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Influence of boss-backing welding to ERW pipe

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\textbf{Abstract}

Station and valve chamber design often encounter the situation of drilling hole at the main pipeline and welding boss-backing to connect the branch pipe. Boss hole location should generally be at least 100 mm away from the longitudinal weld or spiral weld. However, because the electric resistance weld (ERW) is difficult to distinguish in practice, some bosses mounting position coincide with ERW or close to. In this paper, the influence of boss-backing welding directly on the longitudinal weld to the original residual stresses of ERW pipe was studied. The microstructure of pipe body and longitudinal weld after welding was also analysis. The testing results showed that the overall residual stresses of ERW pipe were relatively small. Residual stress at the longitudinal weld region were smaller than those at the pipe body region. After the boss-backing welding, the axial residual stress at the longitudinal weld and the circumferential residual stress at the pipe body region near the intersection increased sharply to 2.5 (444 MPa) and 3.8 (433 MPa) times, respectively. The invaded width and depth to the ERW pipe after welding were about 15.167 mm and 3.376 mm. Granular bainite with necklace type M-A constituents could be observed at the invaded zone. It is suggested that small welding heat input should be adopted for boss-backing welding.

1. Introduction

The station and valve chamber are the essential parts in the storage and transportation of oil and gas. Electric resistance welding (ERW) pipe has the advantages of high production efficiency, low cost, high dimensional accuracy and easy automation, and it is widely used in pipeline construction of oil and gas conveying station/valve chamber [1–3]. In order to meet the installation needs of valves, instruments and flanges, the station and valve chamber design often encounters the situation of making holes on the main pipe and boss-backing welding (branch pipe seat) to connect the branch pipe [4–7], as shown in figure 1(a). The opening position should generally be staggered 100 mm from the longitudinal weld or spiral weld of the main manifold [8]. However, in practical operation, because the weld line of ERW pipe is difficult to be identified, some bosses are installed close to or even coincide with the weld line, which may lead to safety risks, as shown in figure 1(b).

The non-compliance points of welding bosses in the stations and valve rooms of pipeline Branch in the western region were once counted by our group, it was found that a total of 42 openings were less than 100 mm from the longitudinal weld of the ERW pipe, as shown in figure 2 and table 1.

Some studies have shown that there is a large residual stress in ERW pipe, the residual stress value in some areas reaches the yield limit of the material, and most of the residual stress shows great harm: Such as strength reduction, reducing the fatigue limit, causing stress corrosion and brittle fracture, etc [9—12]. When a cross weld is formed between the bump installation weld and the ERW straight weld, the extremely complex residual stress distribution near the weld intersection and the change of the structure of the ERW pipe body and the heat affected zone after the multi-pass welding thermal cycle could all affect the overall performance of ERW pipe [13—15], and shorten the service life of the welded pipe and limit its service life.

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Therefore, to study the influence of boss-backing welding on the microstructure and properties of ERW pipes is of great significance to ensure the service life of ERW pipes. In this paper, a small hole detection method was used to study the ERW pipe commonly used in the station/valve chamber of a pipeline company, the influence of the boss-backing welding on the ERW pipe straight weld on the original residual stress of the pipe was studied, and the influence of the boss-backing welding on the pipe body and the microstructure of the heat affected zone was also analyzed. The study has important theoretical significance and guiding function for correct design and site construction of boss-backing welding.

2. Experimental

2.1. Materials

The test material is the commonly used ERW pipe in the main pipeline of an oil and gas transmission station/valve room. The steel grade is L415MB and the specification is Φ406.4 × 12.5 mm. The welded pipes used in the test were the same steel grade and specification produced by Baosteel, its chemical composition is shown in table 2, and the calculated CE_{IIw} and P_{cm} values are also listed in the table 3. The specimens were transversely cut along ERW pipe, the plate tensile and impact samples were machined based on the ASTM A370-2012a and GB T229-2007 standards. The tensile test and impact test were carried out on the MTS C64 universal testing machine and the NC-500 impact testing machine respectively, the tensile and impact properties of the materials are shown in table 3.

\[ CE_{IIw} = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15} \]  \hspace{1cm} (1)
The boss used for the test was a welded boss with a working pressure of 12 MPa, the material is A350 LF2 and specification is DN400 × 25 mm (figure 3).

2.2. Test method
A Φ 25 mm diameter holes was opened in straight weld position of ERW pipe through the thermal cutting. According to the welding procedure of the second station/valve chamber of West-to-East gas pipeline of China,
Table 2. Chemical composition of L415MB ERW pipe (mass fraction, %).

| C   | Si  | Mn  | P   | S   | Cr  | Mo  | Ni  | Nb  | V   | Ti  | Cu  | Al  | B   | CE_{eq} | C_{eq} | P_{cm} |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|--------|--------|
| 0.068 | 0.21 | 1.25 | 0.0098 | 0.0035 | 0.024 | 0.002 | 0.0067 | 0.041 | 0.024 | 0.019 | 0.017 | 0.028 | 0.0002 | 0.298 | 0.292 | 0.152 |
### Table 3. Mechanical properties of L415MB ERW pipe.

| Specimen                  | Specification mm | Tensile Strength Rm/MPa | Yield strength 0.5%EUL/MPa | Elongation A/% | Impact Akv/J |
|---------------------------|------------------|-------------------------|----------------------------|----------------|--------------|
| Pipe body 90° transverse  | 38.1 × 50         | 570 \(10^{-3} \text{s}^{-1}\) | 530                        | 37             | 207          |
| Welded joint Transverse   | 38.1             | 532 \(10^{-3} \text{s}^{-1}\) | /                          | /              | 365          |
the boss was welded by the welding method of GTAW backing and SMAW filling the cover surface. The specific boss-backing welding process is shown in table 4.

The change of residual stress on ERW pipe before and after boss-backing welding was measured by CM-1L-32 static resistance strain gauge and BE120-2CA-K strain flower. In the process of testing, the position of the blind hole was reasonably arranged to ensure that the distance between each measuring point was more than 12 mm after considering the specific size of the pipe. The effects of thermal cutting and multi-pass welding on the base metal and weld microstructure of ERW pipes were observed by OLS 4100 laser scanning confocal microscope, MEF4M metallographic microscope and image analysis system.

The keyhole method is a semi-destructive method for the determination of residual stress. By measuring the strain release caused by the machining of the keyhole, the original residual stress of the keyhole can be converted through the calculation of elastic mechanics. The mechanical effect of the keyhole release method is equivalent to that of the reverse loading. According to the elastic mechanics, the formulas for calculating the principal stress \( (\sigma_1, \sigma_2) \) and principal stress Angle \( (\gamma) \) of the measured points can be obtained [16]:

\[
\sigma_1 = \frac{\varepsilon_1 + \varepsilon_3 - \varepsilon_2 - \varepsilon_4}{4A} \quad 4B \cos \gamma
\]

\[
\sigma_2 = \frac{\varepsilon_1 + \varepsilon_3 - \varepsilon_2 - \varepsilon_4}{4B \cos \gamma}
\]

\[
\gamma = \arctan \frac{\varepsilon_2 - \varepsilon_3}{\varepsilon_1 - \varepsilon_3}
\]

where \( A \) and \( B \) are referred to as strain release coefficients, and their expression is as follows [17]:

\[
A = -\frac{1 + \mu}{2E} \frac{R^2}{r_2}
\]

\[
B = -\frac{1}{2} \frac{R^2}{E} \frac{1 + \mu}{r_2}\left[ 1 + \frac{R^2}{4} \frac{(\eta_1^2 + \eta_2^2 + \eta_3^2)}{\eta_2} \right]
\]

where \( E \) is modulus of elasticity and \( \mu \) is Poisson ratio. The calculation formula of welding residual stress is as follows (\( \sigma_x \) is the longitudinal residual stress and \( \sigma_y \) is the circumferential residual stress) [18]:

\[
\sigma_x = \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2} \cos \gamma
\]

\[
\sigma_y = \frac{\sigma_1 + \sigma_2}{2} - \frac{\sigma_1 - \sigma_2}{2} \cos \gamma
\]

Then the residual stress values could be calculated by equations (2)--(9), and the schematic diagram of strain gauge is shown in figure 4. During the test process, the measuring point near the weld is X direction along the weld, and Y direction is perpendicular to the weld direction. When calculating the residual stress, positive values indicate tensile stress and negative values indicate compressive stress.

The residual stress test was carried out by blind hole drilling on the drilling machine, as shown in figure 5. According to the stress testing standard, the distance between each measuring point should be more than 6 times of the diameter of the small hole, that is, more than 12 mm. In the testing process, combined with the specific size of the pipe, the position of the hole was reasonably arranged to ensure that the measuring point and the
| Weld pass  | Materials type | Welding materials specifications (mm) | Direct current polarity | Weld Current (A) | Weld voltage (V) | Weld speed (cm min⁻¹) | Argon flow rates (L min⁻¹) | The length of Tungsten electrode | orifice nozzle diameter (mm) | Argon arc | The length of the | Note: DCEN- indicates that the electrode connected to the welding material is associated with the negative electrode of the power supply; DCEP- indicates that the electrode is associated with the positive electrode of the power supply. |
|-----------|----------------|---------------------------------------|-------------------------|-----------------|-----------------|-----------------------|---------------------------|-------------------------------|------------------------------|-----------|-----------------|--------------------------------|
| Root welding | ER50-6         | 2.0                                   | DCEN                    | 80-120          | 10-14           | 5-10                  | 7-12                      | 6-9                           | 8-10                         | 2-4        |
|            | 2.5            | DCEN                                  | 100-160                 | 10-16           | 5-10            | 7-12                  | 6-9                       | 8-10                         | 2-4                           |
| Fill/cover | E5015          | 3.2                                   | DCEP                    | 90-140          | 18-26           | 5-12                  |                           |                               |                              |
|            | E5015          | 4.0                                   | DCEP                    | 100-150         | 18-26           | 8-15                  |                           |                               |                              |
boundary should be kept above 15 mm, and the distance between each measuring point should be kept above 12 mm.

### 3. Results and analysis

#### 3.1. Residual stress

The original residual stress distribution of ERW pipe is shown in figure 6. As can be seen from the figure 6 that the axial residual stress on the ERW pipe is higher than that of the circumferential residual stress, and the maximum axial and circumferential stresses are 203 MPa and 152 MPa respectively. There is no apparent stress concentration in the straight weld area. The maximum axial and circumferential residual stresses on the straight
weld are 178 MPa and 114 MPa respectively, which are far lower than the yield strength of the material, and are 34% and 22% of the yield stress of the welded pipe body. Figure 6(a) shows the comparing magnitude of residual stress on the straight weld of ERW pipe and 100 mm away from the straight weld. The axial and circumferential residual stresses in the area 100 mm away from the straight weld are slightly larger than those in the straight weld, the maximum axial residual stress difference is 47 MPa and the maximum circumferential stress difference is 45 MPa. It can be seen from figure 6(b), the distribution of residual stress is relatively uniform at various distances from the straight weld, and the rule is still the axial residual stress is higher than that of the annular residual stress. The difference between the two residual stresses are small between 45 mm and 55 mm from the weld, however, the difference increases as the distance continues to increase. The distribution of residual stress on ERW pipe is closely related to its welding and forming process, the sizing and hydraulic test after welding are both important processes that lead to the axial residual stress value being greater than the circumferential residual stress value.

The distribution changes of residual stress on the ERW pipe after the boss-backing welding are shown in figure 7. It can be seen that the residual stress on the straight weld of ERW pipe near the boss rises steeply after boss-backing welding, and the increase range of axial residual stress is much greater than that of circumferential residual stress. The amplitude of the axial and the annular residual stresses are 444 MPa and 201 MPa respectively, which are about 84% and 38% of the base metal yield strength, the amplitude of the axial and the annular residual stresses increase by 2.5 and 1.4 times compared with the original peak distribution of ERW pipe. The increase of residual stress value decreases gradually with the increase of distance from the boss. The distribution of residual stress on the ERW pipe at different distances from the welding seam is more uniform, and the overall residual stress value is relatively small. Boss welding changes the original distribution state of residual stress, and makes the residual stress at the edge of the boss rise rapidly. The distance from the boss weld

![Figure 6. Initial residual stress distribution of ERW pipe. (a) Straight weld and pipe body from 100 mm of straight weld and (b) pipe body at various distances from straight weld.](image)

![Figure 7. Residual stress distribution on ERW pipe after boss-backing welding. (a) Distance from the central axis, (b) Different distance from straight weld pipe body.](image)

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is longer, the influence of welding process on residual stress is smaller, and the increase amplitude of residual stress is smaller. The range of stress concentration on the straight weld is about 92 mm, which is consistent with the change rule of ERW straight welded pipe, the residual stress value of the pipe body at the edge of the boss increases rapidly after the boss is welded. However, the increase range of circumferential residual stress in welded pipe body is much greater than that of axial residual stress. The amplitude of the axial and the toroidal residual stresses are 256 MPa and 433 MPa respectively, which are about 48% and 82% of the yield strength of the base metal. The peak distribution increases by 1.4 and 3.8 times compared with the original state of ERW pipe, and the circumferential stress concentration of the welded pipe body is about 51 mm.

3.2. Microstructure

3.2.1. Microstructure of ERW
The microstructure of ERW pipe body is a mixture of polygonal ferrite, pearlite and a small amount of granular bainite (PF + P + B grains), with the grain size of 10.6, as shown in figure 8(a). The straight weld microstructure of ERW pipe is a mixture of polygonal ferrite and a small amount of pearlite (PF + P), with the grain size of 10, as shown in figure 8(b).

3.2.2. Thermal cutting openings on microstructure
The influence thermal cutting on the structure of the area near the opening is shown in figure 9, the influence range of thermal cutting tissue is funnel-shaped, with the largest surface width of about 3.649 mm, and the width of uniform area of 3.523 mm. The microstructure near the pore edge is coarse granular bainite structure generated by the transformation of original austenite grains, some grain boundaries can be seen, and the average size of original austenite grains is about 29 μm. The large M-A island inside the grain is mostly long strip or round. The microstructure shows that the residence time near the pore edge at high temperature (1100 °C) is longer, which results in the significant growth of the original austenite grains. However, the cooling rate is relatively low during the phase transition process, and there is no obvious orientation arrangement of M-A islands in the grain. The appearance of M-A island will result in an increase in the microhardness value of the edge zone. However, M-A island does great harm to impact toughness. It is generally believed that the M-A island is easy to form crack source and crack propagation channels. The larger the M-A island, the more the number of M-A island, the greater the damage to toughness, especially low temperature toughness. The grain size of the fine grain zone in the transition zone shows not big different from that of the base metal, but the change of microstructure shows that the thermal cycle experienced in this zone leads to the relative decrease of the polygonal ferrite content while the increase of the granular bainite content, and the fine and dispersed M-A islands are evenly distributed in the granular bainite grains.

3.2.3. Effect of boss welding on microstructure
The width and thickness of the upper surface of the penetrated ERW pipe after boss-backing welding are 15.167 mm and 3.376 mm respectively, accounting for about 27% of the total wall thickness. After the boss-backing welding, the original pipe body and straight weld microstructure in the invaded area disappeared,
and the microstructure was mainly transformed into the following three types: a small amount of weld microstructure in the surfacing layer, coarse heat-affected zone microstructure and fine grain microstructure, as shown in figure 10.

The weld microstructure of the surfacing weld is the coarse columnar grains that nucleate and grow directly on the base metal. The grain morphology of the proeutectoid white ferrite is outlined along the grain boundary of the slender columnar grains, and the fine acicular ferrite structures are found within the grains, as shown in figure 10(a). The coarse grain microstructure of the ERW pipe body and straight weld are coarse granular bainite (figure 10(b)), a small amount of polygonal ferrite and a mixture of coarse granular bainite (10(c)). The discontinuous distribution of block M-A at grain boundary of granular bainite is connected into lines, and a chain structure could be observed. The microstructure of the fine grain zone between the pipe body and the straight weld of the ERW pipe is basically the same, which is a mixture of polygonal ferrite PF, quasi-polygonal ferrite QF and a small amount of pearlite at the grain boundary, as shown in figure 10(d).

3.3. Result analysis
After the ERW pipe is welded, the microstructure and properties of the direct weld and heat-affected zone could be improved by online heat treatment, which results in that the residual stress value of the direct weld and its adjacent area is lower than that of the pipe body, and there is no stress concentration in the direct weld area of the ERW pipe compared with the conventional weld. However, after the punch directly opened near the straight weld, the axial residual stress of the straight weld near the cross weld and the circumferential residual stress of the pipe body increase by 2.5 and 3.8 times respectively. That is to say, in the actual operation process, the straight weld in the area near the cross weld of 93 mm after the convex welding bears not only the internal pressure, but also the axial and annular tensile stress, which is extremely unfavorable to the safety of actual pipeline operation [19–23].

The original microstructure of ERW pipe is uniform and fine, and the impact toughness of pipe body and weld is high. After the thermal cycle of the convex welding, except for the average microhardness of the fine grain area is 180 HV1, which is the same as the base metal, the hardness values of the three types of microstructure in the 3.376 mm thickness area are all higher than that of straight weld zone (203 HV1). The grain size of granular bainite and original austenite in the coarse grain area of ERW pipe and straight weld zone is basically the same, but the morphology, quantity and size of M-A shows different. The chain M-A island at the grain boundary of
granular bainite grains in coarse grain zone is easy to form as crack source and crack propagation channel, which has great influence on toughness, especially low temperature toughness. Therefore, it is recommended to adopt a smaller welding heat input during the convex welding and to increase the welding cooling rate, which could avoid the formation of chain-like structures in the intrusion area of ERW pipe [24, 25].

4. Conclusions

This paper studied the influence of the boss-backing welding on straight weld of commonly used ERW station pipe (L415MB, φ406.4 × 12.5 mm) residual stress and the microstructure, the main conclusions are as follows:

1. The overall residual stress on ERW pipe is small, and the maximum axial and circumferential residual stress is 203 MPa and 152 MPa, respectively. The residual stress value of the straight weld and its adjacent area is lower than that of the pipe body.

2. After the boss-backing welding, the axial residual stress of the straight weld near the cross weld and the circumferential residual stress of the pipe body increase by 2.5 and 3.8 times, which is 444 MPa and 433 MPa, respectively.

3. After boss-backing welding, the penetration width of the ERW pipe upper surface is 15.167 mm and the thickness is 3.376 mm. The microhardness of the invasion zone is higher than that of the original pipe body,
and the chain-like bainite structure could be observed in the coarse grain zone. Therefore, it is suggested to adopt smaller welding heat input during welding.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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