Ensuring industrial safety of pipelines with developed hard sections

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Abstract. Oil refining and petrochemicals have a wide demand for pipelines from heat resistant chromium steels. One of the main reasons for frequent failures of more stressed joints may be the presence of wide solid and brittle layers having significant areas in metal volume with maximum clusters of imperfections of metal structure and creating excessive concentration of additional residual deformations and stresses in welded joints, which are most saturated with defects inherent in welded joints. Presence of such extended sections leads to reduction of process strength of welded joints, increases tendency to formation of cold cracks and sharply limits time of laying of thick-walled welded joints of pipelines before subsequent high-temperature thermal treatment. The work carried out studies on welding pipe blanks in order to compare different methods of 5CroMo16 steel treatment during welding and determine the most efficient mode. Regularities of stressed state of different-module structural elements with wide solid layers are established.

1. Introduction
Negative reaction to thermal deformation cycle of welding, manifested in formation of quenching nonequilibrium structures in hard brittle interlayers, affects industrial safety of welded pipelines, reducing crack resistance, reducing deformation capacity and increasing predisposition to brittle breakage [1-4]. Mechanical inhomogeneity, consisting in the difference of properties of characteristic zones of welded joint, serves as a source of complex stressed state in structural elements of pipelines operating under internal pressure [5-7].

During semi-automatic welding in the protective gas medium, the use of pearlite welding materials is regulated, which do not exclude subsequent high-temperature thermal treatment of welded joints [8-11]. At the same time metal of seam and near-bone zone has significantly higher hardness than base metal. The highest hardness up to 380-409 HVs have near-bone zones along the fusion line, and the structure of these sections is the largest needle drasticamente. Presence of wide areas with high hardness and arising residual welding stresses in local micro-loads of freshly packed structure require immediate heat treatment. When welding thick-walled pipelines, heat treatment shall be carried out immediately after welding is completed.

2. Experimental procedures
In order to localize the dimensions of the solid layers in the near-bone zones, it is necessary to use a welding technique that allows to adjust the parameters of thermal cycles directly during welding and
contributes to obtaining a "compressed" thermal cycle of welding with a short length of their propagation area over the zone of thermal influence [12-14]. For this purpose, methods of semi-automatic welding in a protective gas medium and automatic flux welding are satisfied when manufacturing pipelines from heat-resistant steels of type 5CrMo16. In these welding processes, concomitant forced cooling can be used most technologically. At the same time metal volume in the zone of thermal influence undergoes reduction, which undergoes shear martensitic transformations and formation of structure with minimum sensitivity to crack formation. Vibration action on welded joints during welding of 5CrMo16 steel makes it possible to increase technological strength and crack resistance of welded joints before high tempering due to reduction of level of residual stresses and microstructure in welded joint.

In order to compare different methods of steel treatment 5CrMo16 during welding and to determine the most efficient mode, studies were carried out on welding pipe blanks in the modes indicated in table 1.

**Table 1.** Versions and modes of semi-automatic welding in the protective gas environment.

| Edge preparation and stacking sequence | D×S coil layers, mm (Sample Number) | Sample number | Imposed layer | Diameter of a wire, mm |
|---------------------------------------|-------------------------------------|---------------|---------------|-----------------------|
|                                       | pre-heated 300-350 °C | 101 | 1,2 | 1,2 |
|                                       | without heating with vibration treatment with the accompanying cooling | 201 | 2-3 | 1,2 |
|                                       | with vibration processing | 301 | 2-3 | 1,2 |

The used materials: the mm $\varnothing$ 159×8 coil from steel 5CrMo16; welding wire of DT-SG CrMo5 $\varnothing$1.2 of mm of AWS 5/ER 502 (production Germany); Mixture of gases Ar-80% CO2-20%.

Vibration processing parameters: frequency 50Hz, amplitude up to 1 mm. Vibration was performed using a pneumatic vibration device, and vibration parameters were captured by the Emerson CSI 1900 vibration analyzer.

Welding parameters with associated cooling: length of nozzle slot - 8-10 mm, air pressure - 0.25-0.30 MPa, water flow rate - 6-10 l/min, width of cooling zone b - 10-12 mm. Forced cooling was carried out using a specially designed device allowing water-air mixture to be fed into the welding zone.

Welding modes were assumed to be similar for different methods and were: current - 160.. 180 A, voltage - 23.. 25 V.

Samples were cut from the coils for metallographic analysis.

Detection of the microstructure of the weld metal, base metal, and HAZ was carried out by chemical etching in a 3% nitric acid solution. It has been found that the application of forced cooling significantly reduces the zone of thermal influence, which accordingly leads to a decrease in the volume of stressed metal in the welded joint. Microstructural analysis showed that the weld metal of sample No. 101 had a martensitic structure with large needles, and the structure of the thermal influence zones of the same sample consisted of ferrite and recrystallized pearlite. The width of the zone of thermal influence is 7 mm. The metal of the seam of sample No. 201 has a martensite structure on the background of a coarse
austenitic grain, and a recrystallized structure with different degree of dispersion is observed in the thermovoltaic zone. The width of the zone of thermal influence is 6 mm. Sample No. 301 is characterized by a large needle martensitic structure of the weld metal and a recrystallized structure for the zone of thermal influence. The width of the zone of thermal influence decreased to 3 mm.

Measurement of the microhardness of the characteristic regions of the welded joint of the test samples was performed on the midline of the sample over all regions of the welded joint at a load of 100 g on the microhardness PMT-3. The welding option - with preliminary heating to 300...350 °C serves as a source for the formation of a relatively wide zone of lining with the structure of large-needle martensite with microhardness up to 380-440 Hμ. At the same time width of peritoneal zones of strut, having structurally non-equilibrium structure, reaches 7 mm. In welding with vibration treatment - the structure of the near-bone zone is improved, it turns out to be finer and has a width of about 6 mm with microhardness Hμ380-430. Weld metal is characterised by microhardness Hμ 340 - 370. During welding without heating with vibration treatment of the seam root and with forced cooling there is achieved reduction of metal volume in the near-bone zone, which undergoes shear transformations, and formation of a specific structure with minimum sensitivity to formation of cold cracks. Positive effect on process and operational strength of welded joints of steel 5CroMo16 for this welding method is in reduction of intensity of diffusion processes during welding (due to reduction of width of non-equilibrium zone in zone of lining) and provision of obtaining of fine-grained more equilibrium bainitic structure of hardening in near-bone zone with microhardness of metal 330-370 Nμm.

3. The results of studies and their discussion

Using shell theory, consider the case where the base elements of welded pipelines have sections with different values of modulus of elasticity E. Let us denote modulus of elasticity of section T through $E^T$, and section M - $E^M$. At the same time $E^M < E^T$. For the case of uniform electrode welding, we have a solid layer.

Nominal circumferential $\sigma_0$ and longitudinal stresses $\sigma_z$ for pipelines operating under pressure within the limits of elastic deformation are determined by formulas:

$$\sigma_0 = \frac{PR}{S}; \quad \sigma_z = \mu \frac{PR}{S},$$

where $\mu = 0.3$ is Poisson's coefficient at elastic deformations; S and R -is the wall thickness and radius of the vessel (tube).

Beyond elasticity $\mu = 0.5$, if the cylinder is closed with bottoms, elastic and plastic deformation retain the condition

$$\sigma_z = 0.5\sigma_0 = 0.5 \frac{PR}{S}.$$

The marked uniform flat stress state in the pipe walls is created away from the joint of different module sections. Due to difference of deformation capacity of different module sections of cylinder, edge forces $Q_{wp}$ and moments appear in vicinity of their joints $M_{wp}$.

At the same time radial movements and rotation angles of mating sections of different-module elements, under the action of external loads, spacer forces, torques and internal edge forces and bending moments are equal to each other. Equations of regional forces:

$$\Delta_{wh} + \Delta_{Q_{wp}-Q_1} + \Delta_{M_{wp}-M_1} = \Delta_{wh} + \Delta_{Q_{wp}-Q_2} + \Delta_{M_{wp}-M_2}$$

(2)
\[
V_{\text{in}} + V_{Q_{\text{sp}} - Q_{1}} + V_{M_{\text{sp}} - M_{1}} = V_{\text{in}} + V_{Q_{\text{sp}} - Q_{2}} + V_{M_{\text{sp}} - M_{2}}
\]  
(3)

where \(\Delta, \nu\) - are radial movements and rotation angles of edges of element M and T, respectively, under action of external loads, forces \(Q_{\text{sp}} - Q\) and moments \(M_{\text{sp}} - M\).

Algorithm of edge problem solution:

a) meridional forces \(S\) and moments \(M\) are determined;
b) spacer forces \(P\) are installed in the same sections;
c) deformations of element edges \(\Delta\) and \(\nu\) due to action of specified forces, edge forces \((Q_{\text{sp}} - Q)\) and edge moments \((M_{\text{sp}} - M)\);
d) defined \(Q_{\text{sp}}\) and \(M_{\text{sp}}\);
e) each element loaded with corresponding external loads, edge forces \((Q_{\text{sp}} - Q)\) and moments \((M_{\text{sp}} - M)\);
f) forces and moments from each system of forces and acting stresses are determined:

\[
S = S_{\text{in}} + S_{Q_{\text{sp}} - Q} + S_{M_{\text{sp}} - M};
\]
\[
T = T_{\text{in}} + T_{Q_{\text{sp}} - Q} + T_{M_{\text{sp}} - M};
\]
\[
M = M_{\text{in}} + M_{Q_{\text{sp}} - Q} + M_{M_{\text{sp}} - M}.
\]

We will analyze loading of cylinder consisting of two elements with different modules of elasticity.

For this case, the use of the algorithm results in the following formulas for determining the basic components of the equation of edge forces (2) and (3):

for the M cylinder:

\[
\Delta_{\text{in}} = -\frac{2 - \mu}{2 \cdot S \cdot E_{\text{m}}} \cdot P \cdot r^2; \quad \Delta_{Q_{\text{sp}} - P_{1}} = -\frac{2k \cdot r^2}{S \cdot E_{\text{m}}}; \quad \Delta_{M_{\text{sp}} - M_{1}} = \frac{2k \cdot r^2}{S \cdot E_{\text{m}}} \cdot M_{\text{sp}}
\]  
(4)

\[
\nu_{\text{in}} = 0; \quad \nu_{Q_{\text{sp}} - P_{1}} = -\frac{2k^2 \cdot r^2}{S \cdot E_{\text{m}}}; \quad \nu_{M_{\text{sp}} - M_{1}} = -\frac{4k^3 \cdot r^2}{S \cdot E_{\text{m}}} \cdot Q_{\text{sp}}
\],

(5)

for the T cylinder:

\[
\Delta_{\text{in}} = -\frac{2 - \mu}{2 \cdot S \cdot E_{\text{T}}} \cdot P \cdot r^2; \quad \Delta_{Q_{\text{sp}} - Q_{2}} = -\frac{2k \cdot r^2}{S \cdot E_{\text{T}}} \cdot P_{0}; \quad \Delta_{M_{\text{sp}} - M_{2}} = -\frac{2k^2 \cdot r^2}{S \cdot E_{\text{T}}} \cdot M_{0}
\]  
(6)

\[
\nu_{\text{in}} = 0; \quad \nu_{Q_{\text{sp}} - Q_{2}} = -\frac{2k^2 \cdot r^2}{S \cdot E_{\text{T}}} \cdot Q_{\text{sp}}; \quad \nu_{M_{\text{sp}} - M_{2}} = \frac{4k^3 \cdot r^2}{S \cdot E_{\text{T}}} \cdot M_{0}
\],

(7)

where \(k = 1,285/(S \cdot r)^{1/2}\);

\(S\) and \(r\) - thickness and radius of the cylinder;
P - internal pressure;
\( \mu = 0.3 \) - Poisson's coefficient;
\( E_m \) and \( E_T \) - elastic modules of cylinder M and T;
\( Q_{sp} \) and \( M_{sp} \) - curves force and moment.

Counting together the expressions (4) - (7) with the equation of the edge forces (2) and (3), it is possible to obtain the following dependencies for calculations of the edge moments and forces:

\[
Q_{sp} = -2k \cdot \mu_k \frac{1 + K_E}{1 - K_E};
\]

\[
M_{sp} = \frac{2(2 - \mu) \cdot P \cdot r^2 \cdot (1 - K_E)}{2\delta \cdot E_m \left[ 4k^2 \cdot r^2 (1 + K_E)^2 - 2k^2 \cdot r^2 \delta \cdot E_m (1 - K_E) \right]};
\]

(8)

where \( K_E = E_m/E_T \) - coefficient of elastic non-uniformity.

The formula (8) can be represented as follows:

\[
\frac{M_{sp}}{Q_{sp}} = -\frac{1}{2k} \varphi(K_E);
\]

(9)

where \( \varphi(K_E) = (1 - K_E)/(1 + K_E) \).

From formula (10) follows a quotient solution, for the case where \( (K_E) \to 0 \)

\[
\frac{\mu_{sp}}{Q_{sp}} = -\frac{1}{2k}.
\]

(11)

This case \( (K_E = 0) \) equivalent to the operation of a cylinder with a rigid closure of one edge.

Thus, a known solution follows from the obtained formula (10), which confirms the validity of the above analysis.

Further, the deformation of the cylinder in which the solid portion at both ends is integrally connected by the soft portions of the base metal is broken down.

For relatively developed hard areas \( (h > E) \), edge effects are found for both ends to the same extent according to formulae (8) and (9). In the case where the length of the hard portions is relatively small, a mutual effect of the edge effects on the deformation of the hard cylinder is detected. To evaluate this phenomenon, we will use the solution of the task of deformation of short cylinders with pinched ends.

\[
\frac{M_{sp}}{Q_{sp}} = -\frac{1}{2k} \cdot \frac{\sinh(ke) - \sin(ke)}{\cosh(ke) - \cos(ke)}.
\]

(12)

A multiplier with hyperbolic sinus and cosine in formula (12) takes into account the length of cylinder \( h \). Thus:

\[
\frac{M_{sp}}{Q_{sp}} = -\frac{1}{2k} \cdot \varphi(kh).
\]

(13)
The function $\varphi(kh)$ changes along a complex curve with a maximum of at $kh \approx 3$. The value of the function $\varphi(kh)$ is about one ($\varphi(kh) \approx 1$). You can split this constraint into three feature areas. The value of the function $\varphi(kh)$ linear functions can be approximated on each section:

at $kh \leq 1,0$

$$\varphi(kh) = 0.2 \cdot kh;$$  \hfill (14)

in an interval $1,0 < kh < 3,0$

$$\varphi(kh) = 0.4 \cdot kh - 0.2;$$  \hfill (15)

at great values $kh \geq 3$

$$\varphi(kh) = 1.$$  \hfill (16)

Next, express the meaning $\varphi(kh)$ through the relative extent of the solid layer $\chi_T (\chi_T = h/S = h_{t}/S)$:

at $0 \leq kh < 1,0$

$$\varphi(kh) = 0.257 \chi_T \sqrt{\eta};$$  \hfill (17)

at $1,0 \leq kh \leq 3,0$

$$\varphi(kh) = 0.2 (0.257 \chi_T \sqrt{\eta} - 1).$$  \hfill (18)

Regardless of the parameter $kh$ the function $\varphi(kh)$ decreases when reduced $\chi_T$. This means that a reduction in the critical extent of the hard brittle interlayers of the welded joint sections of the pipelines results in $\chi_T$ decrease in the edge forces and moments.

4. Conclusions

As a result of the work done, it is shown that as the relative length of the interlayers decreases, the edge forces and moments, and therefore the performance characteristics of the equipment, decrease. At the same time accompanying forced cooling in the area of high temperature of welding heating helps to reduce difference of concentration of diffusion-active carbon in solid solution of weld metal and base metal. This is due to quenching of the performed weld for austenite and incomplete dissolution of initial carbides in the near-bone zones of the main welded metal at compressed thermal cycle of welding.

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