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Investigation of Welded Joints of Long-Term Operated Gas Pipeline Controllable Rolled X70 Steel

The complex properties (mechanical, microstructure, and electrochemical) of controllable rolling X70 steel pipes of the main gas pipeline with a diameter of 1420 mm after an operation for 20 years and emergency reserve pipe after a similar period of storage were studied. Taking into account specified heterogeneity caused by the technological effect on X70 steel of controllable rolling, it is difficult to draw unequivocal conclusions about the effect of operational work on changes in the condition of welded joints of investigated pipes. It was established that operating loads did not significantly affect the characteristics of base metal and welded joints. Electrochemical properties (corrosion potential, hydrogen recovery potential, anodic curves slopes) of long-term operated pipes of different manufacturers (Ukraine, France) and stock pipes in NS4 solution are similar. Due to the high reserve of impact viscosity at standard temperature conditions, investigated pipes are characterized by satisfactory resistance against breaking.

Keywords: *X70 pipeline steel, microstructure, yield strength, tensile strength, elongation, impact toughness, corrosion potential, cathodic polarization, hydrogen reduction.*

1. INTRODUCTION

Large-diameter, high-pressure underground gas pipe–lines play an important role worldwide in transporting natural gas over long distances from its source to con–sumers. The high cost of such objects makes it difficult to replace them quickly, so extending their service life is one of the subjects of active discussions regarding introducing the latest technologies for their control [1]. Ensuring the safe and reliable operation of pipeline systems is extremely important. Pipeline ruptures are always possible, and their failure can cause human, environmental and financial losses.

Almost all long-term operated underground gas pipe–lines are affected by operational factors, resulting in cor–rosion-mechanical cracks [2-7]. One of the sources of such cracks is randomly distributed defects caused by the manufacturing process or steel degradation. The com–bined action of stress (for example, ring and/or residual stress) and the natural soil environment containing dif–ferent amounts of moisture and oxygen further facilitates the initiation of cracks and accelerates their propagation through the pipe wall [8].

The first publicly documented gas pipeline accident related to stress-corrosion cracking (SCC) occurred in 1965. SCC was identified in the United States in the early 1970s; it was subsequently recognized as a cause of pipeline accidents in many other countries. Some authors think that cathodic protection increases the fatigue limit of pipe steels, and in some cases, the fatigue endurance can be even higher under cathodic polarization than in air. However, these results are inconsistent from a fracture mechanics point of view, which demonstrates that cathodic polarization increases the crack growth rate [9].

There is evidence that the use of cathodic pola–rization leads to steel hydrogenation. In registered cases, after one or two years of operation, an increase in the hydrogen content on the outer surface of the pipes was found to be more than six times, and after 15 years – approximately ten times [10].

It is believed that the long-term operation of main gas pipelines causes a change in the mechanical properties of steel in the volume of the pipe wall, in particular, the

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characteristics of resistance to brittle fracture [13, 14], negatively affecting their operational functions [14].

Studies during 21 years of operation at 30 °C established the susceptibility of the welded joint of X52 pipe steel to aging. It was determined that aging causes an increase in ferrite grain size, which is unfavorable for mechanical properties. Coagulation of grains causes the nucleation of microvoids, and an increase in the dia–meter of the voids and a decrease in their density were noted in the fractures of the impact samples. This con–tributed to brittle failure under impact tests. There is also a slight increase in the overall corrosion rate due to forming more brittle and porous corrosion products [15].

As a result of deformation aging at 250°C, it was established that the yield ratios of steels with ferrite-pearlite microstructure at various preliminary deforma–tions are significantly higher than those with ferrite-cementite microstructure due to greater interaction between particles and dislocations for hardened and tempered steel than for normalized steel. Therefore, the resistance of normalized steel to deformation aging is significantly better than that of hardened and norma–lized steel. This difference is explained by different pipe manufacturing technology: thermomechanical control for welded pipes and traditional heat treatment for seamless pipes [16].

The microstructure and mechanical properties of ferritic-martensitic X70 steel were studied after aging at 200–250°C for 5–15 min. The pipe with ferrite-martensitic microstructure showed excellent resistance to strain aging: only a decrease in the yield strength of less than 0.77 was noted, while the tensile strength, relative elongation, and impact toughness were not changed [17].

The possibility of using electrochemical approaches to analyze the technical condition of structural metal materials at the design stages and their long-term operation in corrosive-water environments has been widely considered [18]. Usually, during design, strength indicators are set with a certain margin. Researchers pay special attention to changes in the strength and viscosity of pipes [11]. It was found that during the analysis of the influence of stresses on the intensity of corrosion damage, it is important to take into account the non-stationary electrochemical processes of the interaction of the metal of the freshly deformed surface with the environment, which is the basis for predicting corrosion durability, corrosion-fatigue strength. The study of the influence of operating factors (duration of operation, absorbed hyd–rogen, contact corrosion, macro galvano-couples, bioac–tive medium) on the corrosion and corrosion-mechanical destruction of steels showed the possibility of using methods of stationary and non-stationary electroche–mistry [18]. There are data [19] that practically all their mechanical and electrochemical properties deteriorate during the operation of main oil and gas pipelines. However, the characteristics of plasticity and resistance to brittle fracture are the most sensitive to operational degradation, and of the electrochemical characteristics, polarization resistance, and corrosion current [19].

The work aimed to investigate the mechanical and electrochemical properties of welded joints of the main gas pipeline made of X70 steel after long-term operation and to evaluate their change compared to reserve pipes.

2. EXPERIMENTAL

Research objects were templets of welded pipes made of X70 steel such as:

- after 20 years of operation: steel and pipe manufacturer in Japan;
- after 20 years of operation: steel manufacturer is France, pipe manufacturer in Ukraine;
- after 20 years of storage: steel manufacturer is not established, pipe manufacturer in Ukraine.

The chemical composition of the metal of pipe fragments was determined by a spectral method using the Spektrovak-1000 device manufactured by Baird company.

Metallographic cuts were prepared according to the standard method. The microstructure characteristics of base metal and welded joints were assessed on NEOPHOT 21 microscope at different magnifications on unetched samples and samples after etching in a 4% alcoholic solution of nitric acid (nital). The digital image was obtained using a SIGETA UCMOS camera.

Mechanical parameters were determined by stretching full-thickness samples of the base metal and welded joints at 6 mm/min rate on the ZDM machine. Impact energy was determined on samples of the base metal and welded joints at temperatures 20, 0, -20, -40, -60, -100 ^{o}C on KM 28 machine.

Electrochemical studies were carried out at room temperature in NS4 electrolytes with such chemical composition, g/l: 0.122 KCl + 0.483 $NaHCO_3$ + 0.181 $CaCl_2$ + 0.131 $MgSO_4$ (pH 8.2) [20].

Specimens for electrochemical tests were prepared according to the standard method. Measurements were carried out using a three-electrode scheme using pressure electrochemical cells in potentiodynamic mode on PI-50-1 potentiostat and PR8 programmers with a potential sweep rate of $5 \cdot 10^{-4}$ V/s. Potentials were measured relative to the silver chloride reference electrode (c.s.e.). The working electrode was X70 steel, a saturated silver chloride electrode was a reference electrode, and a platinum electrode was an auxiliary electrode. Electrochemical parameters were determined from voltammeter curves using a graphic-analytical method.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Study of chemical composition

According to chemical composition, the base metal of all investigated pipes belongs to low-carbon steel, micro-alloyed with vanadium and niobium, and meets the requirements of TS 14-3-995 [21] for the X70 steel category (Table 1). With the relatively close chemical composition of base metal, it can be noted that the metal of ling-operated pipe manufactured in Ukraine has a little higher carbon and manganese (at the level of 0.11 and 1.8%, respectively) content compared to the metal of other investigated pipes. By the content of elements in welds' metal of pipe (Table 1), it was established that welding of the seam was performed using standard welding wires Sv-08GNM used at plants. The seam of the Japan pipe was welded using Mn-Mo-Ti alloy wire.

Table 1. The chemical composition of base metal and longitudinal weld metal of main gas pipeline pipes.

Pipe size (mm), pipe/steel manufacturer, pipe condition	Control zone	Mass part of elements, %													
		C	*Mn*	*Si*	*S*	*P*	*Al*	*Ni*	*Mo*	*Ti*	*V*	*Nb*	*Cr*	*H*	C_{eq}
1420×15,7; Ukraine/France, operated	Base metal	0,117	1,80	0,316	0,008	0,021	0,030	0,03	0,03	0,002	0,05	0,033	0,03	0,00007	0,41
	Weld	0,081	1,59	0,521	0,011	0,023	0,015	0,14	0,26	0,003	0,03	0,018	0,09	-	-
1420×18,7; Japan/Japan, operated	Base metal	0,077	1,71	0,275	0,008	0,024	0,031	0,04	0,04	0,001	0,05	0,029	0,04	0,00007	0,38
	Weld	0,063	1,71	0,406	0,010	0,025	0,013	0,04	0,18	0,026	0,03	0,017	0,04	-	
1420×15,7; Ukraine, emergency stock	Base metal	0,081	1,57	0,285	0,005	0,015	0,029	<0,04	0,03	0,003	0,06	0,031	0,04	0,00008	0,37
	Weld	0,076	1,53	0,550	0,010	0,017	0,017	0,26	0,32	0,003	0,03	0,017	0,08	-	-
Requirements of TS 14-3-995		Not more than													
		0,12	1,70	0,50	0,01	0,02	0,05	-	0,30	-	0,08	0,06	-	-	0,41
Requirements of TS 40/48/56		No data													≤0,41

Table 2. Characteristics of the microstructure of external seams metal.

Pipe/steel manufacturer, size, condition of pipes	Structures character	Volume fraction of non-metallic	HV_5
Ukraine/France, 1420×15,7 mm operated	Acicular ferrite, up to 16% polygonal pre-eutectoid ferrite, individual areas of pearlite, evenly distributed martensite-austenite crystallization phase	0,49	223-232
Japan/Japan, 1420×18,7 mm, operated	Acicular ferrite, up to 10% of polygonal pre-eutectoid ferrite, uniformly distributed dispersed martensite-austenite crystallization phase	0,20	223-227
Ukraine, 1420×15,7 mm, emergency stock	Acicular ferrite, up to 20% of polygonal pre-eutectoid ferrite, individual areas of pearlite, uniformly distributed martensite-austenite crystallization phase	0,58	223-232

3.2 Microstructure investigation

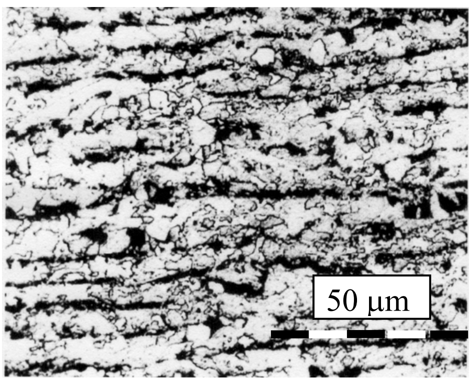
Contamination with non-metallic inclusions of base metal in the operated pipe and stock pipe no more than 3 points for oxides and silicates according to GOST 1778. Inclusions are mainly represented by complex oxides (oxysulfides) and silicates (sulfosilicates); mainly, they have a globular or close to a globular shape. A small number of plastic and brittle silicates of irregular shape and non-deformable silicates were found. No significant accumulations of non-metallic inclusions were found in the zone of axial liquation and near-surface layers of the base metal.

The microstructure of the base metal of investigated pipes is ferrite-pearlitic with grain elongation in the rolling direction, which is typical for micro-alloyed steel produced using controlled rolling (Figure 1).

From the analysis of experimental results, it can be assumed that the microstructure of the base metal of all investigated pipes is quite similar. There is a difference in the part of the pearlite component of the operated and stocked pipe produced in Ukraine, which is 20%, while the pearlite component part in pipe produced in Japan are little lower, nearly 10%. The base metal of the operated pipe (Japan) is characterized by a larger ferrite grain size (11-8) microns compared to the stocked pipe and operated pipe produced in Ukraine (11-15) microns. The striation of the base metal of pipe produced in Japan corresponds to ball 2 (pearlitic strips are more fragmented, and small carbide discharges are observed in the ferrite grains), the striation of other pipes (after the operation and after stock, produced in Ukraine) estimated by ball 3. Metal hardness is (180-190) HV_5 for Japanese pipe, (and 190-200) HV_5 – for operated and stocked Ukrainian pipe. It should be noted that such microstructures of base metal are typical for controllable rolled steel X70 type, micro-alloyed by vanadium and niobium. And the peculiarities of the observed microstructure are conditioned to differences in the chemical composition of steel (for example, reduced carbon content, as mentioned above) and the peculiarities of steel manufacturing technology by different manufacturing plants.

The results of the quantitative assessment of conta–mination of seams metal (part of non-metallic inclusions area), performed on the "Omnimet" installation by auto–matic counting of inclusions when viewing 100 fields of view (magnification 800 times) on the polished surface in the central part of welds with an area 5 mm, are presented in Table 2.

In the metal of the external and internal seams of investigated pipes, mainly dispersed globular non-metallic inclusions were found, which are mainly complex oxides and, less often, oxysulfides.



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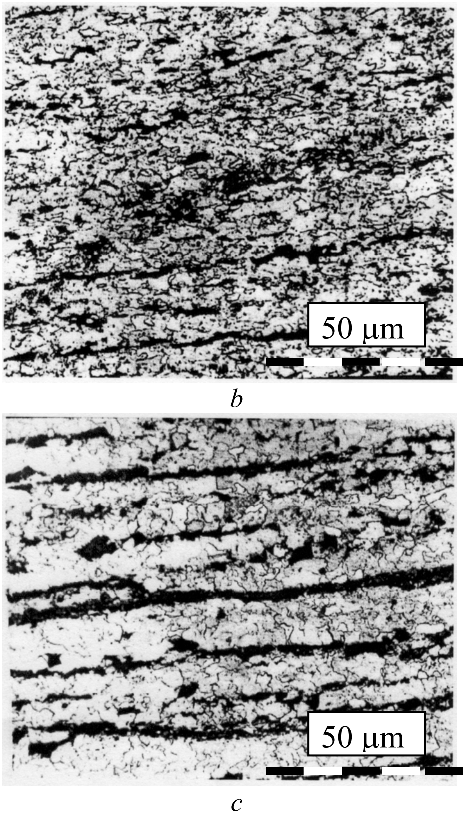


Figure 1. Microstructure of base metal of pipes:

a – after 20 years of operation, steel manufacturer France, pipes manufacturer Ukraine; b – after 20 years of operation, steel and pipe manufacturer Japan;

c – after 20 years of storage, the steel producer is not established; pipes manufacturer Ukraine

It should be noted that at less general contamination by non-metallic inclusions of Japanese-made pipe, most of them (up to 96%) is finely dispersed, and their size not exceeds 1.5 microns. The volume part of non-metallic inclusions in the metal seams of Ukrainian pipe is 2-3 times greater (Table 2), while up to 15% of non-metallic inclusions exceed the size 3 microns, and the size of some of them reaches 7 microns.

Revealed differences in non-metallic phase in the metal of domestic and foreign-made pipe seams are due to the use of different fluxes during their welding. The microstructure of the external seams metal of invest–tigated pipes is fine-grained and relatively uniform across the cross-section of welds. It is a mixture of ferrite formations of various morphologies and dis–persed phases of martensite-austenite crystallization.

Acicular ferrite and polyhedral ferrite grains were found in the weld metal, pre-eutectoid ferrite in the form of continuous layers or individual polygonal grains with different shape ratios, and individual areas of lateral lamellar ferrite were located along the secondary boun–daries (Figure 2). The peculiarity of the microstructure of the metal welds of pipes produced in Ukraine (both emergency stock and after operation), in comparison with foreign pipes, is a larger proportion of pre-eutec–toid ferrite and the presence of single areas of pearlite approximately twice. No developed polygonization boundaries were found in the metal of all investigated seams. The martensite-austenite crystallization phase in metals welds structure is fairly evenly distributed and represents dispersed allocations of different shapes (polyhedral, acute-angled, elongated) and etching (light in the middle and darkly colored along the contour – martensite islands, and evenly darkly colored – bainite allocations). The saturation of weld metal by the martensite-austenite crystallization phase of the operated Japanese pipe is less than that of the weld metal of the pipes produced in Ukraine (emergency stock and after operation). The integral hardness of the base metal of the outer seams of investigated pipes is within 223-237 HV_5.

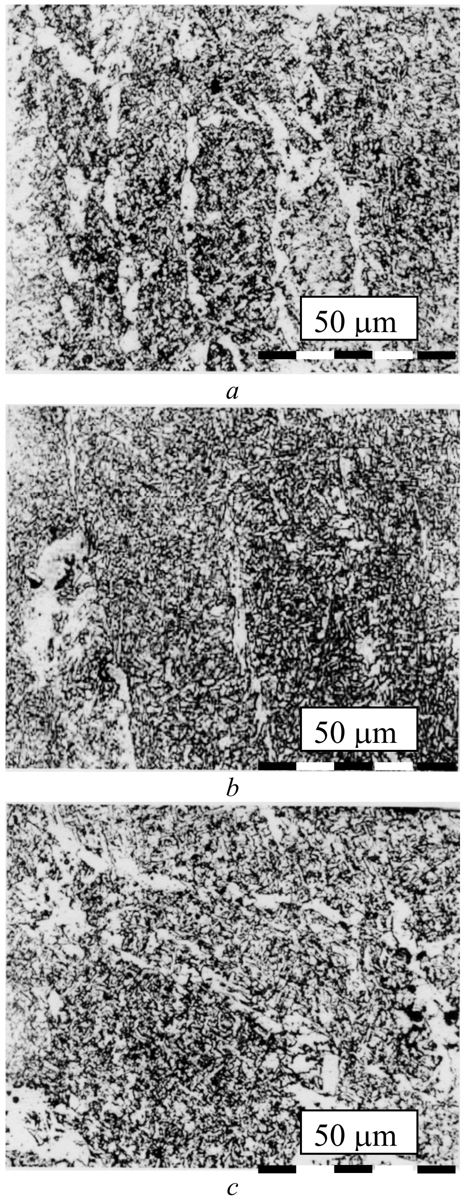


Figure 2. Microstructure of outer weld metal of pipes:

a – after 20 years of operation, steel manufacturer France, pipes manufacturer Ukraine; b – after 20 years of operation, steel and pipe manufacturer Japan;

c – after 20 years of storage, the steel producer is not established, pipes manufacturer Ukraine.

The microstructure of the metal in the area of a coarse grain of the heat-affected zone (HAZ) of all welded joints mainly consists of upper bainite, that is, ferrite with an ordered carbide phase (Figure 3).

Table 3. Results of metallographic analysis of heat-affected zone metal.

Pipe/steel manufacturer, size and condition of pipes	Coarse grain region				HAZ	
	Grain size, µm	Length, mm	HV_5	Structures character	Length, mm	HV_5
Ukraine/France, 1420×15,7 mm operated	~60	≤ 0,40	218-227	Ferrite with lamellar carbide phase, a mesh of pre-eutectoid ferrite along the boundaries	≤ 3,3	177-227
Japan/Japan, 1420×18,7 mm, operated	~90	≤ 0,45	210-218	Ferrite with dispersed lamellar carbide phase, pre-eutectoid ferrite is absent at the boundaries	≤ 4,0	165-218
Ukraine/not known, 1420×15,7 mm, emergency stock	~70	≤ 0,40	219-230	Ferrite with lamellar carbide phase, a mesh of polygonal ferrite at the boundaries	≤ 3,5	177-230

The microstructure of metal in the coarse grain area of HAZ and its dimensional parameters differ depen–ding on the pipe manufacturer due to the features of the steel chemical composition and applied welding technology (Table 3).

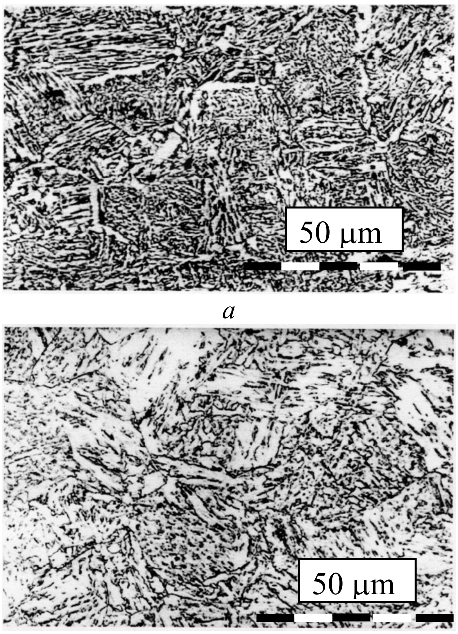


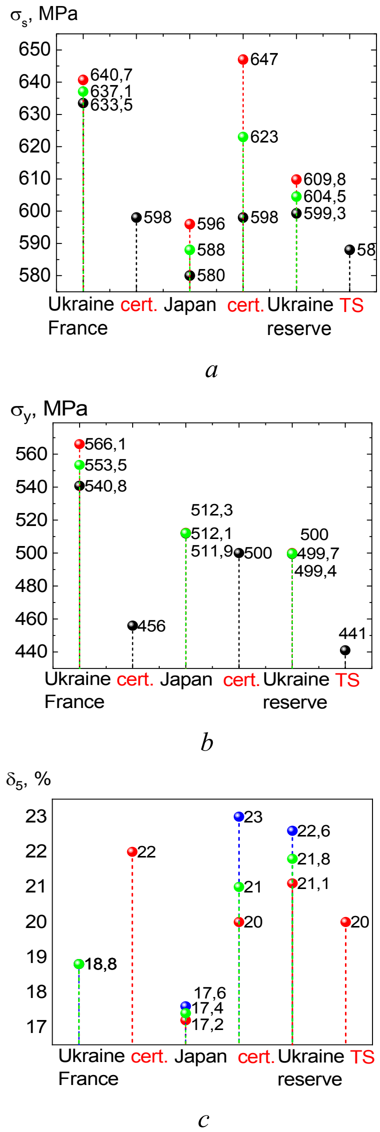
Figure. 3. Microstructure of heat-affected metal in the coarse grain area of operated pipes, made in Ukraine (France) (a), in Japan (b).

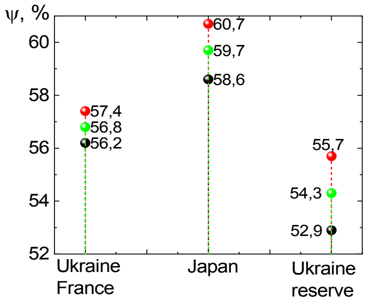
Thus, the identified microstructure of the base metal and weld metal are characteristic of the pipe metal of considered types. Some differences in the structured nature are due to peculiarities of the chemical composition of the steel, the used welding materials (wire and flux), and welding technology. Signs characterizing the influence of operational loads on the metal of the gas pipeline were not detected during the metallographic studies.

3.3 Study of indicators of mechanical properties

Mechanical properties of the base metal. As stated earlier, the long-operated pipe of the main gas pipeline was made in Ukraine from steel produced in France. The emergency supply pipe was manufactured at the Ukraine pipe factory from X70 steel of imported production. Since it is not always possible to establish the number of pipes from which fragments were cut, the level of mechanical properties of the metal was evaluated according to certificates for similar pipes used for the construction of the gas pipeline. Figure 4 presents the results of mechanical tests.

The yield strength of operated pipes and emergency reserve pipes exceeds the normalized TS 14-3-995 value (not less than 441 MPa): pipes manufactured in Ukraine (metal made in France) – by 22%, manufactured in Japan – by 16%, emergency reserve pipes – by 13%, Figure 4, a.





d

Figure 4. Mechanical properties of the base metal of investigated pipes: a – tensile strength limit; b – yield strength; c – relative elongation; d – relative narrowing.

The yield strength of operated pipes and emergency reserve pipes exceeds the normalized TS 14-3-995 value (not less than 441 MPa): pipes manufactured in Ukraine (metal made in France) – by 22%, manufactured in Japan – by 16%, emergency reserve pipes – by 13%, Figure 4, a.

The tensile stress of the operated pipe produced in Ukraine to the emergency reserve pipe exceeds the standardized TS value (not less than 588 MPa) by 6% and 3%, produced in Japan – which is at the minimum value level according to TS 14-3-995 requirements (598 MPa), Figure 4, b.

Indicators of relative elongation (δ_5) of base metal of the pipes after operation do not answer the established requirements (at least 20%), Figure 4, c: for the pipe manufactured in Ukraine, δ_5 = 18.8%, for Japanese-made pipe, δ_5 = 17.4%, which is lower than the standard value by 6% and 13%, respectively.

Normative documents do not regulate the indicator of relative narrowing. For stock pipes, this indicator has the lowest average value, 54.7%, while for operated pipes, it is slightly higher, 56.8 and 59.7% for pipes ma–nufactured in Ukraine (France) and Japan (Figure 4, d).

Impact viscosity according to KCV^{-15} (Figure 5, a) and KCU^{-60} (Figure 5, b) indicators for all tested pipes is higher than the values standardized by certificates, respectively.

The base metal of emergency supply pipes meets the requirements of regulatory documentation according to all standardized parameters (σ_y, σ_s, σ_y/σ_s, KCV^{-15},

KCU^{-60}, δ_5). At the same time, it should be noted that the strain stress limit of the base metal of all pipes, when testing flat full-thickness samples, exceeds the normative level, Figure 5.

Thus, the base metal of pipes after operation according to the standardized characteristics σ_y, σ_s, σ_{ys}/σ_s, KCV^{-15}, KCU^{-60} responds to the requirements of technical conditions according to which they were manufactured, and BR 2.05.06 [9]. Indicators of relative elongation do not answer the requirements of technical conditions. An overestimation of the relative narrowing index compared to this index for the emergency stock pipe was noted, which is not regulated by current documents.

Test results of impact bending (KCV) of base metal samples in the temperature range from plus 20 to minus 100°C are shown in Figure 6.

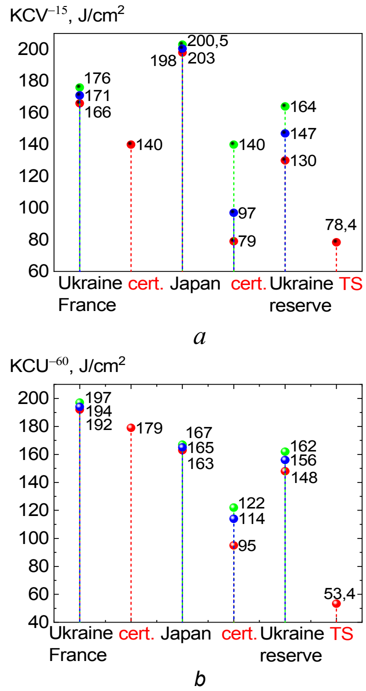


Figure 5. Impact viscosity of the base metal of tested pipes at different temperatures KCV^{-15} (a) and KCU^{-60} (b).

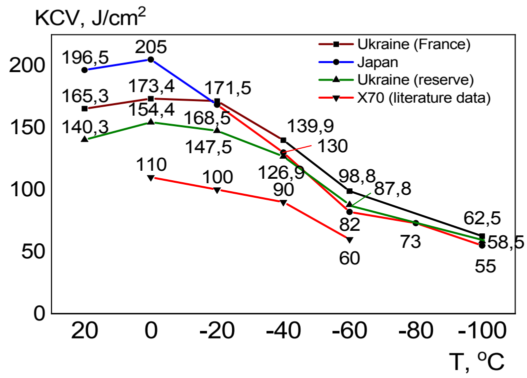


Figure 6. Temperature dependence of the impact viscosity of the base metal of investigated pipes.

The impact viscosity of the base metal of pipes after operation in the temperature range from plus 20 to minus 40 °C is high; the value of this indicator for all pipes is close. At the temperature of 0 °C, the KCV value for investigated pipes is several times higher than the value standardized by technical conditions (at least 78.4 J/cm^2).

Viscous-layered fracture with splits formed during the breaking of controllable rolling steel is observed when testing impact samples in the entire temperature range: from plus 20 to minus 100 °C. Completely brittle failure occurs at the test temperature minus 100 °C. Similar results regarding impact toughness were obtained on the base metal of the emergency stock pipe.

Mechanical properties of welded joints. Welded joints of pipes after operation and stock according to the indicator of strain stress correspond to regulatory docu–mentation, Figure 7. During that tests, sample rupture occurred at a distance of 37–40 mm from the fusion line of the seam with the base metal.

Results of impact bending testing of welded joint samples are presented in Figure 8, a (cut along the seam and along heat affected zone at the distance 2 mm from the intersection point of fusion lines of internal and external seams) in the temperature range from +20 to -40°C.

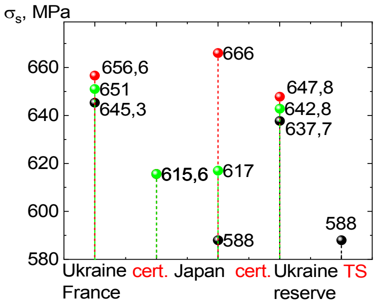


Figure 7. Strength limit of welded joints of the pipes under investigation and stock pipe

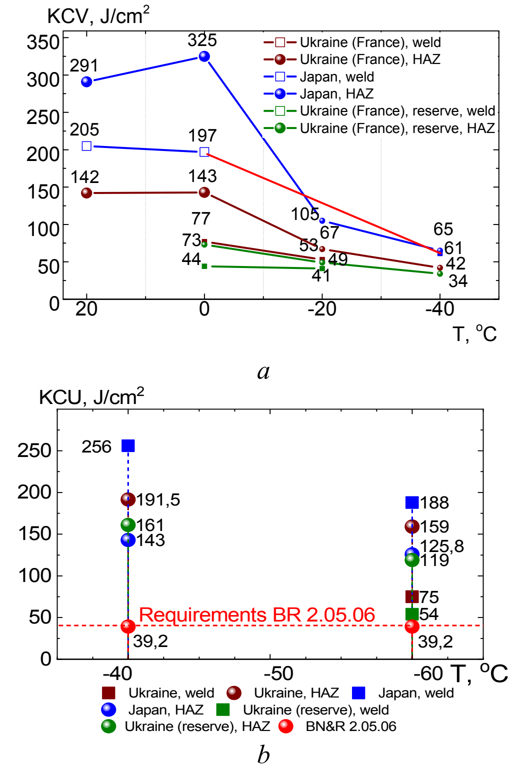


Figure 8. Temperature dependence (a) of impact tough–ness KCV and impact toughness KCU of the welded joint (b).

The value of the impact strength of the seam and heat-affected zone of welded joints of pipes after the operation, as well as emergency storage pipe with sufficient reserve, exceed the indicators established in BR 2.05.06 (KCU^{-40}, Figure 8, a) and technical conditions (KCU^{-60}, Figure 8, b). When testing samples with a sharp cut, the impact strength (KCV) of weld and HAZ, except for emergency reserve pipe, is at the level (or higher) of the values established for the base metal BR 2.05.06 (at least 78.4 J/cm^2), Figure 8, a. Weld metal of the emergency stock pipe has the lowest values of impact viscosity: KCV^0 = 44 J/cm^2 and KCU^{-60} = 54 J/cm^2.

The impact toughness of studied seams is lower than that level for the base metal, except for the pipe pro–duced in Japan, the impact toughness of its weld metal is at the base metal level.

3.4 Electrochemical studies

Changing corrosion potential of base metal X70 steel of the pipes mentioned above is given in Figure 9, a.

As can be seen from the curves in Figure 2, a, at beginning of measurements, corrosion potentials differ by approximately 200 mV, but after 30 s their values stabilize. For pipe steel after the operation, corrosion potentials equal -0.658 V for the Ukrainian (France) pipe and -0.645 V for the pipe made in Japan. For the metal of stock pipe, corrosion potentials are slightly more negative, -0.684 V.

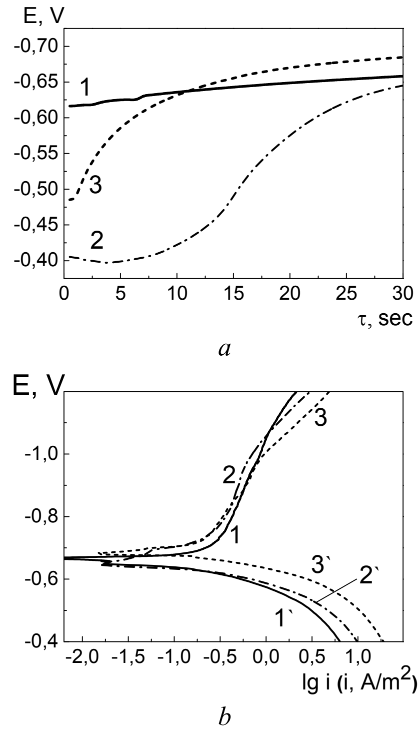


Figure 9. Changing of corrosion potentials in time (a) and polarization curves (b) in NS4 solution of base metal of studied samples of X70 steel: a – after 20 years of opera–tion, steel manufacturer France, pipe manufacturer Ukraine; b – after 20 years of operation, steel and pipe manufacturer Japan; c – after 20 years of storage, the steel producer is not established, pipes manufacturer Ukraine.

From the polarization curves presented in Figure 9, b, it can be seen that the nature of anodic and cathodic curves is the same. The limiting diffusion current on the base metal of all the pipes has close values: 0.402 A/m^2 (Japanese pipe), 0.480 A/m^2 (Ukraine/France pipe), and 0.378 A/m^2 (storage pipe), Table 4.

Table 4. Electrochemical characteristics of X70 steel pipe samples

Pipe/steel manufacturer	E_{cor}, V	b_a, V	J_{O2}, A/m²	E_{H2}, V	Cathodic currents density, A/m², at potentials		
					-0,75 V	-0,95 V	-1,05 V
Ukraine/France operated	-0,658	0,053	0,480	-0,950	0,356	0,703	0,997
Japan/Japan operated	-0,645	0,046	0,402	-0,970	0,254	0,570	0,958
Ukraine, emergency stock	-0,684	0,064	0,378	-0,980	0,261	0,738	0,988

Hydrogen recovery potentials on the samples of operated pipes of different manufacturers are -0.970 V for Japan (Japan) and -0.950 V for Ukraine (France), and on a sample of reserve pipe is -0.980 V (Table 3). That is, the hydrogen reduction potentials of the opera–ted pipe are 0.010 and - 0.030 V negatively compared to the storage pipe. That is more likely to argue that these potential differences are due to differences in steel production technology.

Anodic curves slopes determined in the region 50 mV from the corrosion potential are 0.046 V, 0.053 V and 0.064 V (Table 3). That is, in NS4 model soil solu–tion, corrosion of X70 steel is described by diffusion ki–netics law.

Previously, we conducted complex studies concer–ning the influence of corrosion factors on this indicator [23,24]. While analyzing the effect of protective poten–tial on the corrosion state of pipe surface under protect–tive coating, some authors suggest determining the current density of the cathodic protection and compa–ring it with the density of the limit current of oxygen reduction. From cathodic polarization curves, the ratio of currents $j_{c.p.} / j_{O_2}$ for operated and storage pipes of X70 steel in NS4 soil electrolyte was calculated, and its analysis was performed (Table 2). In potentials range from -0.75 V to -1.05 V, the ratio for base metal of investigated pipes increases with approximately the same trend; only numerical values differ (Figure 10).

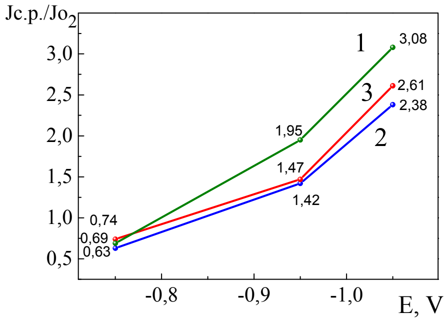


Figure 10. Change in the ratio $j_{c.p.} / j_{O_2}$ defined for X70 pipe steel: 1 – after 20 years of operation, steel manufac–turer France, pipe manufacturer Ukraine; 2 – after 20 years of operation, steel and pipe manufacturer Japan; 3 – after 20 years of storage, the steel producer is not established, pipe manufacturer in Ukraine.

So, for pipes:

- after 20 years of operation, Ukrainian (France) pipe – from 0.69 up to 2.61;
- after 20 years of operation, Japan pipe – from 0.63 up to 2.38;
- after 20 years of storage, Ukrainian pipe – from 0.74 up to 3.08.

4. CONCLUSIONS

The complex properties of pipes with a diameter of 1420 mm made of controllable rolling steel of strength category X70 after operation of the main gas pipeline for 20 years and emergency reserve pipe after a similar sto–rage period were studied. According to chemical composition analysis, the main metal of all investigated pipes belongs to low-carbon steel, micro-alloyed with vanadium and niobium, and meets the requirements of TS 14-3-995 for X70 steel. According to the content of ele–ments in the pipe's weld metal, it was found that welding was performed using typical welding wires used in pipe welding plants. Welded joints of the investigated pipes are characterized by structural heterogeneity typical for steels of controllable rolling and welding technologies.

Based on the results of studying mechanical pro–perties, it was established that parameters of base metal and welded joints of long-term pipes answer the requi–rements of technical conditions. All mechanical indi–cators of stock pipes meet the requirements of technical conditions. Relative elongation of base metal of ope–rated pipes does not correspond to standardized value.

Operating loads did not significantly affect the viscosity characteristics of the investigated pipes' base metal and welded joints. Due to high reserves of impact viscosity at standard temperature conditions, investi–gated pipes are characterized by satisfactory resistance against breaking.

Electrochemical properties of long-term operated pipes of different manufacturers and stock pipes in a model soil environment NS4, namely: corrosion poten–tial, hydrogen recovery potential, and anodic curves slopes, are within the data scatter. The ratio of the cat–hodic protection current to limit diffusion current, which characterizes the efficiency of cathodic protection, for the base metal of various pipes increases with appro–ximately the same tendency. Still, numerical values differ, from 0.42-0.69 to 2.38-3.4.

Taking into account specified heterogeneity caused by the technological effect on X70 steel of controllable rolling, it is difficult to draw unequivocal conclusions about the effect of operational work on changes in the condition of welded joints of investigated pipes. It is probably reasonable to assume that the most noticeable changes can occur in the "soft" areas of heat affected zone of longitudinal welded joints, resistance against the destruction of which, taking into account the influence of operating factor, will depend on viscosity reserves of base metal of pipes in the initial state.

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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NOMENCLATURE

b_a	anodic polarization curve slope
E	electrode potential
E_{cor}	corrosion potential
E_{H2}	hydrogen reduction potential
i	current density
Jc.p.	current at a cathodic potential
J_{O2}	limit diffusion current of oxygen recover
HV_5	Vickers hardness at 5 kilogram-force
KCV	impact toughness for samples with V-notch
KCU	impact toughness for samples with U-notch
T	temperature

Greek symbols

σ_{ys}	yield strength
σ_s	tensile strength
δ	relative elongation
δ_5	relative elongation on a 5-fold sample
ψ	relative narrowing
τ	test duration

Superscripts

a	anodic
eq	equivalent
H_2	hydrogen
ys	yield stress section

s	tensile strength
cor	corrosion
c.p.	cathodic polarisation
O_2	oxygen

ИСПИТИВАЊЕ ЗАВАРЕНИХ СПОЈЕВА КОНТРОЛИСАНОГ ВАЉАНОГ ЧЕЛИКА X70 ЗА ГАСОВОД ДУГОГ РАДНОГ ВЕКА

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Проучавана су комплексна својства (механичка, микроструктура и електрохемијска) управљивих котрљајућих челичних цеви x70 магистралног гасовода пречника 1420 мм после 20 година рада и резервне цеви за ванредне ситуације након сличног периода складиштења. Узимајући у обзир назначену хетерогеност узроковану технолошким дејством на челик X70 контролисаног ваљања, тешко је извући недвосмислене закључке о утицају оперативног рада на промене у стању заварених спојева испитиваних цеви. Утврђено је да радна оптерећења нису значајно утицала на карактеристике основног метала и заварених спојева. Електрохемијска својства (потенцијал корозије, потенцијал рекуперације водоника, нагиби анодних кривина) дуготрајних цеви различитих произвођача (Украјина, Фран–цуска) и матичних цеви у раствору NS4 су слична. Због велике резерве ударне вискозности при стандардним температурним условима, испитиване цеви се одликују задовољавајућом отпорношћу на ломљење.