Application of alternative technologies in repair of rolled and welded tube to tubesheet joints

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Abstract. The article proposes a technology of repair of composite (i.e. obtained by welding and expanding) tube to tubesheet joints of heat-exchanging apparatuses using friction welding operations devoid of heat treatment. The objective of the investigation was to determine the influence of using the proposed technology for repairing the composite joints made of 15Cr5Mo steel on the properties of the joint. Samples made by different technologies were tested for strength and tightness. The result of the study was the confirmation of compliance of the characteristics of the samples made by the proposed technology with the samples made by the currently widely used technology utilizes arc welding.

1 Introduction

Heat transfer devices find application across various sectors like mining, petroleum, and energy production. Plate and shell-and-tube types stand out as prevalent types among heat exchangers.

The efficacy and stability of shell-and-tube heat exchangers are significantly shaped by analogous qualities of tubes to tubesheet joints, which are also made by welding operations [1]. Approximately a quarter of shell-and-tube heat exchanger failures stem from the deterioration of joint tightness along weld seams, caused by various factors including corrosion, cracks and related concerns. Welded tube to tubesheet joints are the most unreliable elements of heat exchangers of this type [2,3].

The integrity of joints, particularly when operating with flammable, explosive, or hazardous substances under elevated pressures and temperatures, is one of the most important operational characteristics of the heat exchanger.

During the operation of the apparatus leakage elimination is carried out during current repair and is accompanied by plugging of worn tubes using metallic plugs from each end, capped at a maximum of 15% of the entire tube quantity. Following this, the device is prohibited from further operation and is brought to a halt for an overhaul, necessitating supplementary procedures and incurring associated expenses [4].

Repair works are very labor-intensive, complicated and associated with difficult working conditions. The cost of carrying out complex repairs ranges from 40% to 70% of the cost of a new heat exchanger depending on its condition before repair.

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Repairing composite joints poses the most complexity, primarily due to the inclusion of welding operations as part of the repair process.

In Russia, one of the prevalent methods employed in the production of heat exchange devices is the M4 variant in accordance with the GOST (Russian National Standard) number 55601-2013, titled "Devices for heat exchange and air cooling. Tube-to-tubesheet fixing", which implies the use of 15Cr5Mo grade martensitic steel.

This category of steels is distinguished by the creation of regions with elevated hardness in both the welded and adjacent areas due to thermal impacts during welding, leading to considerable residual welding stresses.

To avert the occurrence of cold cracking, the welding procedure involves preheating the welded components as a precautionary measure (for steel 15Cr5Mo heating temperature before and during the welding process is from 350 to 400 °C) and subsequent high-temperature heat treatment (for steel 15Cr5Mo high tempering at a temperature of 750 ... 760 °C), which in turn increases the labor intensity of obtaining welded joints for both repair and manufacturing of welded products [5].

Post-weld heat treatment for extensive steel structures proves to be costly, primarily attributed to extended holding periods, gradual heating and cooling rates, and the considerable expense incurred during downtime for repairs. Hence, it becomes imperative to explore avenues for minimizing or obviating the need for heat treatment whenever feasible [6].

To circumvent the requirement for heat treatment during the maintenance of tube bundles made of 15Cr5Mo steel, it becomes imperative to overhaul the common technology for fabricating composite joints. This necessitates replacing the conventional arc welding operation with an alternative approach that inflicts significantly reduced thermal stress on the metal. This objective can be achieved by substituting the arc welding process with friction welding during the repair of composite joints [7–9].

As per the findings in reference [10], employing friction welding enables the creation of enduring joints possessing mechanical and plastic properties akin to those of the base metal within the zone of thermomechanical influence, all without the necessity for thermal operations.

Research on the weldability of 15Cr5Mo steel has affirmed the fundamental feasibility of achieving top-notch permanent joints through friction welding technology. However, these studies did not account for the design and geometric parameters of composite joints.

2 Research methodology

To determine the effect of using proposed technology in repair of composite joints made of 15Cr5Mo steel on the properties of the joint, samples simulating joints of this type (Figure 1) underwent testing for tightness using hydraulic pressure, as well as for the resistance to tearing out tubes from tubesheets. As a replacement for the tubesheet, equivalent sleeves were used in the samples.

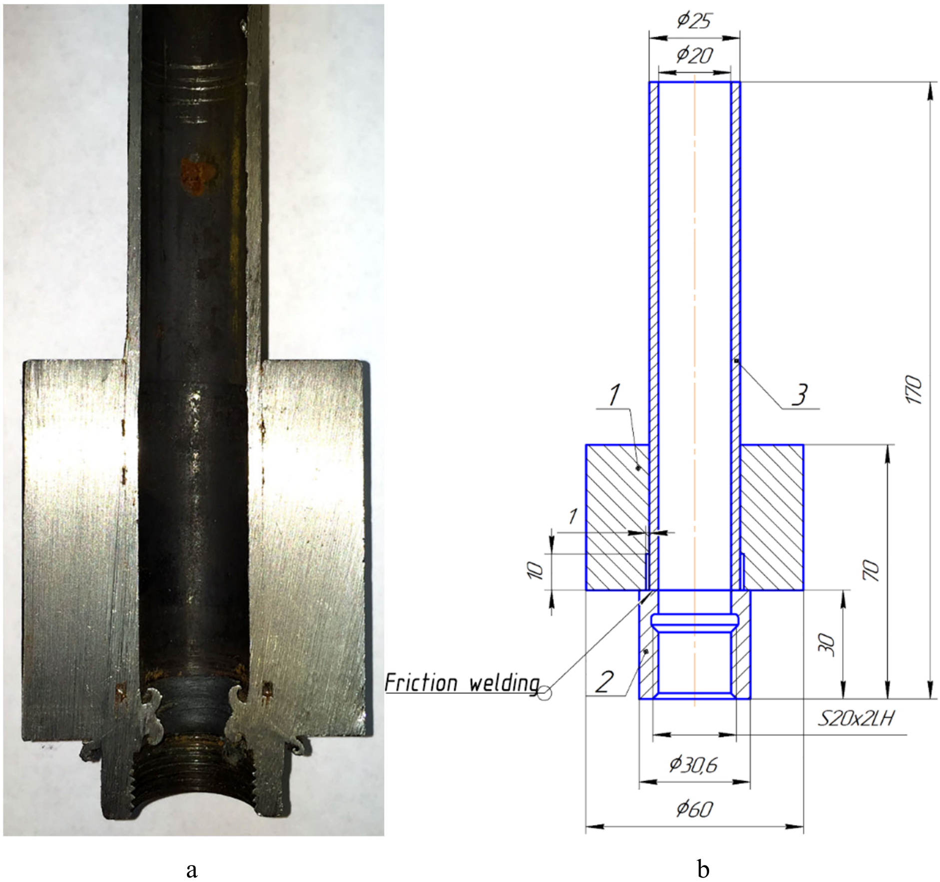

Fig. 1. Sample simulating composite joint made by friction welding (a - sample in section, b - drawing of the sample): 1 - equivalent sleeve; 2 - welded sleeve; 3 - tube.

For the tests 10 samples from 15Cr5Mo steel were made (Table 1).

Table 1. List of samples made for testing.

Testing	Technology of sample manufacturing	
	proposed	**common**
for tightness by applying hydraulic pressure	2 test samples	2 test samples
for the resistance to tearing out tubes from tubesheets	3 test samples	3 test samples

Friction welding of samples according to the proposed technology was conducted using the specialized friction welding machine.

The samples produced according to the common technology were fabricated using tungsten inert gas welding in accordance with GOST 14771-76 "Arc welding with shielded gas. Welded joints" with preheating and post-weld heat treatment (high tempering).

Following the welding procedures, all types of tube samples underwent expanding within equivalent sleeves in accordance with the manufacturing technology of the joint and the requirements of GOST number 55601-2013.

Tests on the strength of a permanent joint by tearing out the tube from the tubesheet were conducted in accordance with GOST number 23691-79 "Tube to tubesheets and collectors joints of heat exchangers". These tests established the strength characteristics of tube to tubesheet joint.

Fixation of the sample was carried out in a special tool, which also allows to apply force to tear out the tube (Figure 2).

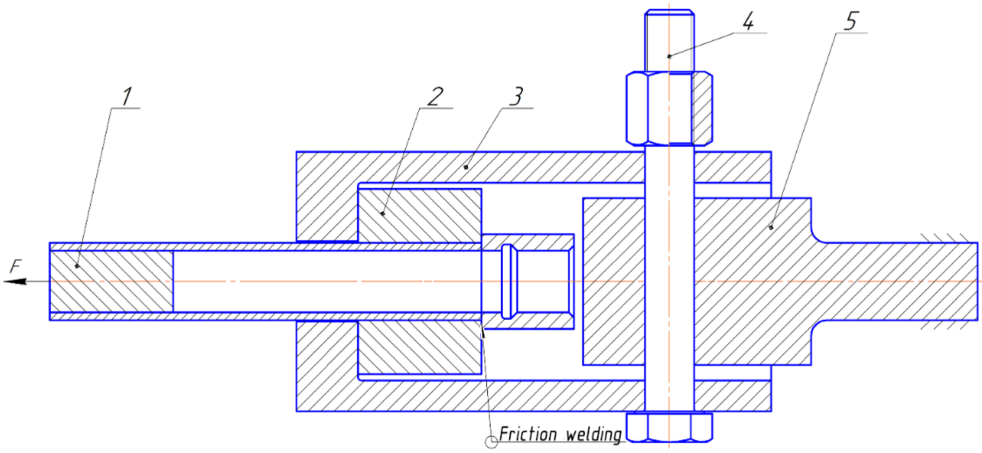

Fig. 2. Drawing of the tool for strength testing of composite joints with the installed test sample: 1 - plug; 2 – test sample simulating composite joint; 3 - tool body; 4 - retaining bolt; 5 – tool tail.

Before the beginning of testing, the free end of the sample tube was fortified with a plug, and subsequently, the sample was inserted into the tool body. Following this, the sample was secured within the tool body using the tool tail and retaining bolt. The plug-reinforced end of the tube was then affixed to the movable chuck of the tensile test machine, while the tool tail was affixed in the fixed chuck. The test proceeded until the sample fractured using a tensile test machine IR-6055-500-0.

Tests of composite joints for tightness by hydraulic pressure were conducted in accordance with GOST number 23691-79 to detect leaks in the zone of tubes expanding and welding with tubesheet.

Tests of samples simulating composite joints were carried out with the aid of a special tool (Figure 3).

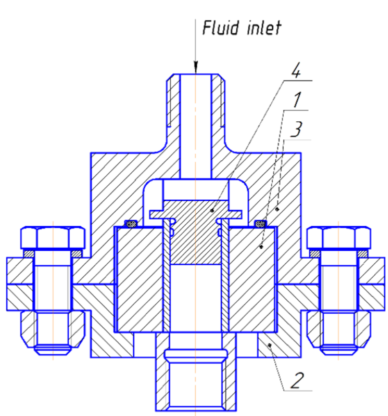

Fig. 3. Drawing of the hydraulic testing tool with the test sample installed: 1 – test sample; 2 - lower part of the tool body; 3 - upper part of the tool body; 4 – plug.

This tool enables the closure of the inner tube cavity and the generation of elevated pressure within the section simulating the intertube space of heat exchanger. This allows an assessment of the tightness of the composite joint to be made.

Before the beginning of tests, the open end of the tube was sealed with a plug, and the sample was positioned in the lower part of the tool body and covered with the upper part of the tool body, and the tool body parts were secured together using studs. The tightness of the assembly was ensured by installing gaskets.

Then the tool with the test sample installed in it was fixed in the water test unit, water was introduced into the orifice in the tool body. Following the fixation of the flange in the water testing unit, a pump was utilized to elevate the pressure to the specified level, with pressure levels monitored via a manometer.

To simulate the thinning of the tube wall caused by corrosion wear after completing the test, a layer of metal was progressively removed from the interior of the sample tube in 0.5 mm intervals, resulting in a 1 mm increase in the inner diameter of the tube. Subsequently, the test was repeated.

In the primary phase, the samples housed within the tool underwent hydraulic test, applying a pressure of 12 MPa. The ascent and descent of pressure occurred at a controlled rate, never exceeding 0.5 MPa per minute. The samples were maintained at the test pressure for a duration of 30 minutes. Than the pressure was released, and a thorough inspection for any potential leaks in the tool containing the sample was conducted.

In the secondary phase, the pressure was elevated following the identical procedure to reach 35 MPa, which marked the upper limit permissible for the water testing unit.

3 Research results and discussion

During tearing out tube from tubesheet for the test samples made by the proposed technology, only 1 test sample failed along the weld. In the case of the test samples made by the common technology, all 3 test samples failed along the weld.

The results of tear out tests are summarized in Table 2.

Table 2. Findings from the strength testing of samples by tearing out tube from tubesheet.

Technology of sample manufacturing	The sectional area of the welded connection, mm^2	Ultimate tensile strength, MPa
proposed	176	810.2 (±0.5)
common	176	654.5 (±21.6)

Photos of the samples after the tearing out tests (Figure 4) displays the location of the rupture within the joint area (on the left - made according to the common technology, on the right - according to the proposed technology).

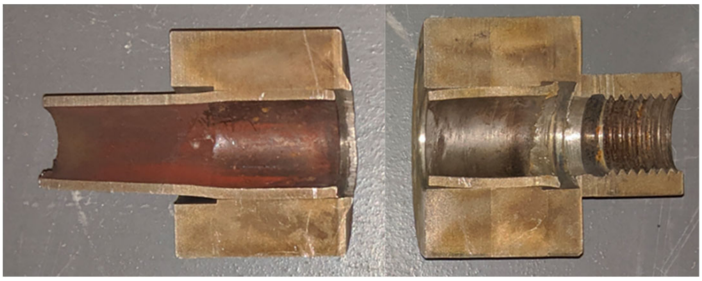

Fig. 4. View of samples subjected to tearing out tests in cross section.

Test results indicate that samples made by the proposed technology, during tearing out tests, an average ultimate tensile strength 23.8% greater than samples made by the common technology. At the same time, the scatter of these values of samples made by proposed technology is an order of magnitude lower than that observed in samples made by the common technology, which is characteristic of friction welding as an automated process.

Table 3 displays the outcomes of hydraulic tests conducted on samples at various test pressures.

Table 3. Results of hydraulic tests of samples by test pressure.

Tube's internal diameter, mm	**Thickness thinning of tube wall, mm**	**Technology of sample manufacturing**	
		proposed	**common**
Primary hydraulic testing phase			
20 ÷ 24	0 ÷ 2	sample is sealed	sample is sealed
Secondary hydraulic testing phase			
20 ÷ 24	0 ÷ 2	sample is sealed	sample is sealed

During testing of samples with tube inner diameter equal to 20 mm, no leaks were detected in any of the samples. The same outcomes were observed in samples with inner tube diameters measuring 21, 22, 23, and 24 mm.

This indicates that the samples made by both common and proposed technologies, are resistant to pressure exceeding the maximum test pressure by almost 3 times, until the tube walls reach a thinning of 80%.

The carried-out tests allow to approve that the common and proposed technologies of manufacturing composite joints allow to provide adequate tightness of the joints under the specified test conditions according to GOST number 34347-2017 "Specifications for steel vessels and equipment subjected to welding. General technical requirements", matching the most extreme operational scenarios, even under conditions where tube wall thinning reaches 80%.

Therefore, employing friction welding for heat exchanger repairs can facilitate to obtain composite joints possessing the necessary operational specifications, eliminating the necessity for thermal treatment.

4 Conclusion

Samples were tested for strength by tearing out tube from tubesheet and tightness by hydraulic pressure. These tests demonstrated that the mechanical properties of the samples made by the proposed technology without additional heat treatment were equivalent to those of samples made by conventional technology with heat treatment.

The joints made by friction welding had a stable quality, i.e. their characteristics had significantly less variation than the joints made by arc welding. However, there are automated arc welding methods that could potentially show a similar result, but they were not used within the scope of this study.

Hydraulic pressure tightness tests were performed with gradual thinning of the tube wall. These tests showed that the potential service life of the joints made by friction welding was similar to that of the joints made by arc welding.

Thus, the technology of friction welding can be used in the repair of heat exchanger tube bundles, as the above-mentioned characteristics of joints made by friction welding are not inferior to similar characteristics of joints made by arc welding.

However, there are limitations to the application of this technology. One of them is the requirement that the spacing of tube holes in tubesheets should be larger than the size of the welded sleeve. In further studies it is planned to produce a mock-up tube bundle with dozens of tubes in order to work out the technology of their fixing and welding considering the real location of tube holes.

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