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Research Paper

Experimental Study of the Residual Stresses in Girth Weld of Natural Gas Transmission Pipeline

Majid Sabokrouh[1], Mohammadreza Farahani[2]

[1] Faculty of Engineering, Mahallat Institute of Higher Education, Mahallat, Iran
[2] School of Mechanical Engineering, College of Engineering, University of Tehran, Iran

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Corresponding author: M Sabokrouh, msabokrouh@mahallat.ac.ir

Abstract. In order to achieve integrated condition in the girth welding of high pressure natural gas transmission pipelines, the weld zones and its surrounding area should have good mechanical properties. Residual stresses are an important defect especially in the girth welding of the pipeline. In this study, two API X70 steel pipes (with spiral seam weld) of 56 inches outside diameter and 0.780 inch wall thickness were girth welded first. The hole drilling tests were conducted for residual stress measurement on the surfaces of the pipes. The hoop tensile residual stress on the external surface of the pipe with the maximum value equal to 318-MPa was measured on the weld centerline. Hoop residual stress distributions in the internal and external surfaces of the pipe were approximately similar. The maximum axial residual stress was observed in the heat affected zone (a distance of approximately 30 mm from the weld centerline). The maximum axial residual stress on the external surface of the pipe was tensile, equal to 137 MPa, and on the internal surface of the pipe was compressive, equal to 135-MPa. Axial residual stress magnitudes in the weld centerline on the internal and external surfaces of the pipe were close together. Away from the weld centerline, axial residual stresses on the internal and external surfaces showed the opposite behavior. Therefore, in the girth welding of natural gas transmission pipelines, the peripheral direction on the internal surface of the pipe is the critical zone and have the highest tensile residual stresses.

Keywords: Residual stress; Assembling; Multi-pass girth weld; Natural gas transmission pipeline; Hole drilling; API X70; Thermomechanical steel.

1. Introduction

Residual stresses can have a detrimental effect on the structural integrity and considered as an important issue in the failure assessment of structures. Girth welds are critical points in the natural gas transmission pipeline. The welding takes about 25 percent of time for creating a new transmission pipeline [1]. Residual stresses refer to those stresses that remain in the body after certain operations; they also are not caused by external loading. The magnitude and distribution of residual stresses are not identified before the construction and usually they are not considered in the design completely [2]. During welding, the stress of the molten weld pool is zero due to the lack of tolerability of the molten zone. After welding, the weld metal and its surrounding are cooled and contracted. Regarding the restrains of the base metals, tensile stresses are generated at the weld. After complete cooling, the residual stresses of weld zone get tensional with a high magnitude [3].

In cylindrical joints (pipes and pressure vessels), longitudinal, transverse, and height directions are indicated by hoop, axial, and radial directions. In these structures, there is a close relationship between the hoop and axial stresses. The circumferential contraction in this type of welding causes axial bending in the cylinder. The angular deformation along the pipe form axial stresses. This issue has a great effect on the distribution of residual stresses in this type of welding [4]. Edwards et al. measured the residual stress of stainless steel with a diameter of 170 mm and thickness of 20 mm using the neutron diffraction method

[5]. In their study, they evaluated the axial residual stress equal to 60% of the material yield strength. Law et al. (2006) evaluated the girth welding residual stresses of X70 steel with a diameter of 275mm and three different thicknesses (5.4, 6.4, & 7.1 mm) using the neutron diffraction. The results show that the maximum residual stress occurs in thinner pipes [6]. Sattari-far and Farahani examined the shape effect and the pass number in the girth welding of the austenitic stainless steel with a diameter of 320 and a thickness of 10 mm. The experimental results and simulation showed a proper match [7]. Rubin et al. evaluated the residual stresses using X-ray diffraction in X70 pipelines with a diameter of 1016 mm and the thickness of 26.2 mm [8]. The residual stress amounts of two methods used in their study indicated that the maximum residual stresses happened in parallel to the heat affected zone of the weld side. Paddea et al. examined the girth welding residual stresses of the ferritic-martensitic pipe with grade P91 using the neutron diffraction testing [9]. The results showed that the maximum tensile residual stresses had happened in the interface of the weld and heat affected zone. Obeid et al. evaluated the parametric of thermal and residual stress and the effect of welding process in the lined pipe recently [10-11]. The investigation of in service behavior of the gas pipeline in the weld induced large residual stress zone requires comprehensive identification of the distribution of these stresses. With regard to the importance of residual stresses and sensitivity of the girth weld in steel pipes, in this study and for the first time, the girth weld on the steel pipe of grade X70 (with an outer diameter of 56 and a thickness of 0.780 inches used in gas pipelines) is considered to determine the residual stress distribution in the weld, heat affected zone, and base steel. The tested steel pipe is a spiral weld seam type (spiral). The welding on two 500 mm spiral API X70 steel pipes with a diameter of 56 and a thickness of 0.780 inches is done using the shielded metal arc welding process. Based on the standards, the welding was carried out using 9 passes, including root pass, hot, filling, and cap passes, respectively. Table 1 shows the welding process parameters for each pass. The geometrical dimensions of the weld groove are presented in Fig. 1(a). Figure 1(b) indicates the welding process [12].

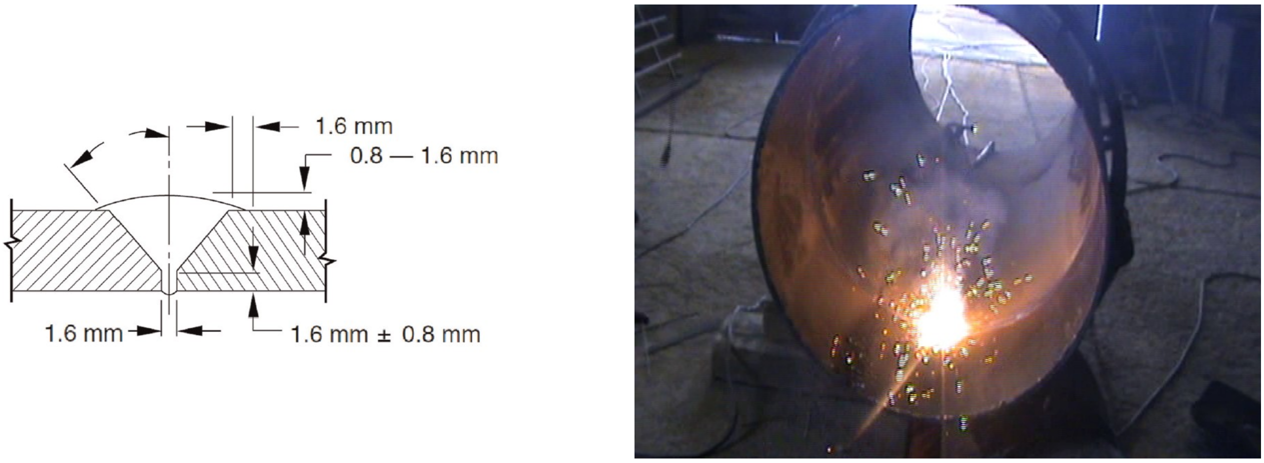


Fig. 1. (a) Dimensions of the weld groove, (b) welding process

Table 1. Welding process parameters

Type of pass	Number of passes	Electrode class	Electrode diameter (mm)	Welding speed (mm/min)	Voltage (V)	Electric current (A)
Root	1	E 6010	3.2	120	23.2	80
Hot	1	E 8010G	4	130	24	100
Filling	4	E 8010G	4	150	24.8	120
Cap	3	E 8010G	5	180	26	150

2. Semi-destructive hole drilling strain gauge measurement

Hole drilling as a semi-destructive method with wide usage of approximately 22% is the most common method of measuring residual stresses. This method is used for determining residual stresses near the material surface. It involves installation of the strain gauges, creating a hole at the center of the strain gauges, and measuring the released strains. The deformation caused by releasing residual stresses is measured and associated with the main stresses by elastic equations [13].

Creating a hole in a material with residual stress will cause changes in the stress field. The stress must be zero at the hole free surfaces. Removing all stresses in the holes creates the surface strain proportional to these stresses. Released strains caused by hole depend on the elastic behavior of the piece, the stress level, and geometry of isolated parts. Measuring these strains shows the stress level. By arrangement such as Fig. 2, the analytic relations will be in the simplest form.

Locations 2a and 2b will have the same results for strain gauges No.2. This shape of strain gauges is called Rosette. By measuring the strain in these three directions, principal stresses, and their directions in terms of constant coefficients and obtained strains would be resulted as follows:

$$\sigma_{\max}=\frac{\varepsilon_1+\varepsilon_2}{4A}-\frac{1}{4B}\sqrt{(\varepsilon_3-\varepsilon_1)^2+(\varepsilon_3+\varepsilon_1-2\varepsilon_2)^2} \qquad A=-\frac{1+\nu}{2E}\left(\frac{1}{r^2}\right) \qquad \varepsilon_r=\sigma_x\left(A+B\cos 2\alpha\right) \tag{1}$$

$$\sigma_{\min}=\frac{\varepsilon_1+\varepsilon_2}{4A}+\frac{1}{4B}\sqrt{(\varepsilon_3-\varepsilon_1)^2+(\varepsilon_3+\varepsilon_1-2\varepsilon_2)^2} \qquad B=-\frac{1+\nu}{2E}\left[\left(\frac{4}{1+\nu}\right)\frac{1}{r^2}-\frac{3}{r^4}\right] \qquad \varepsilon_\theta=\sigma_x\left(-A+B\cos 2\alpha\right) \tag{2}$$

$$\tan 2\alpha = \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_3 - \varepsilon_1} \tag{3}$$

where ε_1, ε_2, and σ_{max} indicate the measured strain by strain gauges 1 and 2 and maximum stresses. α is also the angle between the strain gauge 1 and the maximum stress (if it would be positive, it will be clockwise). If the residual stress level was too high with respect to the base metal yield strength, the strain gauge hole drilling method would not be approved by standards due to loss of linear relationship between stress and strain·

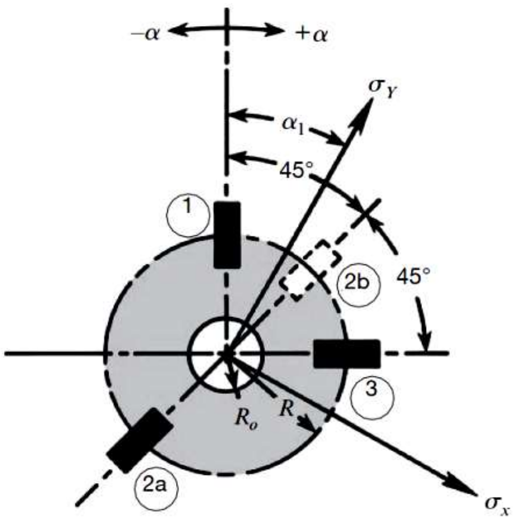


Fig. 2. Arrangement of rosette strain gauges [14]

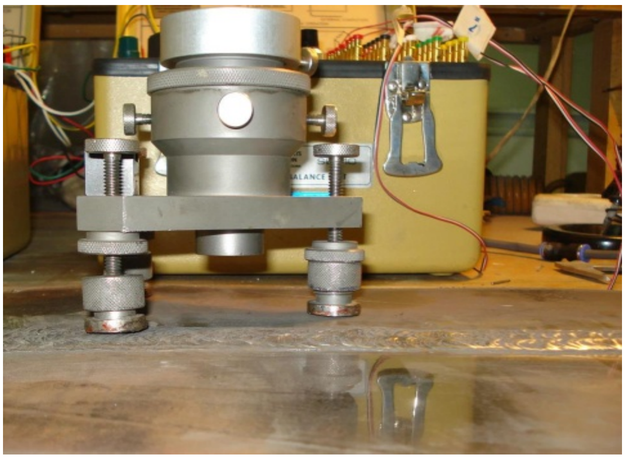
The hole drilling method is only used to evaluate surface stresses and it cannot evaluate stresses in depth. Therefore, this method is not able to evaluate radial residual stresses. Considering that this pipe is thin-walled, the level of these stresses is very limited and negligible [15].

In this study, the drilling operation was carried out according to the ASTM E817 standard and the released strains were measured. According to the standards, the milling is worthless in depths greater than 2 mm. At first, the residual stresses were evaluated in different areas of the heat affected zone. Figure 3 a, b, and c show the location of the first strain gauge, the milling machine, and indicator strain (VISHAY P-3500) in the heat affected zone, respectively.

By this method, the hole drilling test in the heat affected zone on the external surface of the pipe was done at intervals of 4, 10, 22, 43, 75 mm distance from the weld centerline. After completing the tests on the base metal, the weld surface preparation was performed to install rosette according to the relevant standard. With regard to the fact that the final pipe welding is done in three parallel passes and circumferential symmetry of the weld, two points were considered on the side and central passes for testing. Figure 4 shows the placement of all rosettes on the external surface of the pipe after performing tests.

After hole drilling test on the external surface of the pipe, this experiment was performed on the internal surface of the pipe similar to previous steps. With regard to the presence of just one weld pass at the inner pipe surface and the specification of residual stress changes on the outer surface, this experiment was performed just on three points on the inner surface. Figure 5 shows the milling and rosette placement on the internal surface of the pipe weld.

(a)



(b)

(c)

Fig. 3. a) Strain gauge placement, b) milling device before drilling, c) indicator strain

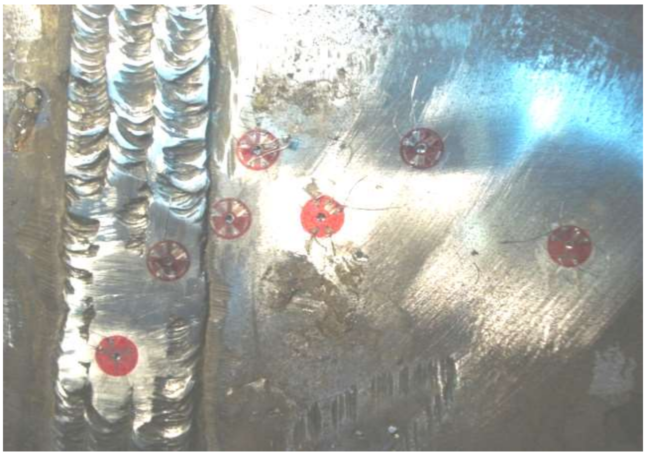


Fig. 4. Hole drilling tests on the external surface of the pipe

(a) (b)

Fig. 5. a) Milling conditions during hole drilling test, b) Rosette installation on the root pass

The rosettes are respectively located at intervals of 22 and 55 mm from the weld centerline and on the weld. Figure 6 shows the assessment points of residual stresses on the internal surface of the pipe.

3. Result and discussion

In order to determine the Young's Modulus and Poisson's ratio of the base metal for converting the released strains to stress, the tensile tests were performed on a flat sample perpendicular to the weld gap.

This test was also done on the round sample from peripheral weld using a Zwick tensile test machine with a capacity of 600-KN and a strain rate of 10 mm per minute according to ASTM E8M standard (Fig. 7). According to the standard, the breaking was not happened in the weld gap.

Fig. 6. The location of the hole drilling test on the internal surface of the pipe

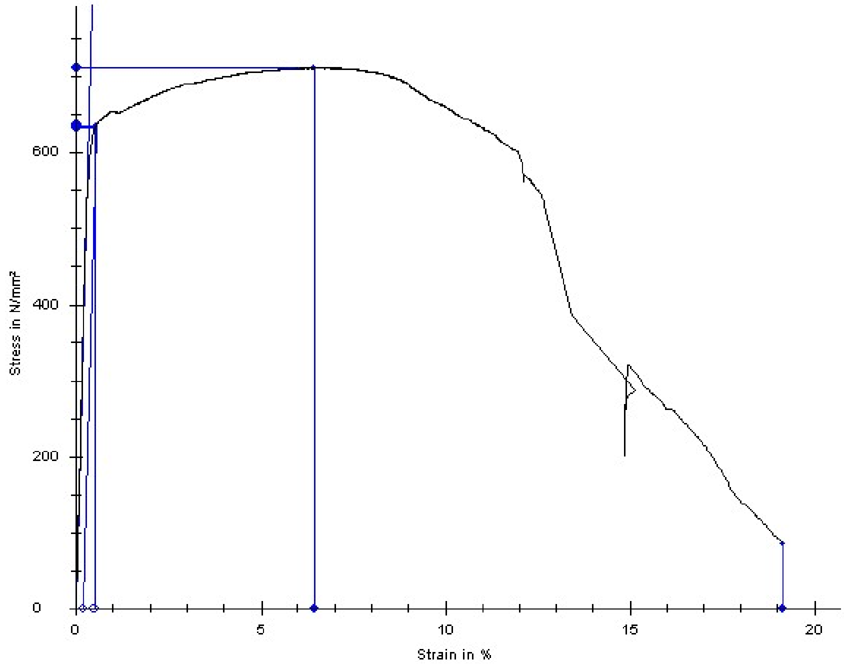


Fig. 7. The stress-strain curve at room temperature for flat sample perpendicular to weld gap

Figure 8 and 9 show the graph of hoop and axial residual stresses on the internal and external surface of the pipe, respectively. As shown in Fig. 8, the maximum amount of stress and average stress values on the external surface of the pipe is more than that on the internal surface.

4.1. Residual stresses on the external surface of the pipe:

The results show that a considerable hoop tensile residual stress was created on the weld. As shown in Fig. 8, the magnitude of this stress in the center of the weld zone (center pass) is equal to 318 MPa which is more than 60% of the weld metal yield strength (505-MPa). With regard to the rigidity of the weld zone and its high restraint, it was expected that this stress be close to the weld metal yield strength.

In the external surface of the pipe and on the edge pass (near the middle pass), the hoop tensile residual stresses are measured equal to 217-MPa, about 42% of the weld metal yield strength. In the heat affected zone (near the weld), the compressive residual stresses are observed. With regard to the rigidity of the pipes and self-equilibrium behavior of residual stresses, the generation of compressive residual stress in this zone looks natural. At a distance of 4 mm from the weld edge, the residual stress (equivalent to 24-MPa) is 5% of the base steel yield strength (633-MPa). This zone follows a dual behavior. The fusion has not taken place in this area, but the material is in the form of a paste. Therefore, the base metal adjacent to the weld zone lost some of its rigidity and shows a behavior similar to the weld. Due to extreme thermal cycles, the martensite transformation and the grain coarsening are inevitable in this zone. Therefore, the mechanical behavior between the weld zone and the base metal seems reasonable.

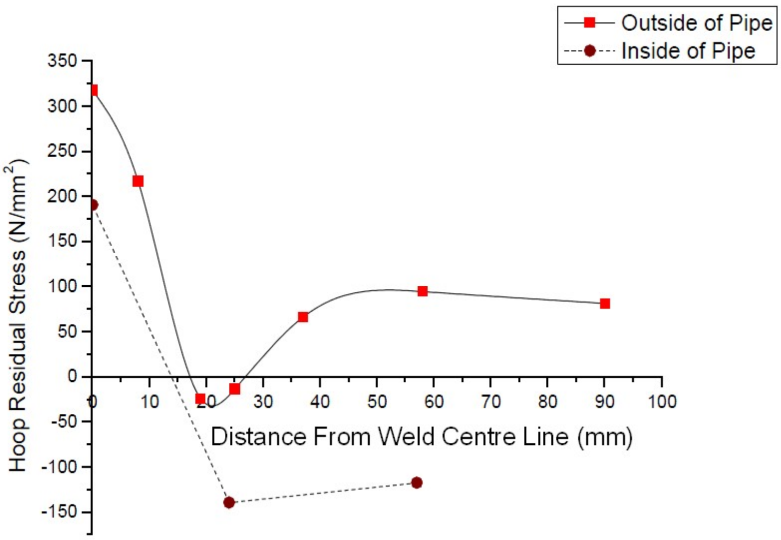


Fig. 8. Distribution of hoop residual stresses on the external and the internal surface of the pipe

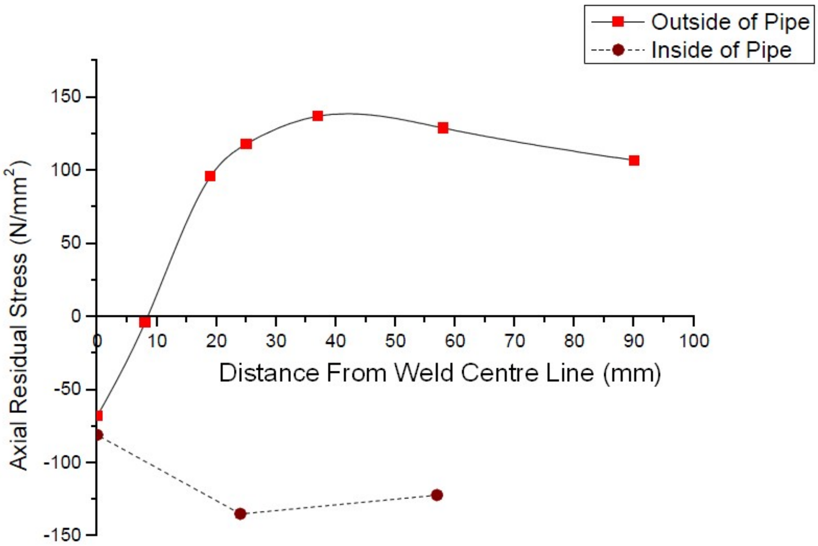


Fig. 9. Distribution of axial residual stresses on the external and the internal surface of the pipe

The residual stress within 10 mm from the weld zone is compressive, but its magnitude has reduced to 13 MPa (3% of the yield strength of the base steel in heat affected zone). To functionalize the distribution of residual stress, 3-degree spline curves were used in order to interpolate the tested points.

Hoop residual stresses in zones away from the weld centerline show a constant tensile behavior (equal to 90 MPa) that is probably due to the pipeline manufacturing process.

Figure 9 shows that the residual compressive stresses perpendicular to the weld were created in the weld centerline zone (equivalent to 68-MPa). This zone is under two simultaneous effects of the angular distortion and the longitudinal shrinkage of the weld. The angular deformation tends to push the external surface of the weld that is interacted with the length contraction and pull the weld inside the pipe. Therefore, it is expected that these stresses are compressive on the weld center. The compressive residual stress increased due to the presence of the martensite phase in this zone. In the lateral pass, this compressive residual stress is reduced to 4 MPa. With increasing the distance from the weld zone, the axial residual stress increased as the strain gauge has measured the axial tensile residual stress equal to 13 MPa at a distance of 20 mm from the weld centerline. Increasing the axial residual stresses is probably depended on the bevel shape. In unidirectional welding, the angular distortion is continuously increased with each pass by increasing the constraint. Residual bending stresses in the weld lateral zone are increased. Due to self- equilibrium inherent nature of residual stresses, at longer distances (up to 200 mm) from the weld, the axial residual tensile stresses gradually reduced and got close to zero.

4.2. Residual stresses of internal surface of the pipe

In order to measure residual stresses on the internal surface of the pipe, the hole drilling test was performed on 3 points. As the root pass is single, one point was given to the weld center. Hoop residual stresses followed a similar trend to the external surface of the pipe qualitatively. It seems that tensile residual stresses inside the pipe have dropped to a certain level compared to the external surface. In the weld centerline area, the tensile residual stress is equal to 191-MPa which shows approximately 40% reduction compared to the corresponding point on the external surface of the pipe (Fig. 9). The compressive residual stress in the heat affected zone of the pipe internal surface and at a distance of 22 mm from the edge of the weld is equal to 139 MPa (about 6 times greater than the maximum compressive residual stress on the external surface). The location of maximum compressive residual stress inside the pipe would occur at a distance away from the edge of the weld. The third point that is located at a farther distance about 57 mm from the weld center has a similar amount of stress (117-MPa) compared to the corresponding zone on the external surface of the pipe (but its direction is different and is compressive). The presence of these stresses could be caused by the forming process a spiral roller for pipe manufacturing that create compressive stresses on the internal radius and make tensile stresses on the external radius. Therefore, in addition to heat input effects due to factors such as electric current, electrode diameter, and welding speed, the initial stress caused by manufacturing processes is also effective on the difference of welding residual stresses on the internal and external surfaces of the pipe. In general, it could be said that the reduction of hoop residual stresses on the internal surface of pipe compared to the external surface is due to some welding variables. These variables could be heat input, weld geometry, the presence of martensite phase and lack of stress relief in the cap pass.

On the contrary to the hoop residual stresses, the axial tensile residual stresses on the internal surface of the pipe follow an opposite trend over the external surface of the pipe. In the weld centerline zone, the residual stress is equal to 81-MPa and it is approximately equal to the estimated amount at the corresponding point on the external surface of the pipe.

In the heat affected zone at a distance of 24 mm from weld centerline, high compressive residual stresses (135-MPa) and in the farther point (a distance of 57 mm from the weld centerline), the amount of residual stress is reduced (up to 122-MPa). The magnitude of residual stress in the points corresponded to the internal and external surfaces of the pipe is opposite.

Due to the higher tensile stresses compared to compressive stresses, it seems that external surface of the pipe is more critical compared to internal surface. Moreover, in terms of hoop stresses, the weld centerline zone can be identified as a critical zone while in terms of axial stresses, the heat affected zone (at a distance of 30 mm from the weld centerline) can be identified as a critical zone.

4. Conclusion

The residual stress is an important defect especially in the girth welding of pipes that has a significant impact on the growth of cracks and corrosion of the pipeline. The results of residual stress assessment in the girth welding of microalloying steel in gas pipelines can be summarized as follows:

1. The hoop residual stress was tensile on the external surface of the pipe and its maximum was equal to 318-MPa that had happened on the weld centerline. With regard to the inherent self- equilibrium behavior of residual stresses, the hoop residual stress was compressive in the heat affected zone.
2. The hoop residual stresses in the internal and external surfaces of the pipe had approximately similar behaviors. However, residual stresses at farther distances from the weld center on the heat affected zone were tensile on the external surface of pipe and compressive on the internal surface of the pipe.
3. The axial residual stresses in the weld centerline gap on internal and external surfaces of the pipe were close together, but away from the weld centerline, they showed opposite behavior to each other.
4. The maximum magnitude of the axial residual stress in the heat affected zone (approximately 30 mm from the weld centerline) was observed. Its magnitude on the external surface of the pipe was tensile equal to 137 MPa while on the internal surface of the pipe was compressive equal to 135-MPa.
5. In the girth welding of thick natural gas transmission pipe of Iran, the weld centerline on the external surface (buried under the soil) is the critical zone and has the highest tensile residual stresses. In subsequent studies using quantumetry, metallography, impact, and hardness experiments, the effect of these stresses on the metallurgical and mechanical behavior of the weld and heat affected zones will be discussed.

Conflict of Interest

The authors declare no conflict of interest.

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