Evaluation of the Possibility of Obtaining Tube-to-Tube Sheet Welded Joints of 15Cr5Mo Steel by Alternative Technological Process

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Abstract. This paper presents the results of the tests of joints of chrome-molybdenum steel, obtained by rotary friction welding. On their basis, conclusions were drawn about the weldability of this type of steel by friction welding, and also the applicability of this welding technology in the manufacture of heat exchange equipment.

1. Introduction
Heat exchanging equipment is a very significant part of the process equipment in the petrochemical and related industries. The share of heat exchange equipment in the petrochemical and petroleum industries is on average 50% [1].

The most widespread among others are shell-and-tube heat exchangers, as this type of heat exchanger has high efficiency, reliability and has a great variety of design.

An important component of the shell-and-tube heat exchangers is a tube bundle consisting of heat exchanging tubes, tube sheets and baffles. Useful life and reliability of heat exchangers of this type is largely determined by similar indicators of tube-to-tube sheet joints [2]. It is manufactured by rolling or rolling with welding according to GOST R 55601-2013 (state standard of Russian Federation) [3].

Rolled and welded joints are used for apparatuses that require increased strength and tightness of tube-to-tube sheet joints, particularly for heat exchangers operating at high pressures and temperatures, or when specific requirements for fire and explosion safety, toxicity or radioactivity of the working medium are imposed on heat exchange equipment [4].

In the manufacture of equipment used in high-temperature, corrosive environments and high mechanical stresses, heat resistant chromium and chrome-molybdenum steels of the martensitic class are widely used [5]. This steels are characterized by the ability for a long time to meet the performance required for the equipment and its components, at a relatively low cost.

However, the manufacture of welded equipment of these steels is difficult due to the susceptibility of this class of steels to harden. To prevent the formation of cold cracks during the welding process, preheating and heat treatment are necessary. Thus, for 15Cr5Mo steel (Russian analogue of X12CrMo5 steel), the preheating temperature is 300-350 °C and the heat treatment temperature is 740-760 °C [6].

The heat treatment operations are not only difficult to implement, but also energy-consuming, this significantly increases the costs of the manufacturers of heat-exchange equipment.
As a result, for today the use of steels of this class, including 15Cr5Mo, is complicated by the complexity of the assembly and welding process in the manufacture of oil refining and heat-exchange equipment using arc welding methods.

2. Experimental procedure and results

2.1. Prerequisites for conducting research
One of the alternative ways of reducing the laboriousness of manufacturing heat exchange equipment of hardenable steels is the use of welding methods with a high concentration of energy in the heating spot (laser welding [7], electron beam welding) or friction welding methods. The use of friction welding methods requires the reengineering of the design of the part elements of heat exchange equipment; although at the same time it significantly reduce the costs of manufacturing and the manufacturing time.

An example of the possible design of tube-to-tube sheet joints manufactured by rotary friction welding is shown in figure 1. After the tube 1 is rolled or fixed relative to the tube sheet 2, the edges are prepared at an angle 3. Then, with special tooling, the bushing 4 is rotated with the friction welding force and the forge force after the rotation is stopped. The internal diameter of the bushing 4 is equal to the flow diameter $d_t$ of the tube 1 [8]. The advantage of this method is that it can be used both in the manufacture and in the repair of heat exchangers, in particular of 15Cr5Mo steel. However, to date, there are no data on the properties of welded joints of 15Cr5Mo steel obtained by friction welding.

2.2. Equipment and modes of welding
To study the properties of these welded joints of 15Cr5Mo steel, tubes with an external diameter of 35 mm and a wall thickness of 6 mm were made. Rotary friction welding was carried out using a rotary friction welding machine “ПСТ-20Т” produced by company “КТИАМ” in Chelyabinsk. Welding modes are shown in table 1.

Then, the test samples were made by electrospark cutting of the welded joints of the obtained samples for static tensile, cyclic strength, impact, hardness tests, study of corrosion resistance and microstructure of various zones of welded joints.

| Rotational speed, rpm | Force, kN | Duration, sec. |
|----------------------|-----------|----------------|
|                      | Friction welding | Forge | Friction welding | Forge |
| 1250                 | 50        | 80            | 7            | 2          |

2.3. Static tensile test
The evaluation of the static strength characteristics was carried out in accordance with the requirements of GOST 1497-84 and GOST 6996-66 at room temperature on cylindrical samples (type
IV in accordance with GOST 1497-84, type XXV in accordance with GOST 6996-66) on the tensile machine “Instron 5982.” The values of the tensile strength $\sigma_v$, yield strength $\sigma_t$, strain $\delta_5$ and reduction of area $\psi$ of samples of the base metal, the weld metal and the zone of thermomechanical influence, obtained as the average value of the results of the test of three samples, are shown in table 2.

It can be seen from table 2 that the characteristics of the static strength of the welded joint obtained are at a higher level than the characteristics of the base metal. The plastic properties of metal of the zone of thermomechanical influence on the basis of the values of the strain ($\delta_5 = 24\%$) and the reduction of area ($\psi = 72\%$) can be considered high, especially taking into account that the welded parts were not subjected to thermal operations that are necessary to obtain the required level of the plastic properties when using fusion welding.

![Figure 2. Photo of the welded tubes joint of steel 15Cr5Mo obtained by friction welding.](image)

A significant increase in the tensile strength and yield stress of the zone of weld metal is observed, with a typical decrease in the values of the strain and reduction of area. Table 2. Mechanical characteristics of samples.

| Mechanical characteristic | Base metal | Zone of thermomechanical influence | Weld metal |
|--------------------------|------------|-----------------------------------|------------|
| $\sigma_v$, MPa          | 268        | 393                               | 1223       |
| $\sigma_t$, MPa          | 522        | 558                               | 1594       |
| $\delta_5$, %            | 33         | 24                                | 7,6        |
| $\psi$, %                | 81         | 72                                | 19         |

2.4. Hardness test

The allocation of the microhardness values along the cross section of the base metal, the zone of thermomechanical influence (TMI) and the weld metal is shown in figure 3.

It can be seen from the figure that the allocation of microhardness along the cross section of the welded joint corresponds to the Gaussian law with a maximum at the center of the weld, that is not typical for welded joints of 15Cr5Mo steel obtained by fusion welding [6].

The results of determination of the microhardness and photos of the macrostructure show that the width of the welded joint is approximately 2.8...3 mm for a 6 mm thick piece that is significantly smaller compared to the arc welding methods. Accordingly, this leads to a decrease in the volume of metal with a high level of stresses and the probability of formation of cold cracks.

![Figure 3. Allocation of microhardness along the cross section of the sample of steel 15Cr5Mo obtained by friction welding.](image)
There are no microhardness rises in the width of the welded joint, which are characteristic for the heat-affected zone of welded joints obtained by arc welding. This is a factor that positively affects the welded joint resource due to the less heterogeneity of the mechanical properties along the cross section of the welded joint. In the authors' opinion, the values of microhardness increased in comparison with the base metal can be explained by the formation of an ultrafine-grained structure as a result of strain hardening during the thermodeformation cycle of friction welding (a similar opinion is expressed in [9]). Thus, it can be concluded that the increased values of microhardness in the zone of weld metal are observed not as a result of the formation of hardening structures, but as a result of a higher “density” of the metal structure of the welded joint. In [9] this fact is explained by an increase in the density of dislocations and grain-boundary hardening as a result of the formation of a highly deformed ultrafine-grained structure.

2.5. Microstructure study
Figure 4 shows micrographs of the microstructure of the characteristic zones of the welded joint obtained with a raster microscope with a 1000-fold magnification. A visual analysis of the micrographs shows that as a result of the thermodeformation welding cycle, the structure of the characteristic zones of the welded joint is more crushed than the base metal and increases the degree of its homogeneity. At the same time, the microstructure of the weld metal is more “disoriented” than the zone of thermomechanical influence and the base metal, which can be explained by the higher level of stresses and deformations arising from the contact of parts during welding and forging process. The above-mentioned character of the microstructure of the zone of weld metal partially explains the increase in the level of mechanical and plastic properties of the weld metal at increased values of microhardness.

![Microstructure of the characteristic zones of the welded joint (1000-fold increase).](image)

**Figure 4.** Microstructure of the characteristic zones of the welded joint (1000-fold increase).
2.6. Impact test
Impact test was carried out with the copra with a vertically falling load “Instron CEAST 9350” on samples in accordance with GOST 6996 (three samples for each type of welding) with V-notch located at the center of the weld and a test temperature of 20 °C. Average values of impact toughness were as follows: for samples obtained by arc welding - 162 J/cm², for samples obtained by friction welding - 151 J/cm². Thus, the impact toughness of samples obtained by friction welding is close to the impact toughness of samples obtained by arc welding using the existing technology (using thermal operations).

2.7. Static bending test
To assess the plastic properties of the welded joint, taking into account the susceptibility of 15Cr5Mo steel to form cold cracks, test for static bending of additional samples of rectangular section in accordance with GOST 1497-84 was carried out.

The tests for static bending were carried out until the surfaces were parallel. No visible cracks were detected after testing on samples of both types. This indicates that the used arc welding technology was implemented properly, and the friction welding technology has allowed obtaining welded joints with an acceptable level of plastic properties without the use of thermal operations.

Figure 5 shows photos of samples after static bending test.

On the sample obtained by friction welding, it can be seen that the weld metal has high strength properties, and as a result of bending the sample obtain a П-shape without any plastic deformation of the weld metal. The absence of cracks in this zone also indicates a favorable stress-strain state of the welded joint after welding.

2.8. Corrosion resistance study
To assess the corrosion rate of the welded joint obtained by friction welding, gravimetric tests were carried out by holding the samples in a 9% solution of sulfuric acid for 160 hours. Based on the results obtained, the corrosion rate was determined to be 36.8 g/m²·h, which indicates that the welded joint has a high corrosion resistance in corrosive environments typical for operating conditions of 15Cr5Mo steel. In the opinion of the authors, the high corrosion resistance is due to the absence of thermal
influence of the arc during the friction welding process, which has a positive effect on the microstructure of the weld metal and the residual stress level.

In addition, the electrode potential values were determined. Determining of the electrode potential values makes it possible to determine the corrosion resistance of welded joint zones and the most vulnerable areas.

The most favorable allocation of potentials is the case of equality of the electrode potentials of the weld and the base metal \((\phi_w = \phi_{b.m.})\), when there is the process of general uniform corrosion. In real production conditions, it is difficult to achieve this equality, so it is preferable to displace the electrode potential of the weld to higher values. The anodic dissolution is transferred to the base metal while reducing the weld corrosion rate \((\phi_w > \phi_{b.m.})\).

Due to the uneven corrosion of the welded joint, the mass index does not fully characterize its corrosion resistance. Therefore, the method of electrode potential was used to evaluate corrosion of welded samples.

Tests of the electrode potentials of the zones of the welded joints were carried out. The electrode potentials of the characteristic zones of the weld and the base metal were registered with a special probe. The value of the electrode potential was recorded with a voltmeter with a measurement error of \(\pm 5\%\). The results of the tests are shown in figure 6.

![Figure 6. Results of measuring of the electrode potential values of samples.](image)

The weld obtained by arc welding has a potential of -0.31 V (silver chloride electrode), and is more noble to the metal of both the tube and the tube sheet.

The potential of the weld of the sample obtained by friction welding has higher value than the potentials of both the tube and the tube sheet.

Thus, from the point of view of electrochemical corrosion, products obtained by friction welding are not inferior to corrosion resistance to products obtained by arc welding.
2.9. Cyclic strength test
To assess the durability of the obtained welded joints, the samples of the base metal and the weld metal were subjected to a symmetrical cyclic tensile load with the beginning at zero, a frequency of 10 Hz and maximum amplitude equal to 0.6 of the yield strength of 15Cr5Mo steel. Tests, including the manufacture of samples with a diameter of 5 mm and length of 25 mm, were carried out in accordance with the requirements of GOST 25.502-79. As a result of the tests, the destruction of samples of both the base metal and welded metal was not observed at the number of load cycles of $10^5$. Thus, it can be concluded that the life of the welded joints of 15Cr5Mo steel with the number of load cycles of $10^5$ is not lower than samples of the base metal.

2.10. Evaluation of test results
On the basis of the results, the weldability of 15Cr5Mo steel by rotary friction welding can be estimated as good; to obtain welded joints with a high level of strength and plastic properties, no additional thermal operations are required, and the life of the welded joints is at a good level. The introduction of friction welding into the technological process of manufacturing welded oil and gas equipment, in particular, tube bundles of heat exchangers of 15Cr5Mo steel, will require a significant upgrade of the friction welding equipment in connection with the design of tube bundles. However, it seems economically expedient because it allows avoiding energy-intensive thermal operations and reducing manufacturing time due to the higher degree of automation of the friction welding process.

3. Conclusion
1) 15Cr5Mo steel has good weldability by rotary friction welding, which allows obtaining welded joints with mechanical and plastic properties of the zone of thermomechanical influence at the level of the base metal without the use of thermal operations.

2) The use of friction welding for the production of tube bundles of heat exchangers of 15Cr5Mo steel is economically expedient, despite the need for a significant upgrade of the specialized welding equipment.

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