

Effect of layerwise structural inhomogeneity on stress-corrosion cracking of steel tubes

Yu A Perlovich¹, O A Krymskaya¹, M G Isaenkova¹, N S Morozov¹,
V A Fesenko¹, I V Ryakhovskikh² and T S Esiev²

¹National Research Nuclear University MEPHI (Moscow Engineering Physics Institute), Kashirskoe Highway 31, 115409 Moscow, Russia

²LLC «Gazprom VNIIGAZ», Moscow region, Razvilka village, Russia

E-mail: YuPerl@mail.ru, OAKrymskaya@mephi.ru, MGIsaenkova@mephi.ru

Abstract. Based on X-ray texture and structure analysis data of the material of main gas pipelines it was shown that the layerwise inhomogeneity of tubes is formed during their manufacturing. The degree of this inhomogeneity affects on the tendency of tubes to stress-corrosion cracking under exploitation. Samples of tubes were cut out from gas pipelines located under various operating conditions. Herewith the study was conducted both for sections with detected stress-corrosion defects and without them. Distributions along tube wall thickness for lattice parameters and half-width of X-ray lines were constructed. Crystallographic texture analysis of external and internal tube layers was also carried out. Obtained data testifies about considerable layerwise inhomogeneity of all samples. Despite the different nature of the texture inhomogeneity of gas pipeline tubes, the more inhomogeneous distribution of texture or structure features causes the increasing of resistance to stress-corrosion. The observed effect can be explained by saturation with interstitial impurities of the surface layer of the hot-rolled sheet and obtained therefrom tube. This results in rising of lattice parameters in the external layer of tube as compared to those in underlying metal. Thus, internal layers have a compressive effect on external layers in the rolling plane that prevents cracks opening at the tube surface. Moreover, the high mutual misorientation of grains within external and internal layers of tube results in the necessity to change the moving crack plane, so that the crack growth can be inhibited when reaching the layer with a modified texture.

1. Introduction

Welded steel pipelines, used for the oil and gas transportation under high pressure, have been known to fail by stress corrosion cracking (SCC), which can be intergranular, transgranular, or a combination of both, depending on the environmental and operational conditions. Recently the problem of SCC has become especially urgent in Russia and other countries, which have extended system of high-pressure main gas pipelines (MGP). The initiation and development of SCC cracks is known to depend on combined effect of three factors: the susceptibility of the material to the SCC, the presence of local tensile stresses exceeding the thresholds and the action of corrosive environment [1-2].

Among features of the material affecting on its susceptibility to the SCC, the structural and textural characteristics should definitely be considered, as well as their inhomogeneity across the tube wall thickness. It is known [3-6] that hot rolling of steel sheets, used for the manufacturing of MGP tubes of large diameter, leads to a formation of layered textured heterogeneity. Thus, parallel to the rolling plane in the external and internal layers of tubes different crystallographic planes are arranged, as well



as crystallographic directions, aligned along the axial and tangential directions, vary across the tube wall thickness. Consequently, during the tube operation its corrosion damage in the different layers is accompanied by the crack formation of different types and orientations. Depending on the accepted at that or another plant manufacturing technology the rolling sheets their layerwise textural and structural heterogeneities differ.

The aim of this work was to identify the texture and structure characteristics of tubes material of main gas pipelines, as well as their layerwise inhomogeneity, which affecting their susceptibility to SCC.

2. Experimental data

Different MGP, located in various environmental conditions and consisted of tubes, having different diameters and made from different steel types, were investigated within the frame of this work (Table 1). Different sections were cut out from each MGP: with fixed by eddy current testing SCC defects and without them. Then from each MGP section the samples of two types were prepared:

1) samples, having the studied surface perpendicular to the tube axis, which is the rolling direction of the initial sheet (RD) (labelled \perp RD), were prepared for registration of X-ray lines;

2) samples, having the studied surface parallel to the rolling plane of the original sheet (denoted \parallel RD), were prepared for texture pole figures (PF) registration of internal (about half of wall thickness) and external (surface) layers of the tube.

Table 1. Main characteristics of studied MGP.

MGP	Characteristics of pipeline steel / operating period	Diameter \times wall thickness of pipeline (mm)	Average operating pressure (MPa)	Depth SCC cracks (detected by eddy current test) (mm)
1	steel K52, thermostrengthened / about 30 years	1220 \times 15.2	5.4	1.0-1.2 not detected
2	steel X70, controlled rolling / about 25 years	1420 \times 1.7	7.4	1.7-2.5 not detected

Assessment of the structural state of samples was conducted by the half-width ($B_{1/2}$) of ferrite's (α -phase) X-ray lines and its lattice parameter, which is the main phase of the tube material. The distributions of these values were constructed across the tube wall thickness. For texture analysis of internal and surface tubes layers by three incomplete PF: $\{110\}$, $\{100\}$ and $\{112\}$, – were registered by means of standard procedure [7]. Then the complete PFs were constructed through orientation distribution function (ODF), which in its turn was restored using LABOTEX software [8]. PF is a pole density distribution (P_{hkl}) of normals of the selected type $\langle hkl \rangle$ in the stereographic projection, with P_{hkl} proportional to the volume fraction of a particular grain orientation.

Figure 1 represents PFs of studied samples, which analysis testifies about the significant texture inhomogeneity of the tubes material from thermostrengthened steel (MGP1). On the tubes external surface the texture is characterized with typical for hot-rolling of bcc metals components $\{110\}\langle 100 \rangle$ and $\{112\}\langle 111 \rangle$, while in the inner layers of tube the components $\{100\}\langle 110 \rangle$ and $\{111\}\langle 110 \rangle$ are predominant. I.e. the majority of grains in the external layers oriented so, that their crystallographic planes $\{110\}$ and $\{112\}$ \parallel to the rolling plane (RP) of the sheet while the directions $\langle 100 \rangle$ and $\langle 111 \rangle$ \parallel RD. In the inner layers the crystallographic planes $\{100\}$ \parallel RP, and the directions $\langle 110 \rangle$ \parallel RD. Therefore, to characterize the texture inhomogeneity along the sheet thickness in this case it is advisable to use the ratios of the integrated intensities $I_{(110)}/I_{(200)}$ and $I_{(110)}/I_{(222)}$ of X-ray lines registered for surface \perp RD. The distribution of this parameters across the tubes wall thickness is shown in figure 2. The values are normalized to the corresponding ratios for the texture free material. It is evident that in the sample with SCC defects (figure 2-a, black lines) the character of layerwise texture inhomogeneity along the tube wall expressed less sharply than in the sample without cracks. The

difference of the texture components ratio in the internal and external layers is higher for the sample without cracks (figure 2-a, red lines). This indicates the higher texture inhomogeneity for this case, which seems to increase the tube resistance to SSC, because during the cracks growth when reaching the layer with a modified texture, their opening is inhibited or stops due to the high mutual misorientation of grains of different layers and the necessity of changing the plane of moving cracks, what requires additional tensile stresses.

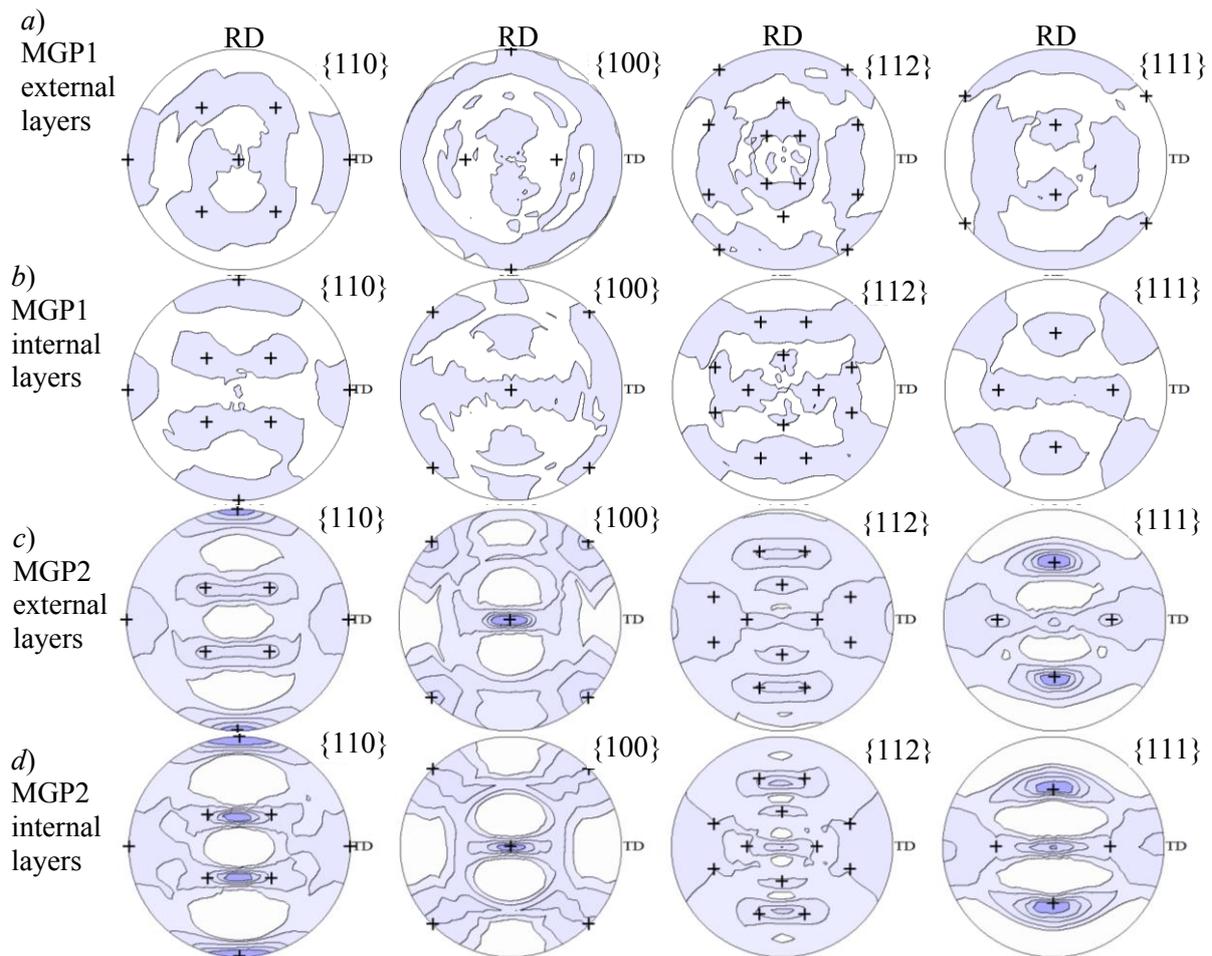


Figure 1. Typical PFs $\{110\}$, $\{100\}$, $\{112\}$ and $\{111\}$ for external and internal layers of therostronghtened tube (*a, b*) and the tube produced using controlled rolling (*c, d*).

The texture of tubes made from sheets obtained by controlled rolling (MGP2) is much sharper, its character has a fundamentally different form: the main components in external and internal layers are $\{100-111\}\langle 110 \rangle$ and additional $\{111\}\langle 112 \rangle$. In this case, the ratios of the X-ray lines intensities $I_{(110)}/I_{(200)}$ and $I_{(110)}/I_{(112)}$ can be used as the characteristics of the texture inhomogeneity along the tubes wall (figure 2-b). This is due to the view of PF $\{100\}$, where the number of normals $\langle 100 \rangle \parallel \text{RD}$ varies depending on the texture features. As one can see the more non-uniform distributions of the texture components ratios are typical for the sample without SCC cracks detected during the defectoscopy. This confirms the suggestion that higher degree of the texture inhomogeneity increases the tube resistance to SSC.

The distributions of the lattice parameters and the half-width of X-ray lines (figure 3) for investigated samples indicate that the content of point defects and lattice distortions on the surface of the tubes is higher than in the underlying layers. This is apparently is a consequence of the saturation

of the surface layers of the sheet with interstitial impurities, what might occur both in the process of hot rolling on the air, and during operating when there is a contact with the soil electrolyte.

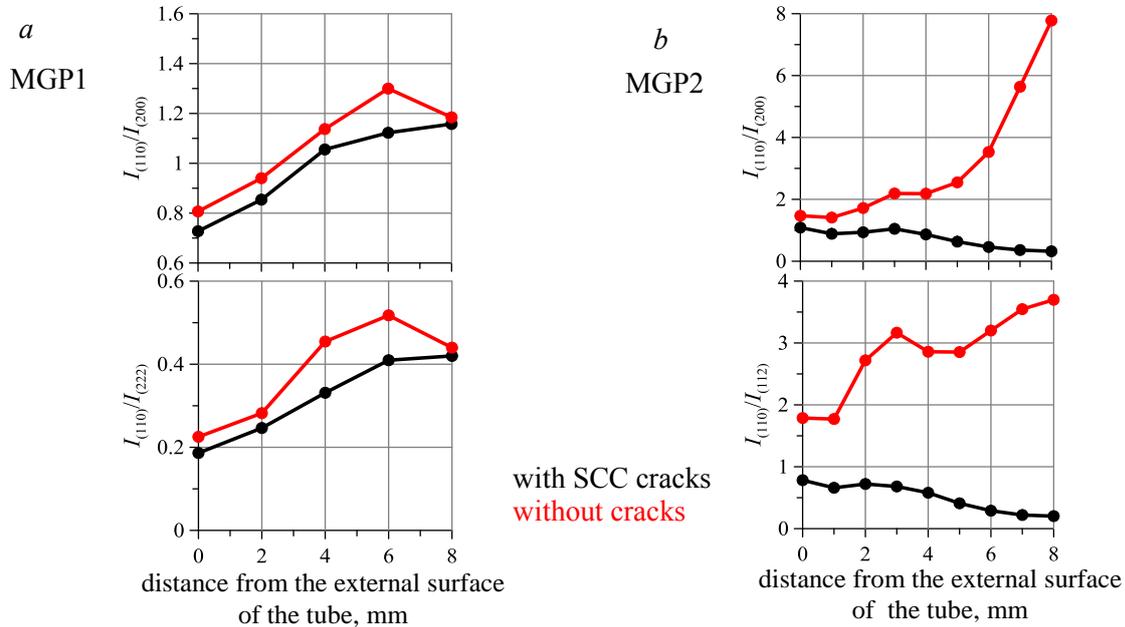


Figure 2. Texture inhomogeneity across the tubes wall thickness of MGP1 (a) and MGP2 (b).

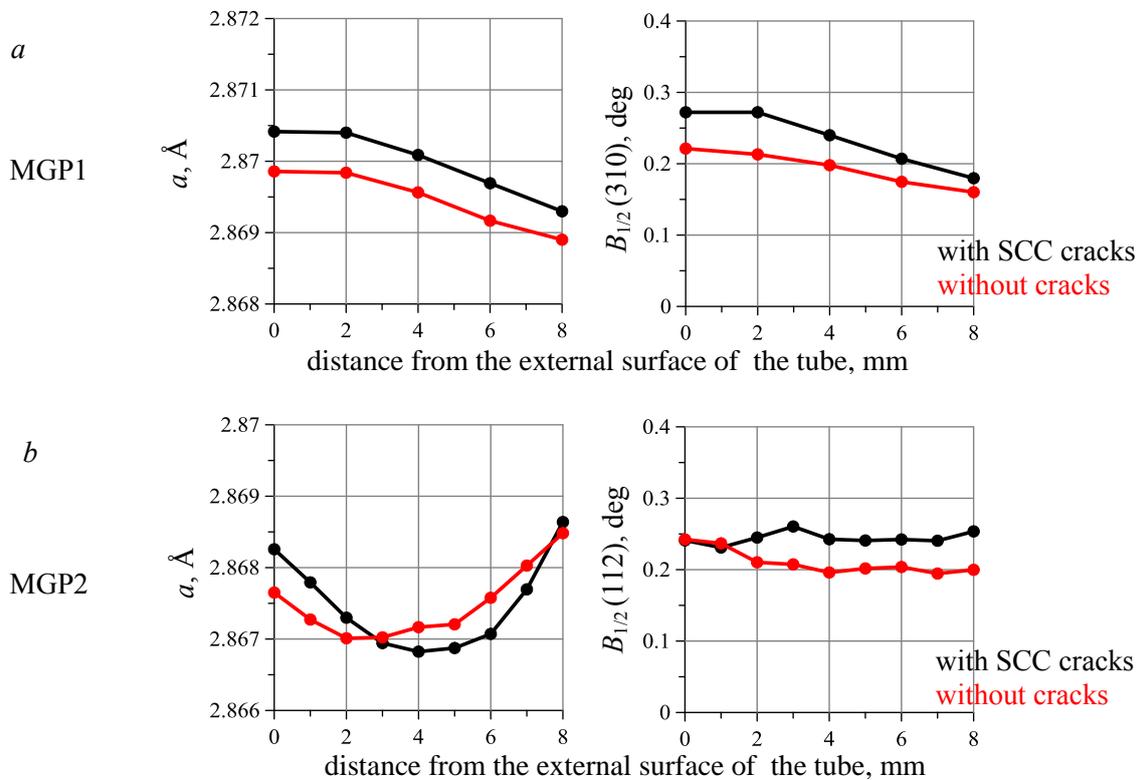


Figure 3. Distributions of the lattice parameter (a , Å) and the half-width of X-ray lines $B_{1/2}(112)$ across the tubes wall thickness of MGP1 (a) and MGP2 (b) controlled rolling (b).

3. Discussion

On the basis of obtained data we can see that depending on the accepted production technology of the sheets rolling at certain plant the layerwise textural and structural inhomogeneity differs, because its character is determined by temperature conditions, the percent of reduction, the strain rate and other parameters of thermo-mechanical treatment of the material [3-5]. Moreover, even within the one plant the rolled sheets may have different inhomogeneity due to temperature variation within the length of the sheet.

The higher non-uniform distribution of textural or structural features may increase the resistance of the tube to SCC. This effect can be explained by saturation of the surface layer of the hot-rolled sheet and obtained therefrom tube with interstitial impurities, whereby its lattice parameter will be higher than that of the underlying layers [3, 4]. This leads to the fact that the inner layers have a compressive effect on the surface layer in the rolling plane, preventing the crack development. In addition, the crack opening can be inhibited when achieves the layer with a modified texture due to the high mutual misorientation of grains of different layers and the necessity of changing the moving crack plane, what requires an increasing of applied stresses. Moreover the initiation of axial cracks on the surface of the MGP is promoted by the presence of high-angle boundaries, which sorbent impurity atoms, thus stress concentration at the crack tip increases. Therefore, the presence of sharp multicomponent texture in the surface increases susceptibility of the tube to SCC. Thereby, it is necessary to create a thin surface layer having single texture component and the texture of the inner layers should significantly differ from the texture of the outer layers. The dependency of the structural and textural characteristics upon the parameters of the specific rolling technology, revealed by investigation of the tubes, could allow elaborating recommendations on optimization of rolling regimes preventing the tubes SCC.

4. Conclusion

The presented X-ray study of the tubes samples from different sections of main gas pipelines shows their significant structural and textural inhomogeneity across the wall thickness. Despite the different nature of textural inhomogeneity of the investigated tubes it was shown that the more non-uniform distribution of the textural characteristics leads to an increasing of their resistance to SCC. Internal and external layers of tubes should be sharply different in texture, because the cracks propagation slows down or stops when reach the layer with a modified texture due to high mutual misorientation of grains and the necessity of changing the plane of moving cracks.

Acknowledgements

This work was performed within the framework of the Center of Nuclear Systems and Materials supported by MEFHI Academic Excellence Project (contract № 02.a03.21.0005, 27.08.2013).

References

- [1] Arabei A B et al 2009 *Steel in Translation* **39** (9) 725
- [2] Zheng W, Elboudjaini M, Revie R W 2011 Stress corrosion cracking in pipelines *Stress corrosion cracking: Theory and practice* ed V S Raja, Tetsuo Shoji (Cambridge: Woodhead Publishing Limited) chapter 19 749
- [3] Perlovich Yu, Isaenkova M 2010 *Int J Mater Form* **3** (1) 1143–46.
- [4] Perlovich Yu 1994 *Proc. 15th Riso International Symposium on Materials Science*. Ed S I Andersen et al (Riso National Laboratory, Roskilde, Denmark) 445
- [5] Jonas J J 2009 *Microstructure and Texture in Steels* ed A Haldar, S Suwas, D Bhattacharjee (London:Springer) chapter 1 3
- [6] Kocks U F, Tome C N, Wenk H R 1998 *Texture and anisotropy* (Cambridge University Press) 675 p
- [7] Perlovich Y, Isaenkova M, Fesenko V 2013 *Zavodskaya laboratoriya* **79** № 7 (1) 25 (in Russian)
- [8] LaboTex v. 3.0 by LaboSoft (Krakow, Poland) on <http://www.labosoft.com.pl>