Improving the efficiency of testing welded joints from thermally hardened steels of spiral seam pipes

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Abstract. When analyzing the places of the destruction of welded samples of thermally hardened steels and the relative transverse narrowing, it was found that in the range of relative thicknesses of the “soft” layer \( \tau < 0.6–0.8 \), when the strength of the welded samples is at the level of thermally hardened base metal. Destruction occurs both on the base metal at a distance from the weld, and along the weakened area in the heat-affected zone. At large values of \( \tau \), the destruction of the welded samples occurs, as a rule, along the weakened area near the weld. A characteristic feature of fracture of welded samples in a weakened section is a decrease in the relative transverse narrowing \( \psi \) compared to the case when the fracture occurs on the thermally hardened base metal at a distance from the weld. However, as is known, the value of \( \psi \) for thermally hardened metal is lower than for normalized. Based on the results of theoretical and experimental studies, as well as taking into account the basic principles of fracture mechanics, recommendations were developed on the choice of hydra model parameters impact testing of the pipeline on a section of 266-505 km in the Tyumen region. The obtained values of the crack depth \( l_c = 3.9–4.3 \) mm correspond to the acts of technical failures of the pipeline in section 335–337 km.

1. Introduction
Oil pipelines are responsible for engineering structures. Accidents and shutdowns of technological field pipelines not only lead to the loss of gas, oil, and oil products but also require the cost of repair and restoration work, which entails high economic costs, estimated at billions of rubles annually. The destruction of pipelines is accompanied by explosions, fires, pollution of water bodies, soil, and air basin, which has a detrimental effect on the flora, fauna, and economy of the country. All this speaks of the urgency of improving the quality and reliability of trunk pipelines through their hydraulic tests. The problem of analysis and safety of oil pipelines occupies a special place in the issue of ensuring their reliability. Oil field pipelines are a system of series-connected elements (pipes, fittings, pipe parts), so the failure of any of them leads to a halt in product transportation and economic losses.

2. Results and discussion
Based on the theoretical analysis and the Swift – Marcigniak criterion, the fracture breaking pressure formula is obtained \( p_{\text{times}} \) for spiral-seam and longitudinal-seam pipes of large diameter, taking into account the biaxial loading coefficient \( m \) when there is no contact hardening in the weld [1]

\[
p_{\text{times}} = \frac{2}{\sqrt{3}} \sigma_c \delta S/R, \quad (1)
\]
where $S^{-1} = B^n(B^2 + C^2)^{1-\tau}$, where $B = \cos^2 \omega + m \sin^2 \omega; C = (1 - m) \sin 2 \omega; R = D_{in}/2$.

For longitudinal pipe with $\omega = 0; B = 1; C = 0$ we get $S=1$, and for a spiral seam pipe at $\omega = \pi/4$ we get $S^{-1} = 0.5(1 + m)^2(5 - 6 m + 5 m^2)^{(1-n)/2}$.

In the presence of contact hardening, characteristic for the welded connection of pipes of large diameter, the formula for calculating $S$ is more complicated [2]

$$S = \frac{1}{B^n(B^2 + C^2)^{(1-n)/2}} + \frac{B^{1-n}K_{elast}}{2(B^2 + C^2)^{2-n}/2^n},$$

moreover, the coefficient $K_{elast}$ depends on the mechanical heterogeneity of the compound $K_c = \sigma_{el}^h/\sigma_{el}^s$ and the relative thickness of the “soft” layer according to

$$K_{elast} = (K-1)(1-\tau)^2/2\tau,$$

where $\sigma_{el}^h, \sigma_{el}^s$ – are the strength limits of the base metal and the “soft” layer; $\tau = h/\delta$ – is the relative thickness of the “soft” layer; $h$ – is the width of the interlayer, and is determined by the hardness of the weld.

It is known that when testing welded joints from thermally hardened steels of spiral-seam pipes, there are dependencies of mechanical properties on the linear energy of spiral-seam pipes, and, therefore, on the relative thickness $\psi$ of the weakened section [3]. Experimental studies [3] show an increase in the strength of the welded joint compared to the strength of the softened section by the action of contact hardening of the “soft” layer. The critical values of $\tau_p$ for thermally hardened steels for soft and hard melts vary in the range 0.5–0.8.

When analyzing the places of the destruction of welded samples of thermally hardened steels and the relative transverse narrowing, it was found that in the range of values $\tau < 0.6–0.8$. When the strength of the welded samples is at the level of thermally hardened base metal, fractures occur as for the base metal at a distance from the weld, and on the weakened area in the heat-affected zone. At large values of $\tau$, the destruction of welded samples occurs, as a rule, along the weakened area near the weld [3]. A characteristic feature of fracture of welded samples in a weakened section is a decrease in the relative transverse narrowing $\psi$ compared to the case when the fracture occurs along the thermally hardened base metal at a distance from the weld, although, as is known, $\psi$ for thermally hardened metal is lower than for normalized [3].

A sharp decrease in $\psi$ during the destruction of welded samples in a weakened area is explained by the fact that as a result of constrained plastic deformation, a rigid stress state develops [4]. It follows from experiments that the smaller the value of $\tau$, the more noticeably the value of $\psi$ decreases. At $\tau = 0.4$, the value of $\psi$ during the destruction of weld specimens in a weakened section is 2–3 times less (10–15%) than in the case of fracture along a base thermally hardened metal [5]. Therefore, ensuring equal strength of the welded joint by reducing the linear energy of welding, it is necessary to take into account the decrease in the deformation ability of the weakened section in the heat-affected zone. Violation of the equal strength of the welded joint can contribute to premature brittle fracture of welded joints of spiral-seam pipes in the presence of a stress concentrator in the specified zone [6].

Under biaxial loading, the destruction of the annular seams of spiral-seam pipes occurs at lower loads compared to the destruction of the base metal, i.e., excessively strong sections of welded joints lead to the loss of equal strength [7].

3. The experimental part

Initial data for determining the maximum pressure: outer diameter $D_{out} = 1420 \text{ mm}$; nominal wall thickness of a spiral seam pipe $\delta = 15.7 \text{ mm}$; minimum minus tolerance on wall thickness $d = 0.75$.
\[ \Delta k_c / (2 \Delta D^2) = 2 \text{ses in experiments on flat samples cut} \]

...this case, critical crack depths... specifications. Substituting... 

This example explains the fact that the average breaking strength... 

The causes of failure are stress concentration, mechanical heterogeneity... of the factory weld, deformation aging of the base metal of the pipe, low-cycle loading of the oil pipeline, causing the appearance of surface cracks, which sharply reduce the strength and ductility of the weld metal when cracks appear on the fusion line [4].

The presence in the pipe of a zone with reduced strength and plastic properties (heat-affected zone) precisely in the place of the maximum stress concentration in the weld leads to the fact that a low-cycle crack is formed over a large length of the weld (according to acts of technical failure 0.6–3.0 m). This example explains the fact that the average breaking stresses in experiments on flat samples cut across the weld from the oil pipeline amounted to \( \sigma_{av} = 300–380 \text{ MPa} \) (0.75–0.95 \( \sigma_b \)), plastic properties decrease (relative elongation \( \delta_k \) from 18.5 to 2.9–8.5\% and the relative narrowing of \( \delta_k \) from 55 to 18–20\%).

Tests of samples with a notch in the center of the weld showed the presence of a critical crack depth \( l_c = 3 \text{ mm} \), after which stresses \( \sigma_{av} \) decrease in direct proportion to the net cross-section of the pipe wall, and the plastic properties \( \delta \) change sharply from 22.5 to 4.1\%, \( \psi \) decreases from 60 to 10%. Impact strength KCV with a sharp notch was 0.4 MJ / m² along the weld fusion line, in the center of the weld 0.3 MJ / m² for the base metal 0.75 MJ / m². According to the requirements of TU 143-721-78, the impact strength should be 0.4 MJ / m², i.e., the toughness of the weld does not satisfy these specifications. Substituting the obtained values for \( \sigma_{av} \) into the formula

\[ \sigma_{kc} = \frac{N_p k_c D}{2 \delta} + \frac{3}{4} \left( \frac{P_{max}}{\delta} \right)^2 \left( \frac{\Delta k_c}{1 - \left( P_{kc} / P_0 \right)^2} \right) \]

We obtain the dependencies of destructive ring stresses \( \sigma_{kc} \) on the length and depth of the crack. In this case, critical crack depths \( l_c \) corresponding to acts of technical failures was obtained [10].
The analysis of the results indicates that the design working pressure of 5.5 MPa will lead to destruction, and it must be reduced. Hydraulic tests carried out with a pressure of 4.8 MPa make it possible to identify defects with a depth of $l_{cr} = 4.4$ mm, and tests with increased pressure of 6 MPa (1.5 times more than the working one) – surface cracks with a depth of 2.2 mm, which corresponds to acts of technical failure. For this pipeline, the working pressure of not more than 4 MPa may be recommended.

4. Conclusion
Recommendations have been developed on the selection of parameters for the hydraulic testing of an oil pipeline in a section of 266-505 km in the Tyumen region. These recommendations are developed based on the results of theoretical and experimental studies, as well as taking into account the basic principles of fracture mechanics.

The obtained values of the crack depth $l_{cr} = 3.9–4.3$ mm correspond to the acts of technical failures of the pipeline in section 335–337 km.

The recommendations are used in the management of the Sibnefteprovod oil trunk pipelines of AK Transneft with an actual economic effect of over 34 million rubles. After conducting hydraulic tests in several sections with a total length of 300 km under increased pressure and repairing the pipeline, accidents, system failures, and oil spills sharply decreased. Recommendations were given on increasing the pipeline resource by three years [10].

Based on the data obtained, longitudinal seam pipes were used for the overhaul of the pipeline. Conducted in Russia and abroad scientific research to increase the strength, ductility, crack resistance of large diameter pipes and their welded joints, refinement of methods, design estimates. These studies allow developing new Building Norms and Rules, State Standards, update regulatory and technical documentation, significantly reduce financial costs for accident recovery, reconstruction, overhaul and ensure the economic and environmental safety of the leading and field pipelines of the Russian Federation.

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