of pipe steel and consumables, including for the purpose of detection of local zones of increased hardness (more than *HV* 260) in its root
Cracks of different orientation of metallurgical origin in weld metal	Application of agglomerated flux and control of its quality Quality control of surface of welding wire Registration of parameters of welding process and control of its stability Control of condition of nozzles
Cracks in repair sections of mill welds performed with the help of multilayer welding	Application of welding wire with limited content of molybdenum (up to 0.3 %) and nickel (up to 0.6 %) as well as aluminate-basic agglomerated flux Certification of welding process for repair of pipe welded joints
Cracks-tears in the near-weld zone	Control of pipe billet and welded joint shape before expanding (deviation of pipe surface profile from theoretical circle in area of welded joint should not exceed 0.15 % D_{out}) Improvement of weld shape (for example, transfer angel of weld to base metal should not be less than 120°) Limitation of expanding value (up to 0.9 %), in particular, for thick-wall pipes of increased strength Additional limitation of maximum allowable concentration of alloying elements, in particular, carbon (depending on strength level), molybdenum (not more than 0.2 %), niobium (not more than 0.05 %), including for pipe steel of increased strength, for example, X80

cooling of welds before ultrasonic testing is eliminated at most pipe plants. Equipment and scheme of testing of welded joints of pipes are improved to significant extent, including due to increase of number of US transducers etc. Detailed list of measures, recommended for prevention of appearance of crack-like defects in welds of large diameter pipes made using submerged arc welding, is given in the Table.

At the same time, in our opinion, increase of guarantee of absence of crack-like defects in pipe welds in addition to technological measures and improvement of means and testing methods, requires setting of additional requirements to technological process of their production in customer normative documents for pipes, for example, limitations of flux humidity, entering of norms of maximum allowable concentration of alloying elements in steel and weld metal, control of applied consumables and shape of pipe billet before expanding, registration of parameters of welding process and its certification before pipe production, etc.

Results of these investigations can be also used for improvement of methods for diagnostics of main pipelines.

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