Prospects for the use of u-shaped welded pipes of steel a316l heat transfer assortment in chemical engineering

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Abstract. To expand the possibilities of using welded stainless steel pipes in chemical engineering, comprehensive studies of the experimental batch of straight-seam and U-shaped laser-welded tubes of A316L steel have been performed. The corrosion resistance, strength and structural-phase changes in the product material during austenization were studied: short-term annealing at 1000 °C. It is shown that longitudinal welded pipes have a high margin of ductility. This opens up prospects for their wide application for the production of bent assortment in the form of U-shaped products. It has been experimentally proved that heat treatment according to the regime of short-term austenization completely eliminates metal hardening, providing relaxation of its elastic stresses and the formation of the structural state necessary for technological redistribution of A316L steel. Heat treatment according to the mode of short-term austenization at a temperature of 1000–1050 °C for 1–5 minutes can be recommended as a mandatory technological operation that completes the metallurgical conversion of laser-welded stainless tubes of heat-exchange gauge.

1. Introduction

Seamless pipes, which are now widely used in nuclear power equipment and chemical engineering, can last at least 30 years. The introduction of new laser welding methods for stainless steels and heat-resistant alloys and automated intelligent control systems for the technological process of production of welded pipes can significantly improve the quality and technological properties of welded pipes.

In many cases, they not only are not inferior, but also surpass the similar properties of seamless pipes. At the same time, labor productivity dramatically increases, and the cost of their production is significantly reduced.

World practice confirms the widespread use of welded pipes for heat exchangers of nuclear power plants and apparatuses of the chemical industry.

The wider introduction of welded pipes in these sectors requires systematic comprehensive research, scientific generalization of the results and the introduction of appropriate amendments to existing national standards and industry standards.

The purpose of this study was to substantiate the possibility of using longitudinal welded laser welded tubes for the manufacture of U-shaped products for chemical engineering. To achieve this
goal, comparative tests of laser-welded longitudinal welded tubes made of A316L steel (GOST 9941-81, EN10217-7) with an outer diameter of Ø25 mm and a wall thickness of 2.0 mm and U-shaped products from them were performed. Experimental samples of laser-welded tubes were made at Tekhno TUB LLC (https://technotube.ru/techno-tube/). U-shaped products from them are made by JSC "VNINEFTEMASH".

2. Results

The objects for research were samples cut from different zones of the welded pipe and the U-shaped product in the initial and annealed states. Annealing corresponded to short-term austenization at 1000°C in air [1, 2]. The studies were carried out from the outer and inner surfaces of the pipe. The labeling of the samples is shown in table 1.

Table 1. Samples for studying the properties of laser-welded straight and bent (U-shaped) pipes made of 316L steel.

| Marking | Type of laser welded pipe | Heat treatment status | Seam Location | Research surface |
|---------|---------------------------|-----------------------|---------------|------------------|
| 6Иш    | without heat treatment    | with a seam           | internal      | outdoor          |
| 62     | straight pipe             | heat treated          | with a seam   | internal          |
| 63     | heat treated              | seamless              | internal      | outdoor          |
| 6НОИ   | without heat treatment    | seamlessly bending    | internal      | outdoor          |
| 6н     | U pipe                    | heat treated          | seam outside the bend | internal | outdoor |
| 6в     | heat treated              | seam inside the bend  | internal      | outdoor          |
| 6с     | heat treated              | side seam             | internal      | outdoor          |

The weld structure of experimental samples of laser-welded straight-line pipes made of A316L steel is presented in figure 1. Metallographic studies were performed on a device OLIMPUS. The width of the weld varies from 0.6 mm (in the center of the section) to 1.2 and 1.3 mm (on the outer and inner surfaces of the pipe). An example of the structure shown in figure 1, indicate that the weld of the experimental pipes has an internal burr with a thickness of up to 200 μm.

![Figure 1](image1.png)

Figure 1. Sample for metallographic studies from a longitudinal welded laser welded pipe of steel grade A316L (the seam is indicated by an arrow) and the structure of the seam.
In order to compare the performance properties tested for corrosion resistance. Samples for research have dimensions (20 × 40) mm. The studied (working) surfaces were polished (to a roughness \( R_a \leq 0.8 \, \mu m \)) and isolated from a flat pair with a contact window (12 × 12) from the active medium in an open glass cell with a silver-silver reference electrode (see figure 2).

Corrosion tests for the tendency to pitting corrosion were carried out by the potentiodynamic method of measuring pitting resistance in an aqueous solution with 16.5 g/dm³ of sodium chloride. In the potential sweep mode at a speed of 0.5 mV/s, the forward and reverse polarization curves were recorded on an IPC-Pro potentiostat with a current meter with a sensitivity of 1•10⁻⁶ A.

On the polarization curves (an example is shown in figure 3a), the corrosion characteristics (potentials) were recorded: the onset of corrosion \( (E_{cor}) \), Pitting formation \( (E_{p.s.}) \), repassivation \( (E_{r.p.}) \). According to which the levels (bases) were calculated: pitting resistance \( (\Delta E_{p.s.} = E_{r.p.} - E_{cor}) \) and repassivation \( (\Delta E_{r.p.} = E_{r.p.} - E_{cor}) \) of samples (see figure 3b). The results evaluated the resistance to local corrosion, taking into account the heat treatment mode.

The results obtained indicate that all the investigated samples of steel A316L have high corrosion resistance in a chloride-containing medium. The basis of pitting resistance varies within \( (400 \div 480) \) mV and can even reach limit values (up to 520 mV).

Heat treatment in the form of short-term (up to 5 minutes) austenization at 1000° C in the straight-seam case practically does not affect the tendency to pitting (local corrosion). However, samples from a longitudinal pipe from the pipe body (without a seam) show pitting resistance at a level 426 and 358 mV, and with a seam of 512 and 420 mV (\( \Delta E_{p.s.} \) and \( \Delta E_{r.p.} \) respectively). This indicates that the metal in the weld zone (metal after laser melting and rapid solidification in the conditions of directional heat removal – quenching from a liquid state) is more corrosion resistant. This is fully consistent with the well-known fact of increasing the corrosion resistance of a material obtained by various methods of quenching from a liquid state. Laser melting is one of the varieties of this method [3].

Annealing a U-shaped pipe reduces pitting resistance. So, without heat treatment, the basis is 521 and 386 mV, and after it – 480 and 305 mV (\( \Delta E_{p.s.} \) and \( \Delta E_{r.p.} \) respectively).

The difference in corrosion resistance of U-shaped pipes before and after heat treatment can be explained by metal softening as a result of austenite recrystallization and phase (\( \alpha - \gamma \)) transformation.

![Figure 2](image_url)

**Figure 2.** Samples of straight and U-shaped laser-welded tubes made of A316L steel (inner and outer surfaces) for pitting tests.
Figure 3. The results of potentiodynamic measurements of the pitting resistance of samples of longitudinal welded and U-shaped laser-welded tubes made of A316L steel: a – an example of polarization curves of potentiodynamic measurement; b – levels (bases) of repassivation and pitting resistance for longitudinal seams; c) for U-shaped samples.

To assess the effect of heat treatment on the stress state of samples (pipes), including those caused by the presence of defects of the crystal lattice of the second type (randomly distributed dislocations) [4], we analyzed changes in the position, width, and profile of X-ray lines in diffractograms. The survey was carried out on a DRON-3M diffractometer in Co-Kα radiation at points with a step of 0.2 degrees and a shutter speed of 10 seconds at a point without rotating the sample in its plane. On the samples with a size of 20 × 20 mm, the (311) line of the γ phase was recorded in the range of angles 2θ from 108.5 ° to 114.5 °. When installing the samples in the prefix GP-13, the weld was positioned vertically (dividing the beam projection in half).

The results of estimating the width of the diffraction maximum (311) of X-ray scattering by the γ-phase (austenite) are presented in Table 2 (last column). The results obtained indicate a significant difference in the shape and width of the diffraction maximum of x-ray scattering by the γ phase in the samples of U-shaped welded pipes before and after heat treatment: more than 3 times. Moreover, the splitting of the Kα1 and Kα2 Co-Kα doublet of X-ray radiation is clearly manifested in all diffractograms of the annealed samples, which indicates a high degree of perfection of the crystal lattice of the γ-phase grain material after annealing.

The obtained graphical and numerical data illustrating the profiles and width of the X-ray lines indicate that as a result of austenization (at 1000 °C) in the samples of welded pipes of the A316L brand, internal stresses are caused by cold deformation of the strip during rolling, plastic deformation during tube forming billet and subsequent bending of welded pipes into a U-shaped product. The
hardening in the metal of a welded pipe made of A316L steel is carried out by primary recrystallization (austenite), the process of which at temperatures of 1000–1050 °C occurs intensively (transiently) and takes no more than 5 minutes in time [5]. In this case, the metal strength (yield strength) is reduced by almost 2 times, the hardness level (HV) decreases from 300-350 MPa to 160-180 MPa, and ductility (relative and uniform elongation) increases by 1.5–2 times [6].

For a comparative analysis of the mechanical properties of laser-welded straight-seam pipes with a size of Ш25х1.5 mm and Ш25х2.0 mm made of a316l steel intended for producing bent products, mechanical tests were performed on a universal breaking machine by static stretching [GOST10006-80, GOST 1497-84, GOST 11701-84]. Experimental samples of pipes were divided into 2 parts: samples in the initial state; samples that have undergone heat treatment. The test results are shown in figure 4.

Figure 4. Influence of the heat treatment mode on the mechanical properties of laser-welded straight pipes Ø25 made of a316l steel: a – strength; b – yield strength; c – ductility.
Table 2. Scheme of scientific and business experience.

| N  | Marking       | The place where the sample is cut in relation to the bend: I-in; N-outside | External (E) and internal (I) pipe surface | The appearance of the sample | H/t, °C | Diffraction maximum shape | Width of the diffraction maximum (doublet), degrees |
|----|---------------|--------------------------------------------------------------------------|---------------------------------------------|-----------------------------------|--------|---------------------------|--------------------------------------------------|
| 1  | 6N0I (seamless) | N                                                                       | E                                           | No                               |        | ![Diagram](image1)       | 1.71±0.9                                          |
| 2  | I             | I                                                                       |                                             |                                   |        | ![Diagram](image2)       | 1.43±0.06                                          |
| 3  | 6nT           | N                                                                       | E                                           | 1000                             |        | ![Diagram](image3)       | 0.44±0.01                                          |
| 4  | I             | I                                                                       |                                             |                                   |        | ![Diagram](image4)       | 0.45±0.01                                          |
| 5  | 6bI           | I                                                                       | E                                           | No                               |        | ![Diagram](image5)       | 1.74±0.08                                          |
| 6  | I             | I                                                                       |                                             |                                   |        | ![Diagram](image6)       | 1.40±0.06                                          |
| 7  | 6bT1          | I                                                                       | E                                           | (T₁) 1000                        |        | ![Diagram](image7)       | 0.42±0.02                                          |
| 8  | I             | I                                                                       |                                             |                                   |        | ![Diagram](image8)       | 0.48±0.01                                          |
| 9  | 6bT2          | I                                                                       | E                                           | (T₂) 1060                        |        | ![Diagram](image9)       | 0.55±0.02                                          |
| 10 | I             | I                                                                       |                                             |                                   |        | ![Diagram](image10)      | 0.51±0.02                                          |
3. Conclusion
The results of mechanical and technological tests of straight-seam laser-welded pipes made of a316l steel for static stretching indicate that even if there is no final heat treatment in the technological cycle of their manufacture, welded pipes have a high margin of plasticity, which allows their applicability for the production of bent grades (U-shaped welded pipes).

Experimental data in the form of changes in the width and profile of the x-ray line of the metal of laser-welded pipes confirm the fact that the final heat treatment under the regime of short-term austenization completely eliminates the metal naklep, providing relaxation of its elastic stresses and the formation of the necessary structural state of a316l steel.

Heat treatment under the regime of short-term austenization at a temperature of 1000–1050 °C for 1–5 minutes can be recommended as a mandatory technological operation that completes the metallurgical conversion of laser-welded stainless pipes of the heat exchange range.

This heat treatment increases the corrosion resistance of the material of U-shaped welded pipes made of a316l steel to the level of their operational requirements when used in products of the heat exchange range for chemical engineering.

Acknowledgments
The work was supported by the Ministry of Education and Science of the Russian Federation, unique project identification number RFMEFI57817X0252.

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