A secondary heat effect on the properties of K70 strength class steel for trunk pipelines

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Abstract. The article presents the results of the technological weldability studies for K70 strength class steel. A gradation of the studied semi-finished products by their repairability (by the number of the allowed local reheat of the material during the welding and repair processes) is proposed. The viscosity reducing of the metal in the overheating zone, determined by the magnitude of the impact test with Charpy samples at the temperature −40° C was a basis for the gradation condition. The influence of the welding heat input and the number of reheats on the HAZ metal viscosity is established. Thus, the obtained results allow us to state the low technological weldability of this steel, taking into the account such an important indicator as the repairability of the material.

1. Introduction
The intensive exploration of the northern seas shelf and regions with a cold climate creates an interest in the elaboration of the K70 strength class steels for the trunk pipelines and determines not only the development and success of the materials science, but the industrial technologies improvement for the semi-finished products manufacturing (smelting and rolling) as well [1 - 4].

When designing new domestic pipelines, there were well-known research results and the developed requirements for the welded pipe joints taken into account [5]. Increased requirements were set for the welding procedure by the impact bending tests at low temperatures. The test temperatures of −40° C normalize impact energy on Charpy specimens with a sharp notch for base metal and welded joint.

The authors noticed the degradation problem of the properties in the heat-affected zone (HAZ) when the results of the dynamic tests at low temperatures on Charpy specimens with an incision in the place of overlapping heat-affected zones, became known. The specimens were cut from welded joints of the standard parts from strength class K70 steel, had been produced by various manufacturers [6]. Among the results, there were drops up to 37 J, which was lower than the regulatory requirements (KV_{min} = 47 J at the test temperature - 40° C). It should mentioned that on the studied details the obtained drops on impact energy below the permissible level in the places of a single heat exposure were not noted.

The fact that various researchers, both in Russia and in other countries, are actively involved in issues of the properties degradation of the metall materials in the heat-affected zone confirms the urgency of this problem [7 - 11].
2. Materials and requirements for the pipes mechanical properties

We used semi-finished steel of strength class K70 with a thickness of 20 mm as the base metal.

The developed in Russia low-alloyed high-strength steel K70 belongs to the manganese alloying system, it contains relatively small additives of Ni, Cu, Mo and microalloying elements Ti, Nb, V with the limitation of the harmful impurities, such as $S \leq 0.001\%$ and $P \leq 0.010\%$. The studied steel meets the applicable requirements to the steels of this strength class being used abroad [4].

According to the requirements, K70 steel should provide tensile strength at the level of $\sigma_B = 690-790$ MPa, 0.2%-proof strength $\sigma_{0.2} = 590-690$ MPa with a ratio of $\sigma_{0.2} / \sigma_B \leq 0.9$ and an elongation after fracture $\geq 16\%$. The impact energy of the base metal at $-40^\circ$C should be not lower than 80 J (the average of 3 tests with a minimum value of $K_V\min \geq 60$ J). The impact energy of the weld metal should be $\geq 65$ J (with a minimum value of $K_V\min \geq 47$ J).

3. Research methodology

There were plates of 1200x500x20 mm in size cut out of the steel for the research, after that the plates were welded with a symmetrical V-shaped edge preparation without a gap into the samples of 1200x1000 mm in size. A groove angle was 60º, a root face was 5 mm.

The welding mode was selected in such a way as to avoid the complete penetration of the root face. After the welding, the weld convexity was mechanically removed and the original edge preparation was restored. After that, the welding was repeated in the selected mode, which ensured the imposition of the HAZ from the second pass on the HAZ of the first one.

Thus, the sample metal was heated in the heat-affected zone up to 10 times (see the scheme in Figure 1). In the experiments, not only the number of heatings (welding passages) was changed, but also the heat input. The studies were carried out with a heat input of 1.5 kJ / mm, 3.0 kJ / mm and 5.0 kJ / mm. The welding was realized by an electric arc with a consumable electrode under a flux on a 2-arc machine ESAB Master A6 (2 arcs in one bath).

![Figure 1. An experimental scheme](image)

Impact bending tests were performed on a Walter + Bai PH-450J pendulum impact testing machine with an impact energy of 450 J. The metal viscosity in the HAZ was determined according to DNV OS-F-101 on transverse samples with a V-shaped notch. The incision was made in the samples in the perpendicular direction to the surface of the plates.

4. Results and discussion

HAZ preliminary measurements on the study samples showed the dependence of its size on the heat input according to the linear law $\delta_{haz} = 1 + 0.8 Qn$, which was confirmed by a calculation [12-13], based on the unsteady heat equation (calculation was performed jointly with V.N. Startsev) according to the proposed tested method in [14-15].

Taking into account the rectilinear uniform motion of the heat source (arc) along the weld seam (in the direction of the coordinate $OX$), a mathematical model of the form was used for calculations:
\[ \rho C_p \frac{dT}{dx} = \text{div}(\lambda \text{grad} T + S), \]

where \( \rho \) is the density, \( C_p \) is the heat capacity, \( \lambda \) is the thermal conductivity, \( S \) are the volume heat sources, and \( T \) is the temperature.

The numerical solution was performed using the Flex-EDF program.

For the modes under consideration the thickness of the HAZ was \( 2.2 \text{ mm} \leq \delta_{\text{haz}} \leq 5 \text{ mm} \), which allows us to confidently assert that the zones of the thermal influence from the subsequent passes to the previous ones are completely superimposed.

When testing the HAZ metal on transverse Charpy specimens, the incision was positioned so that it fell on a section of large grain (near the fusion line) on the studied semi-finished products of K70 steel, the impact work obeys the law:

\[ KV \geq 75 - 5n, \]

where \( n \) is the number of reheats.

As it was established in previous research [6], the decrease in the properties of HAZ was associated with the formation of a fragile high-strength martensitic or martensitic-bainitic structure, which contained a high level of carbon and alloying elements, having appeared during the repeated heating along the grain boundaries at the overheating site of the HAZ (Figure 2).

![Figure 2. Weld joint structure of the longitudinal seam pipe from steel K70](image)

Based on the obtained results, the parts, made of steel K70 strength class, were graded according to their repair ability, namely, according to the number of permissible repeated local heating of the product material, for example, carried out during repair work (see Table 1).

| Degree of the parts reliability | Heat input, kJ / mm |
|--------------------------------|---------------------|
|                                | 1,5                 | 3,0                 | 5,0                 |
| critical parts                 | 3                   | 2                   | -                   |
| parts of increased reliability | 5                   | 3                   | 1                   |
| 1,5                            | unlimited           | 4                   | 2                   |

The gradation was made taking into account the fact that the viscosity of the metal in the heat-affected zone, determined by the average value of the impact energy, must satisfy the presented requirements depending on the minimum value level \( KV \geq 65 \text{ J} \), which is pointed in the regulatory documentation:
- for critical parts \( \geq 0.9 \text{ [KV]} \);
- for parts of increased liability \( \geq 0.8 \text{ [KV]} \);
- for non-critical parts ≥ 0.7 [KV];
- for non-essential parts, KV is not regulated.

In an analysis of the obtained results, there is a direct dependence of the HAZ metal impact testing energy value on the heat input during the welding and the number of reheats. In particular:
- at Qn = 5 kJ / mm, the average value of the impact energy varies from 49 J (with 1 reheat) to 37 J (with 2 reheats);
- at Qn = 3 kJ / mm, the average value of the impact energy varies from 59 J (with 2 reheats) to 47 J (with 4 reheats);
- at Qn = 1.5 kJ / mm, the average value of the impact work varies from 61 J (for 3 reheats) to 53 J (for 5 reheats).

After 10 reheats the average value of the impact energy is fixed at 45.5 J.

The average decrease in the impact energy with an increasing in the number of reheats practically fits into 8 ± 2% for one repeated welding pass.

Although, in order to improve the technological weldability during the development of the K70 strength class steel, it was envisaged to increase the purity of harmful impurities S and P, as well as to reduce the content of C <0.10% (at Mn ~ 1.7-1.9%, Cu ≤ 0.5%, Mo ≤ 0.5%, Ni ≤ 0.5%, microalloying elements (V, Nb, Ti not more than 0.12%) in steel, so the obtained results allow us to insist on the low technological weldability for this steel, taking into account such a most important indicator as the repairability of the material.

5. Conclusion

The metal reheats are typical for a number of many industrial technologies, primarily such as welding and repair work, using electric arc gouging, especially applied on high-strength steels of K70 strength class, which leads to a decrease in the properties of the material in the heat-affected zone.

The described degradation of properties is observed in the form of decreasing in an impact energy on Charpy specimens with an incision, located in the coarse grain area. Each subsequent heating for the welded joints made from steels of K70 strength class leads to a decrease in an impact energy by 8 ± 2% and it appears to be lower than the regulatory level requirements.

Thus, the obtained results allow us to state the low technological weldability for this steel, taking into account such an important indicator as the repairability of the material.

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