Evaluation of Vibration Treatment Effect on Mechanical Properties of Welded Joints of Steel Pipes 5CrMo16

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Abstract. In modern refining conditions associated with increasing requirements for the quality of products produced and ensuring the safety of processes, the operating conditions of the equipment are becoming more complicated, and the range of materials used is expanding. A significant part of the equipment, especially used to carry out high-temperature processing processes in hydrogen sulfide and oxidative sulfur-containing media, is made of heat-resistant chromomolybdenum steels of the type 5CrMo16, the welding process of which is quite complicated. In this work, studies of the mechanical properties of welded joints made of steel are presented 5CrMo16 under various modes of loading welded joints during welding, and new results on the crack resistance of welded joints during repeated heating are also experimentally obtained. Conclusions on the level of residual stresses in the samples, strength characteristics of the weld, as well as the fracture resistance of the weld metal of the examined samples were made.

1. Introduction

A characteristic object of widespread use of chromomolybdenum steel of the brand 5CrMo16 are coils of tubular furnaces, which are most heat-stressed and belong to responsible structures operating in very harsh conditions [1,2]. They are susceptible to corrosion-erosion wear on both the inner and outer surfaces of the pipes [3]. In industrial practice, there are often cases of deviations from the technological mode of operation of heating tubular furnaces associated with significant overheating of pipes, which inevitably leads to a change in the structural state and, accordingly, mechanical properties of coil metal. This often leads to premature destruction of coils and emergency stops of tubular furnaces [4].

Type 5CrMo16 steels are advantageously distinguished from high alloyed austenitic steels by lower cost, better hot deformability and machinability by cutting, high thermal conductivity and lower temperature coefficient of linear expansion, greater relaxation capacity and possibility of changing mechanical properties within wide limits by thermal treatment [5,6]. However, the increased tendency of martensitic steels to brittle fracture in a quenching state complicates their welding technology. With a carbon content of more than 0.1%, martensitic steels tend to form cold cracks during welding due to the high degree of tetragonality of the martensitic crystal lattice. In welded joints of martensitic steels, cracks can be observed in the process of continuous cooling at temperatures below the temperature of the start of martensitic conversion (for high-chromium steels no more than 360 °C), as well as in the
process of holding at normal temperature (delayed failure). As the carbon content increases, the martensitic conversion start temperature and the martensitic conversion end temperature (typically 240 °C) further decrease, resulting in an increase in martensitic hardness and brittleness. Given this, as well as the need to ensure high ductility and toughness of welded compounds, the carbon content of chromium martensitic steels is limited to 0.2%. To prevent the formation of cold cracks during welding of these steels, preliminary and concomitant heating to 300-350 °C is used [7,8].

At the same time, the preheating temperature should not be excessively high, as this can lead to release brittleness due to a decrease in the cooling rate of the metal in the near-seam zone in the carbide formation temperature range. In addition, high temperature heating, as well as welding with high linear energy, provides a long-term overheating of the near-seam metal, which causes grain growth, accumulation of impurities at the grain boundaries and, as a result, a decrease in the ductility and toughness of the welded joints [9,10].

2. Revalence
From the position of technological and operational strength, the weakest link of welded structures from martensitic steels is the formation of zones of increased hardness of various origins [11].

A feature of repair and welding works performed on equipment made of steel 5CrMo6 is the need for preliminary and concomitant heating of welded joints in order to reduce the likelihood of cold cracks and increase the technological strength of the welded joint. However, this operation significantly reduces the productivity of work, increases energy and labor costs and is not always possible in installation conditions.

In production conditions, it is very important to quickly and qualitatively carry out repair and restoration work in compliance with all existing standards, which often involve the replacement of coil sections, and this results in high material costs.

Thus, it is necessary to develop scientifically sound resource-saving technologies for repairing equipment from steel 5CrMo16, aimed at increasing the technological strength of welded joints, eliminating the labor-intensive heating operation, and increasing the productivity of work. In recent years, a fairly large number of works have appeared aimed at solving problems of this type. To reduce the tendency to form cold cracks, it is proposed to use ultrasonic and vibration energy, concomitant cooling, explosion and friction energy, laser irradiation and other methods [12–18].

Taking into account the specifics of the industry, in our opinion, the most applicable method of vibration treatment of welded joints in the process of welding, which will reduce the level of residual stresses, increase the mechanical properties of the weld and the productivity of work due to the elimination of the heating operation.

3. Task setting and applied methods of solution
The aim of this study was to assess the effect of vibration treatment on the metal properties of welded joints, which will further allow the development of repair technology using the accompanying vibration treatment of parts during welding.

3.1. Samples for studies
Studies were carried out on full-scale samples (tube coils) of 5CrMo16 grade heat-resistant martensitic steel using the various treatments shown in table 1.

Electric arc welding was carried out in the following modes: DC current of reverse polarity, welding current strength from 95 to 115 A, voltage 22 V. Power source - rectifier VDU-506. The electrodes used were OK 75.75 with a diameter of 3.2 and 4 mm. Vibration treatment with a frequency of 100 Hz was carried out using a pneumatic vibration device VSh10. Vibration processing with a frequency of 50 Hz was carried out by an electromechanical eccentric vibrator.

Tests were carried out on pipe coils with a diameter of 219 mm, a thickness of 10 mm, cut from a coil of a pipe furnace in service for more than 10 years, and coils obtained from a new pipe. Edges of
welded coils were made in accordance with GOST 16037-80 by type C17, in accordance with repair technology used in production conditions.

### Table 1. Types and modes of sample processing.

| Type | Sample type of accompanying sample welding | Post-welding heat treatment (high tempering) |
|------|--------------------------------------------|---------------------------------------------|
| 1    | Vibration treatment at frequency 100 Hz and amplitude 0.1... 0.2 mm | no                                          |
| 2    | Vibration treatment at frequency 50 Hz and amplitude 0.4... 0.6 mm | no                                          |
| 3    | Preheated welding at 300-350 °C.           | no                                          |
| 4    | Welding without preheating                | no                                          |
| 5    | Vibration treatment at frequency 100 Hz and amplitude 0.1... 0.2 mm | yes                                         |
| 6    | Vibration treatment at frequency 50 Hz and amplitude 0.4... 0.6 mm | yes                                         |
| 7    | Preheated welding at 300-350 °C            | yes                                         |
| 8    | Welding without preheating                | yes                                         |

Since when welding these steels there is a high probability of cold cracks, the regulatory documentation indicates the need for preliminary heat treatment and immediate after welding subsequent heat treatment [19].

After welding, visual inspection, color flaw detection and radiographic inspection of welds were carried out, the results of which showed the absence of cracks in the welds.

### 3.2. Investigation of residual micro-stresses

Samples of welded blanks were made for the study to determine the level of micro-stresses in the weld.

X-ray diffraction analysis of the samples was performed on an X-ray diffractometer "DRON-3M" in CoKα radiation with a graphite monochromator on a diffracted beam. The experimental data were processed using the Maud software package. The program algorithm uses the Ritveld method. The advantage of this method is that imperfections of crystals such as defects, doubling do not create measurement errors.

### 3.3. Static tensile test at high temperature

Since the operating condition of this steel provides for operation at high temperatures, tests of weld metal for static tension at high temperatures were carried out in the operation. For further studies, the most optimal processing in terms of frequency and amplitude of vibration was chosen - frequency 50Hz, amplitude - 0.4... 0.6 mm.

The study was conducted to determine the effect of the treatment mode during welding on the strength of the weld metal at high temperature. The test temperature was determined from the possible operating conditions of this steel - 500 °C, loading speed 2 mm/min. The tensile test was carried out on the Instron 5982 test machine. Samples were manufactured in accordance with GOST 6996 (type XXV).

### 3.4. Crack Resistance Studies

Tests of welded joints at high temperatures with constant loads or deformation rates are designed, first of all, to determine their heat-resistant properties during high-temperature operation. However, they can also be used to assess the tendency to crack during thermal treatment, since the behavior of welded joints in thermal treatment is subject to general patterns of creep deformation [20].

For the study, heterogeneous samples of steel 5CrMo16 with a diameter of 159 mm, a thickness of 10 mm and a length of 250 mm, welded in two modes, were made, in which additional loading during
heating was carried out due to a rigid base of austenitic steel AISI 321, plates with a size of 100 × 10 × 285 mm. The samples were then heated in an oven, changing the temperature from 200 to 600°C with exposure at each interval for 1 hour. If the sample did not break down during the first heating to 600°C, then after 30 minutes of cooling under indoor conditions, additional heating was carried out at temperature 600°C. Thus, the samples were loaded in several cycles until a crack appeared.

4. Results of experimental studies

4.1. Investigation of residual micro-stresses

The results of the X-ray diffraction analysis of residual micro-stresses in the test samples are summarized in table 2.

| Sample type | Base metal | Weld 1 | Weld 2 | Weld 3 | Weld 4 | Weld 5 | Weld 6 | Weld 7 | Weld 8 |
|-------------|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Size of microtension (MPa) | 101.0 | 569.7 | 499.5 | 495.9 | 540.0 | 151.9 | 146.9 | 135.0 | 179.6 |

From the obtained results, it can be seen that at the interoperative cycle before the post-welding heat treatment, the minimum level of residual stresses is observed in samples made with vibration treatment at a frequency of 50 Hz and an amplitude of 0.4... 0.6 mm and using pre-heating. After the post-welding heat treatment, the stress level in the samples becomes significantly lower and approaches the level of residual stress in the base metal in terms of values.

4.2. Static tensile test at high temperature

Based on the results of tests, a diagram of the dependence of the strength of the weld metal on the type of processing during welding operations was built (table 3).

| Sample type | Weld 2 | Weld 3 | Weld 4 | Weld 6 | Weld 7 | Weld 8 |
|-------------|--------|--------|--------|--------|--------|--------|
| Metal strength (MPa) | 766.6 | 643.7 | 599.0 | 447.1 | 417.5 | 373.2 |

The results of the weld and weld static tensile tests show that the tensile strength at a temperature of 500 °C when using vibration treatment in the process of welding before heat treatment is on average 13% higher than according to the existing technology with accompanying heating, and after heat treatment by 11%. Compared to heat-free welding, the tensile strength is increased by 18% and 15%, respectively.

4.3. Crack Resistance Studies

The results of the tests (table 4) show that the metal fracture resistance of the seam of samples obtained with vibration treatment is significantly increased compared to the existing manufacturing technology.

| Welding side treatment type | Number of cycles before crack occurs |
|----------------------------|--------------------------------------|
| Preheated welding at 300-350 °C | 2                                    |
| Welding with vibration treatment at frequency 50 Hz, vibration amplitude 0.4 - 0.6 mm | 5                                    |
5. Conclusions
1. The results of the determination of residual stresses in the weld weld show that at the interoperative cycle before the post-welding heat treatment, the minimum level of residual stresses is observed in samples made with vibration treatment at a frequency of 50 Hz and an amplitude of 0.4-0.6 mm, as well as when using preheating.

2. The results of the tests of the weld and the weld joint for static tension at high temperatures (500 °C) show that the strength characteristics of the weld when using vibration treatment in the process of welding before heat treatment are on average 16% higher than according to the existing technology, and after heat treatment - 11%. Compared to heat-free welding, the tensile strength is increased by 21% and 15%, respectively.

3. The results of the fracture resistance tests during reheating show that the fracture resistance of the weld metal of samples obtained with vibration treatment instead of the existing heating technology is significantly increased.

6. References
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