Technology and equipment for laser welding of annular pipes junction in fixed position of gas-main pipelines

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Abstract. A new multi-run technology of laser welding of butt joints of pipes is an alternative to arc welding used in the construction of gas-main pipelines. Conceptually new schemes for performing a root, filling and facing passes into a special narrowed cutting are presented. The analysis of thermal cycles of heating and cooling of metal, characteristics of hardness, strength and viscosity of welded joints obtained by a specially designed laser welding machine for annular pipes junction in fixed position.

1.Introduction
New projects for pipelines for land and sea transportation of gas are characterized by higher technical requirements, in particular ultra-high operating pressures, using large diameter pipes of strength categories K60 [1].

At present, there are sufficiently reliable and proven technologies for connecting such annular pipes junction in fixed position by arc welding methods. However, these technologies are associated with the introduction of a large amount of heat and high running energy, which leads to overheating of the metal in the heat affected zone (HAZ). Welds have a large volume of welded metal, which in composition can differ from the main one. It requires a sufficiently large size of the edge preparation and a significant amount of wire to fill it.

These difficulties can be overcome by using laser energy sources for welding [2-4]. The use of laser radiation for welding pipe’s materials allows to increase productivity, to obtain more favorable structures, both in the weld and in the transition zone, to provide a high level of mechanical properties and tightness of the welds. Temperature-deformation conditions in the welded joint zone contribute to reducing the probability of hot and cold cracks formation. At present, there is a certain experience in the use of laser welding for pipe joining. However, all these methods of laser welding have a number of shortcomings related to the complexity of the equipment, the need to use high power laser radiation or additional sources.

In this regard, this paper presents a new laser technology for welding of main pipelines, the use of which will enable us to solve the important task of creating unique gas transmission systems.
2. Results and discussion

Given the shortcomings inherent in existing methods, it was suggested to use the combined multi-run laser welding method. The scheme of the combined multi-run weld, consisting of the root, fill and lining passes, is shown in figure 1.

![Figure 1. The scheme of the combined multi-pass weld obtained by laser welding with a filler wire: 1- root pass; 2- filling passes; 3-facing pass.](image)

To create a similar weld, as well as for arc welding, it is necessary to make the edge preparation, which is filled with a filler wire. However, according to the proposed laser technology, it is possible to obtain much narrower joints, 6 times less than with manual arc and 3 times less than with the most progressive automatic arc technology.

The most crucial, technologically speaking, is the root pass. It has special requirements for exceeding the melting above the surface and eliminating the lack of fusion. Of particular complexity is the need for welding in the ceiling position.

Based on the existing physical concepts of the formation of a welded joint during laser welding (Figure 2), gravity (F2) and surface tension forces (F4) play a key role in the welding of the root part.

![Figure 2. Scheme of forces acting on the welding bath in the ceiling position: F1 - gravity; F2 is the static vapor pressure; F3 is the reaction force of the vapors; F4 is the surface tension force.](image)

Entering of additional material in the form of a filler increases the volume of molten material in the weld pool, which should lead to the filling of possible gaps and the formation of a reverse weld. However, when welding in a ceiling position, it is increases the force of gravity. To balance this force, it is necessary to increase the surface tension force. This was achieved by introducing filler material into the tail part of the bath, which contributed to a decrease in the melt temperature (Figure 3).
Figure 3. Melt thermograms when inserting a filler wire into the front and tail sections of the bath.

It can be seen from equation (1) that the coefficient of surface tension increases with decreasing temperature:

\[ \sigma = \sigma_0 - \alpha(T - T_0), \]  

where \( \sigma \) and \( \sigma_0 \) are the surface tension at temperatures \( T \) and \( T_0 \) respectively, \( \alpha \approx 0.1 \) is the temperature coefficient of surface tension.

In accordance with it, the surface tension force, determined by the equation (2):

\[ F_4 = \pi d \sigma \]  

Thus, a decrease in temperature in the tail part of the bath increases the surface tension in the root of weld and does not allow gravity forces to lower the liquid material below the penetration surface (figure 4).

Figure 4. Appearance and macrosection of the root weld obtained in the ceiling position.

It has been experimentally proven that the wire feed angle should be from 30° to 45° relative to the beam, an additional positive effect is achieved with the use of uphill welding.

Optimization of the welding mode of root weld in different attitude was carried out using an analysis of the statistical model developed based on the results of a full-factor experiment on the dependence of the formation of the excess of the melting and the width of the melting on the welding parameters. The resulting regression models of the relationship between the height of the bead at the root of the weld (H) and the width (L), laser radiation power (P), the wire feed speed (\( V_{\text{wp}} \)), the welding speed (V) and the beam focusing position (F) are as follows:
\[
H = -5.666 + 0.388 \cdot P + 4.800 \cdot V_{\text{пр}} + 0.193 \cdot F + 0.085 \cdot V \cdot V_{\text{пр}} - 0.043 \cdot P^2 - 4.285 \cdot V^2 - 0.327 \cdot V_{\text{пр}}^2 - 0.011 \cdot F^2 \tag{3}
\]

\[
L = 1.519 + 0.215 \cdot P - 3.333 \cdot V + 0.075 \cdot V_{\text{пр}} + 0.222 \cdot F \tag{4}
\]

The analysis obtained from equations (3), (4) made it possible to determine the following welding parameters: \(P = 4.5\) kW, \(V = 0.6\) m / min; \(F = 9\) mm, \(V_{\text{пр}} = 3.5\) m / min. These parameters ensure that excessive penetration the surface in the range from 1.4 to 1.5 mm with a melt width of 2.6 to 2.75 mm.

The conducted welding experiments on the selected modes confirmed the calculated values.

For the welding of the filling passes, a wire end arrangement was applied at a distance of 1 to 2 mm ahead of the point of the focused beam at an angle from 30° to 45°. In this case, the wire with the jet transfer of metal is melted and the largest melt bath is formed, which facilitates rapid filling of the edge preparation. To ensure a more even filling of the edge preparation, it was suggested to use oscillations of a laser beam with a cross-shaped form with a frequency of 200 Hz and an amplitude of 2.5 mm across the weld.

The main purpose, when optimizing the welding modes for filling passes, is to create the largest possible volume of the weld pool in order to ensure the minimum number of passes. One of the parameters determining the geometry of penetration is the position of the beam focusing. Experimentally determined parameters of the location of the beam focusing above the surface from +15 to +17 allow to obtain the required width of the weld 4.5 mm, its sufficient area and the smallest penetration.

Optimization of the filling pass welding mode in different attitude was also carried out using the analysis of the statistical model based on the results of a full-factor experiment of the dependence of the depth of penetration \((G_{\text{зп}})\) and the height \((H_{\text{зп}})\) of the bead on the power of the laser radiation \((P)\), the wire feed speed \((V_{\text{пр}})\) and welding speed \((V)\). The position of focusing the beam into the model was not introduced, since it was chosen in advance. The calculated design regression models have the following form:

\[
G_{\text{зп}} = -7.282 + 1.878 \cdot P - 0.200 \cdot V_{\text{пр}} \tag{5}
\]

\[
H_{\text{зп}} = -0.718 - 0.172 \cdot P + 0.975 \cdot V_{\text{пр}} - 1.244 \cdot V \tag{6}
\]

Analysis of the dependencies obtained by equations (5), (6) allowed to determine the following welding parameters: \(P = 5.5\) kW, \(V = 0.6\) m / min and \(V_{\text{пр}} = 5.0\) m / min. To increase the volume of the melt, downhill welding must be carried out. When changing the parameters of modes in a given range, a compromise is reached between the desire to maximize the value of the height of the formed bead and the decrease in the depth of penetration. Welding experiments on the selected modes allowed to ensure the filling of the cutting with the minimum quantity of passes. The macrostructure of the resulting welded joint with a thickness of 25.8 mm is shown in figure 5.
To create a surface bead with a smooth transition to the base metal, guaranteed fusing of the edge preparation and some overstating of the bead, it was suggested to perform the facing pass. The modes of this pass are: $P = 8.0$ kW; $V = 0.6$ m / min, $V_{\text{opr}} = 5.0$ m / min. Welding is performed with beam oscillations with a frequency of 200 Hz, amplitude of 2.5 mm. There is downhill welding.

The obtained welding regimes create rigid thermal cycles in the weld and HAZ with cooling rates from 95 to 120 °C / s, which can lead, according to the austenite decomposition diagrams for tube steels, to the formation of hardening structures, including the martensitic phase with increased hardness. As a method that reduces the rigidity of thermal cycles, it is suggested to apply preheating to a temperature of 170-180 °C, which reduces the cooling rate to 40-60 °C / s. Microstructural studies showed that under these conditions, bainitic structures with a packet size of about 43.2 μm and an insignificant amount of ferrite were obtained in the weld and the weld zone, in contrast to the arc technology that forms ferrite and ferritic-carbide mixture in the structure [5].

It is established that when layers are applied in the process of laser welding in all attitudes, each subsequent layer does not lead to overheating of the weld metal and HAZ of the previous one (figure 6). As a result, in contrast to arc technology, the multilayered laser welding does not significantly affect the structural changes in the weld and HAZ of the previous layers.

Figure 5. Macrostructure of a welded joint with thickness of 25.8 mm.

Figure 6. Thermal cycle of multiple heating and cooling of the HAZ metal when welding in the ceiling position, obtained when: 1-root weld; 2-the first filling pass; 3-the second filling pass; 4-the third filling pass.

The sizes of the sections of overheating, complete recrystallization (normalization) and incomplete recrystallization were determined by theoretical calculation of critical temperatures and by experimental
measurement of the maximum temperatures in the HAZ of root and filling welds in various parts of the HAZ. The dimensions of these zones during laser welding were 2-2.5 times smaller than in arc welding.

Measurements of the hardness of the weld metal and the HAZ of the filling and root passes showed that when welding with preheating in the upper part of the facing weld, it is 320-340 HV10, and as the distance from the center of the weld in the HAZ is reduced to 260-250 HV10 (figure 7).

![Figure 7. Hardness distribution in the weld metal welded joints, obtained during welding with preheating](image)

Analysis of the distribution of hardnesses along the HAZ has shown that as the distance from the fusion line decreases, the hardness of the metal decreases to values characteristic of the main metal, which vary within 200-230 HV10, in contrast to arc technology, where the average hardness of the weld does not exceed 220-240 HV, and the weld zone 210-230 HV. Thus, hardness of welds are at the level of the requirements imposed on the welded joints of the pipelines.

The investigations gave grounds for recommending this technology as an experimental for welding of main pipelines.

To implement the new technology in industrial conditions, welding system prototype for annular pipes junction in fixed position was developed, consisting of a guide belt through which two carriages move with a welding head fixed to it in the form of a focusing system and a wire feeder (figure 8). The system allows multi-run welding of pipes from 720 to 1420 mm in diameter with a wall thickness of 12 mm to 38 mm. As a laser source of radiation, an Ytterbium fiber laser of the LS series is produced by IPG "IRE-Polyus". The control unit of the system is built on a modern element base of microprocessor technology and provides a single interface for setting welding parameters, calibration, diagnostics and troubleshooting.
Figure 8. Welding system prototype for annular pipes junction in fixed position.

The system passed the certification tests and was recommended for operation in the welding of pipelines in the field. During these tests, the estimated fracture toughness test showed that the chemical composition of the weld metal does not adversely affect the tendency to form both hot and cold cracks. The fracture toughness tests carried out using the DNV-OS-F101 methodology made it possible to establish that the CTOD criterion is in all cases significantly higher than the normative value. Analysis of the macro and microstructure of the investigated welded joints obtained at optimal regimes showed the absence of crack-like defects in them.

Ultrasound and X-ray inspection methods, as well as 3D tomography, inadmissible internal defects in the form of cracks, gas pores and incomplete penetration did not reveal.

In accordance with the regulatory documents, mechanical tests for the static extension of welded joint and weld metal, static bending and impact strength were performed. Static tensile tests carried out on full thickness samples showed an equal strength of the welded joint with the main metal of the pipe. Impact bending tests were carried out at a temperature of -40 °C for the weld metal and the weld zone. According to regulatory requirements, the toughness of the weld metal and the HAZ in impact tests at -40 °C must be at least 50 J/cm² (according to Charpy), and the minimum impact strength for one sample must be at least 37.0 J/cm². The test results showed that the impact strength of the weld metal and the fusion line is 2.5-3 times higher than the required values. When testing for static bending, all samples with a bending angle up to 120° did not collapse, cracks and delaminations did not appear.

Certification tests were carried out for compounds welded using ESAB Pipeweld SGC-ST 70S-6 filler wire. To evaluate the possibility of using other grades, welded joints obtained with three types of wires were additionally tested for tensile and impact strength. As the tests have shown, the use of other brands of filler wires does not significantly affect the properties of welded joints.

3. Conclusion

Based on the results of certification for construction organizations, a technological instruction was developed to regulate the requirements for the use of welding materials, laser equipment, geometric parameters of edges preparation, parameters of orbital welding of large diameter pipes in fixed position.

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