Influence of metal structural heterogeneity in a sheet tube billet on forming mechanical properties and crack resistance of steel pipes for operation in the Arctic climate conditions

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Oil and gas main pipelines, which provide delivery of gaseous and liquid raw materials from the Russian distant Arctic and Sub-Arctic regions for processing at the production facilities in the central RF areas, remain the base of the transportation system for energy carriers. New pipeline systems are expanding far and far to the north and north-east mostly uninhabited territories with weakly developed transport infrastructure and extremal operating conditions — low climatic temperatures and increased corrosion activity of mined raw materials. Analysis of operation of pipeline systems in such conditions displayed enormous rise of the number of accidents and rejects at pipelines in comparison with operation of such pipelines in the central RF regions. Thus, metal structural heterogeneity in a sheet tube billet, presented by its increased banding and difference of grain size as well as presence of large non-metallic inclusions, are considered as one of the key causes of rise of the number of accidents. The results of investigation of the effect of non-metallic inclusions and heterogeneity of the structural state of a sheet billet on mechanical properties, crack resistance and corrosion resistance of the basic metal and heat-affected zones are presented in this research. The examined tubes are used for transportation of energy carriers at the minimal possible climatic temperatures.

Key words: steel structure heterogeneity, low climatic temperatures, difference of grain size, banding, crack resistance, mechanical properties, corrosion resistance.
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Introduction

Growth of consumption of energy carriers, first of all oil and gas, is one of the global tendencies of industrial development; it required accelerated development and re-orientation of the directions of their delivery transportation systems [1, 2]. Oil and gas producing companies are still remained the base of global economy and are considered among the most high-tech and science-intensive industrial branches. Continuation of the works for development of raw material deposits in the Far East, Eastern Siberia, Yamal and continental shelf led to building the new pipelines in the eastern and south-eastern directions [3—5]. In its turn, it allowed to increase capacities of accompanying enterprises, including metallurgical works, which rises production volumes of steel, rolled products and pipes of various use; the reliability problems of operation of pipelines made of these products are the basic in solving the problems of efficient operation of oil and gas companies [6—8]. It is known that essential part of developed and potential resources of hydrocarbons is located in the Arctic region, what requires development of the new deposits [9—11]. There are complications appearing, which are connected with the climatic features of the regions: low and extremely low temperatures, sometimes down to -60 °C, soils with different aggressive degree, with increased saltiness and humidity.

All these factors can lead to severe variation of the complex of properties of construction materials [12—14], which leads to appear of corrosion defects and brittle destruction [15—17]. Workability of the objects of oil and gas infrastructure can be provided in these conditions by metallurgical quality of material, among other factors [18—20]. Undoubtedly, this problem is mostly sharp for equipment including longitudinal electrically welded steel pipes with allowable operating temperature down to -60 °C [21, 22]. Material of pipes should be characterized by good weldability and should provide the required complex of mechanical properties (high strength and sufficient ductility). It should be noted that quality control of pipes, which are operated in the Arctic regions, is carried out according to the regulatory base developed for middle latitudes. Increased accident risk of pipelines often becomes the result of such control for formal correspondence to the requirements of regulatory documentation for pipes, rolled products and materials [23, 24]. Metallurgical quality of longitudinal welded pipes, which are mainly used in building and development of deposits, field and main pipelines, can be provided by use of optimal technologies of their production [18, 20, 21].

The technologies of controlled rolling, allowing to improve parameters of thermomechanical processing and containing combination of deformation stages, high-temperature holding and cooling, are more and more widely used together with development of the new, more economically alloyed steels. As a result of this processing, the structure and properties of steels re forming; high toughness parameters are provided together with strength properties [25–27]. Such processing should promote rising of steel cold resistance and strength due to intensification of recrystallization processes and obtaining of fine and ultrafine dispersed structure; however, definite structural heterogeneity in rolled products is observed together with a positive effect after controlled rolling. First of all it is related to forming of banding and grain size inhomogeneity of the structure [28–30]. While banding is most intensively observed in the surface layers of a sheet billet, maximal grain size inhomogeneity is typical for the central sheet part, what is connected with non-uniform cooling rate of rolled products, especially for sheet thickness exceeding 15–20 mm [18, 31, 32].

The aim of this work is research of the influence of structural factors on workability of pipe products manufactured of low-alloy steels in the conditions of extremely low climatic temperatures.

Technique of research

The research of the complex and microstructure of pipeline materials were carried out for revealing the effect of material structural heterogeneity on workability of pipes used in the Northern regions. Pipe templates were cut off during mounting and construction operations at the linear facility. All examined pipes completely met the requirements of the GOST 3183-2015 and were cut off the existing pipelines during maintenance operations, which were not connected with quality problems or appearance of defects. Influence of structural heterogeneity of the basic metal and heat-affected zones of pipe welding joints on cold resistance, corrosion resistance and cracking resistance was evaluated for cut off metal of pipes with 1420 mm diameter and 22 mm wall thickness made of Kh65 grade steel. When determining the collection of pipes for this research, materials with most close chemical composition (as soon as it is possible during industrial production) were chosen preferably.

Chemical composition of the basic metal in templates, which were cut off the examined pipes for manufacture of samples, is presented in the **Table 1**. Testing of mechanical properties within the temperature range from +20 to -60 °C were conducted in the tensile testing machine INSTRON 8801 and pendulum impact machine INSTRON 600MPX. Material microstructure was examined in the optical microscope Reichert-Jung MeAF-3A and the scanning electron microscope Zeiss Supra 55VP, while fractographic examination of destruction surfaces of samples was carried out in the unit JAMP-10S.

Corrosion resistance of steels was evaluated during testing in the potentiostat VersaSTAT 4 in accordance with the standards ASTM G3, G5, G59, G102. The testing was carried out at the room temperature in 5 % NaCl air-free solution without and with CO_2 saturation; pH value was measured in this case before and after CO_2 blowing. Chlorine-silver electrode EVL-1M3.1V was used as a comparison electrode.

Results and discussion

The results of mechanical testing on evaluation of strength, ductility, impact strength and cracking resistance of pipe metal are presented in the **Table 2**.

Table 1. Chemical composition of the basic metal of examined pipes

Pipe No.	Chemical composition, % (mass.)							
	C	Mn	Si	∑(V+Nb+Ti)	N	S	P	∑(Pb, Sb, Sn, Bi)
1	0.11	1.42	0.22	0.12	≤0.02	0.005	0.014	0.0081
2	0.11	1.34	0.31	0.09	≤0.02	0.006	0.011	0.0074
3	0.12	1.41	0.24	0.11	≤0.02	0.006	0.012	0.0062

Table 2. Mechanical properties and cracking resistance of the basic metal and welded joint of pipes

Pipe		Static mechanical properties at 20 °C			Impact strength KCV		Cracking resistance CTODmin	
No.	Cut off place	$\sigma_в$	$\sigma_{0.2}$	δ_5	At the temperature, °C			
					20	-60	20	-20
		MPa		%	J/cm²		mm	
1	BM	596	482	24.4	172	108	0.17	0.09
	ML	611	–	14.6	140	20	–	–
	HAZ	588	–	17.2	168	39	0.09	0.07
2	BM	614	501	29.0	286	216	0.32	0.34
	ML	633	–	17.9	147	46	–	–
	HAZ	581	–	19.0	220	48	0.18	0.19
3	BM	605	510	27.3	407	338	0.76	0.91
	ML	600	–	19.3	310	56	–	–
	HAZ	592	–	19.1	232	154	0.21	0.28

BM – basic metal; ML – melting line; HAZ – heat-affected zone

Analysis of the obtained values of mechanical properties of pipe metal at the temperature 20 °C displayed that data scattering does not exceed 15 %, what meets the requirements of the standard data of the GOST ISO 3183-2015. However, testing of pipe metal outside the range of the requirements of this GOST showed the following results for data scattering of impact strength: 1) more than 2.4 times and by 3.3 times for the basic metal; 2) more than 3.0 times and by 2.5 times for the melting line; 3) more than appr. 4.0 times for the heat-affected zone at the distance ~2 mm from the melting line – in all three cases at the temperatures -40 and -60 °C respectively.

Maximal difference in testing results of pipe metal was revealed during evaluation of cracking resistance CTODmin: the best and the worse results were varied from each other more than by 10 times (from 0.09 to 0.91 mm). Views of pipe metal fractures with the best and the worse impact strength parameters at the temperature -60 °C are presented in the **Fig. 1**. Such essential data scattering of metal cracking resistance and mechanical properties in the examined pipes during temperature lowering can lead to appearance of the areas prone to brittle destruction in an operating pipeline. Taking into account the fact that all pipes are manufactured from the same steel grade and via the technology which is common for all these steels, the only cause of such essential data scattering of the obtained results for the basic metal properties should be an inherited heterogeneity of structural state of initial sheet billets and presence of non-metallic inclusions in them.

First of all, it concerns inclusions appearing during melting, while difference in the values of metal mechanical properties and cracking resistance in the heat-affected zone of a pipe welded seam should be determined by different influence of heating during welding, which intensifies metal sheet structure heterogeneity under the effect of high temperatures. Microstructure of the pipe basic metal in two sections through pipe wall thickness (1/4 and 1/2 of its thickness) is presented in the **Fig. 2**. Analysis of the structural state revealed significant differences in microstructure of the examined samples. It was shown that the shape of ferrite grains in a pipe with high level of impact strength is mainly granular and corresponds to description A1.6 according to the GOST 54570-2011 (round ferrite grains with weak orientation in rolling direction), while grain size inhomogeneity, which reaches maximal level in 1/2 of wall thickness section, is relatively small. Thus, an average size of the five largest grains in a visible for microscope area of a polished section was 16.8 μm for the grains with No. 11–12 according to the GOST 5639-82. Pipe metal structure with the worse properties corresponds to the description A1.8 according to the GOST 54570–2011 (large ferrite grains are stretched along the rolling direction, while grain size inhomogeneity is expressed rather stronger and makes (by the five largest grains) 46.4 μm for the grains with No. 11 according to the GOST 5639-82 (Fig. 2*a* and 2*b*).

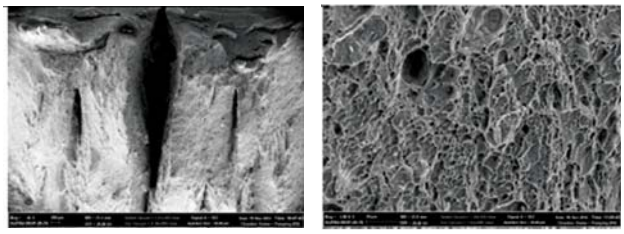
a *b*

Fig. 1. Fracture surfaces of the samples of pipe basic metal after impact strength testing at -60 °C: *a* – pipe No. 1, KCV = 98 J/cm², *b* – pipe No. 3, KCV = 316 J/cm²

Study of the boundaries of ferrite grains of all pipe steels was carried out via Auger spectroscopy and allowed to evaluate segregation level of the most dangerous impurities within ferrite boundaries, depending on the grain size inhomogeneity level. The steels characterized by average phosphorus content at the level 0.011–0.014 % (mass.) and average sulfur content 0.005–0.006 % (mass.), as well as by summarized concentration of non-ferrous metals (antimony, tin, lead and arsenic) ≈ 0.0014 % (mass.) were examined. It is shown that content of these elements within ferrite grain boundaries was equal to 0.102 % (mass.) for the pipe No. 1 steel, 0.0347 % (mass.) for the pipe No. 1 steel and 0.041, 0.0189 and 0.0027 % (mass.) for the pipe No. 1 steel respectively, for destruction surfaces of the samples cut off in 1/2 of wall thickness section. It means that the level of heterogeneity of steel chemical composition (average / grain boundaries) in the area of grain size inhomogeneity made 3.7–7.2 times for phosphorus, 3–7 times for sulfur and 6–12 times for non-ferrous metals.

Thus, it was confirmed that increase of grain size inhomogeneity degree in steels and growth of the size of ferrite grains in the medium part of a sheet lead to decrease of the square of inter-grain boundaries and, respectively, to increase of the level of non-equilibrium segregations of impurities within these grain boundaries, decrease of the value of activation energy for crack origination and propagation and to severe lowering of impact strength and cracking resistance of pipe metal (especially during testing at the lowered temperatures). All these observations correspond well with the results of other researches, e.g. [33–35]. It was established that the maximal level of structure banding (ball 5 according to the GOST 5640-2020, scale 3) was detected in 1/4 of the pipe No. 1 wall thickness; this material displayed the minimal impact strength and cracking resistance values – ball 1–2 according to the same standard for the pipe No. 3 (Fig. 2*c* and 2*d*).

So, the influence of steel structure heterogeneity, which appears during controlled rolling of a sheet pipe billet, on forming the properties of the basic metal and the area of welded joint in thick-walled pipes for the main pipelines was established. This heterogeneity has very slight effect on reliability of pipes during their operation in the regions with moderate climatic temperature conditions, but it can deteriorate reliability seriously for the pipelines operated in the Arctic or Sub-Arctic regions.

The pictures of non-pickled polished sections of the pipe basic metal are presented in the Fig. 2*e* and 2*f*. Their analysis allows to confirm influence of non-metallic inclusions (NMI), as one of the structural inhomogeneities, on mechanical properties and cracking resistance of pipe metal [31–33]. It was revealed that pipe metal is contaminated by

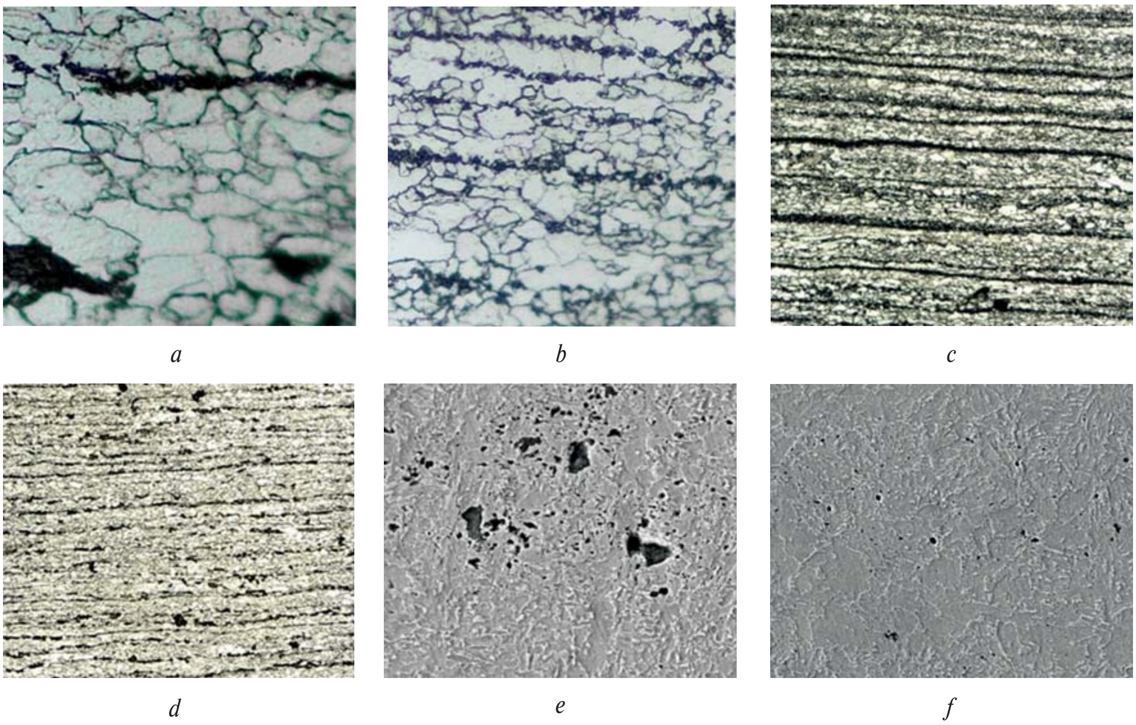

Fig. 2. Structural heterogeneity of the basic pipe metal: *a, b* — 1/2 thickness of pipe cross section, grain size inhomogeneity (×500); *c, d* — 1/4 thickness of external pipe surface, banding (×100); *e, f* — non-metallic inclusions in pipe metal (×1250)

non-metallic inclusions in any case. Maximal NMI amount was revealed in metal of the pipe No. 1, and minimal NMI amount 0 in metal of the pipe No. 3. These inclusions have mainly round form, their average size does not exceed 10—15 μm. Material of the pipe No. 1 contains NMI with size up to 40 μm, and of the pipe No. 1 — 20—25 μm. Taking into account varying of cracking resistance values for pipe metal, the size 20 μm can be estimated and accepted as the L parameter — the size of maximal inclusion, which is determined via the Griffits — Orovan equation. Typical composition of the inclusions for the examined pipes No. 1 and No. 3 are presented in the **Table 3**.

Analysis of the obtained results allowed to establish that these inclusions are compounds with complicated composition, based on Fe, Al and Ca oxides as well as Ca sulfide.

Typical microstructures of the areas of pipe welded joints (along the melting line) and the area with acicular structure in the heat-affected zone of the welded joint are presented in the Fig. 3. Based on this, it can be concluded that forming of microstructure in these areas, including forming by size and shape of grains, directly depends on initial (inherited) microstructure in sheet billet metal, while mechanical properties in these areas are also forming via thermal effect on initial microstructure.

Investigation of grain boundaries in the heat-affected zones of pipe welded joints, which were carried out via Auger spectroscopy, displayed additional thermal effect on fractures of the samples after testing on impact strength and cracking resistance. This thermal effect is connected with welding heating and leads to increase of concentration of impurities within grain boundaries and to deterioration of negative effect of impurities on low temperature properties of the examined steels (**Table 4**).

Especial attention in the research was paid to the problems of the effect of structural state heterogeneity on corrosion resistance of pipe metal. The studies of pipe metal corrosion resistance (see Table 4, **Fig. 4**) were conducted in accordance with the requirements of ASTM G3, G5, G59, G102 and resistance to sulfide cracking under stress according to the standard NACE TM-0177 (method B).

It is concluded from the Table 4 and Fig. 4 that electrochemical corrosion rate is directly connected with structural heterogeneity of steels. Buckling areas were revealed on the surface of the samples tested via NACE TM-0177 method

Table 3. Typical composition of non-metallic inclusions in metal of the examined pipes

Pipe No.	Inclusion No.	Chemical composition, % (mass.)					
		O	Ca	S	Al	Si	∑(V+Ti+Nb)
1	1	2.29	14.61	12.40	0.29	0.12	1.24
	2	9.26	17.03	13.21	1.94	0.27	1.16
	3	22.81	29.97	10.88	9.96	0.22	1.61
3	1	10.80	2.71	1.73	10.44	2.65	0.31
	2	35.20	4.62	1.05	31.65	0.16	0.27
	3	15.36	–	0.20	9.52	3.51	0.48
	4	17.45	–	0.12	12.23	2.61	0.61

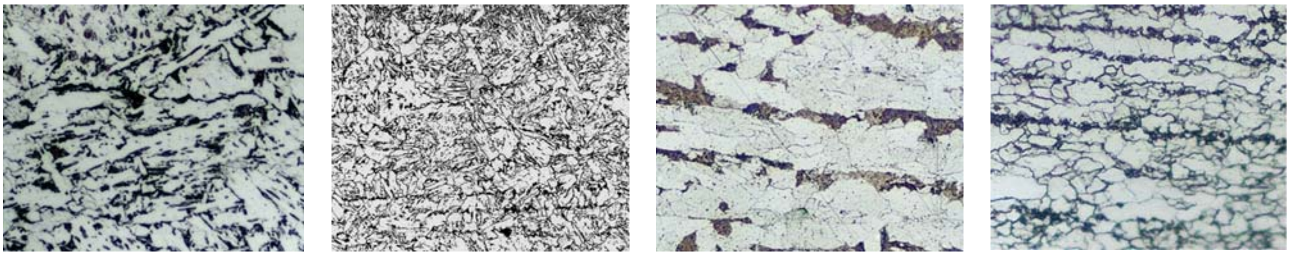
a *b* *c* *d*

Fig. 3. Steel microstructure along the melting line of the welded joint (*a*, *b*) and the heat-affected zone on the distance 2 mm from the melting line (*c*, *d*): *a, c* – pipe No. 1 and *b, d* – pipe No. 3,×500

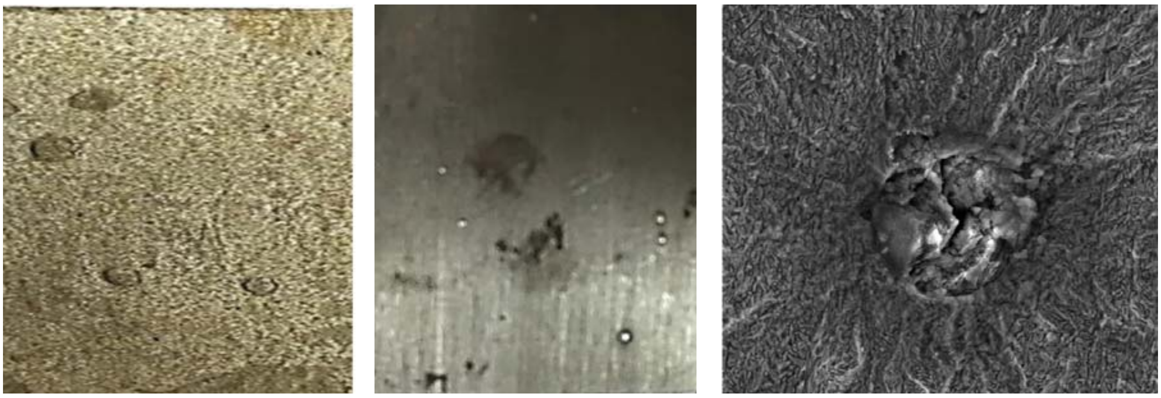
a *b* *c*

Fig. 4. The samples after testing on susceptibility to sulfide cracking under stress: *a, b* – the samples after testing (*a* – before cleaning; *b* – after cleaning with visible blisters); *c* – blister

Table 4. Influence of grain boundary segregations of impurities on impact strength and cracking resistance of pipe metal

Pipe No.	CTODmin, mm		KCV^{-60C}, J/cm^2		P		Σ(Pb, Sb, Sn, Bi)		S	
					% (mass.)					
	BM	HAZ	BM	HAZ	BM1)	HAZ2)	BM	HAZ	BM	HAZ
1	0.09	0.07	108	39	0.102	0.141	0.0097	0.0313	0.0347	0.0393
2	0.34	0.19	216	48	0.053	0.093	0.0051	0.0083	0.0211	0.0234
3	0.91	0.28	338	154	0.041	0.052	0.0037	0.0039	0.0189	0.0207

1) Content of the element was obtained after fracture analysis of the samples, cut off in the section of 1/2 sheet thickness.
2) Content of the element on the distance ~2 mm from the melting line.

Table 5. Electrochemical corrosion rate

Pipe		Electrochemical corrosion rate				Susceptibility to sulfide cracking	
No.	Examined area	Medium	V_k, mm/year	Medium	V_k, mm/year	Load, % from $\sigma_т$	Presence of defects
1	BM	5%NaCl	0.19	5%NaCl+CO$_2$	0.78	90 %	Multiple blisters
	HAZ*		0.23		–		
2	BM		0.17		0.67		Separate blisters
	HAZ		0.20		–		
3	BM		0.14		0.58		–
	HAZ		0.18		–		

*The metal samples, which imitate HAZ metal, were obtained via conduction of additional heat treatment of the basic pipe metal. Evaluation of correspondence of imitating structure and HAZ structures were controlled by metallographic method.

(see Fig. 4*a*), which were identified as blisters after cleaning with removal of sediments (see Fig. 4*b* and 4*c*). These blisters were formed in location areas of non-metallic inclusions with diameters ~20 μm and less. The boundaries around inclusions were subjected to pickling and micro-cracks were revealed on the surface of inclusions; they can propagate into a main crack during pipeline operation and lead to pipe destruction.

Conclusion

The complex of conducted researches aimed on evaluation of mechanical properties, cracking resistance and corrosion resistance of low-alloy pipe steels allowed to determine the main causes of increasing accident risk for the pipelines located in the Arctic, Northern and North-Eastern regions of Russia. It was established that structural heterogeneity (grain size inhomogeneity, banding, increased concentration of impurities within the boundaries of ferrite grains, presence of large corrosion-active non-metallic inclusions) can be considered as the causes of accelerated reject of pipeline pipes in the Arctic conditions. Thus, it was shown that additional control of metallurgical quality for pipe steels, which are aimed for the oil and gas industry and operated in the Northern Russian regions, is required to be introduced.

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