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Short technical note

Non-uniformity of residual stress profiles in butt-welded pipes in manual arc welding

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ABSTRACT

Welding residual stresses in pipes of small diameter are especially critical when the fluid transported has high acidity. In manual welds, various factors can alter the behavior of residual stresses. The present work presents experimental results on the profile of residual stresses in manually welded butt joints. The residual stress measurements were carried out on the external surface with a mini-diffractometer X-ray. The results show that significant variations can occur in the welding residual stress behavior even under similar welding conditions.

1. Introduction

Industrial pipes have a fundamental role in different sectors of the chemical, petrochemical, nuclear and oil industries. Frequently, manual welding processes such as SMAW and GTAW, especially for pipes with a small diameter/thickness are used to join these pipes. The appearance of residual stress is an inherit characteristic of the welding processes, due to localized heating that causes localized expansion of the material and its contraction on cooling (Withers and Bhadeshia, 2001; Kou, 2002). Coupled to the effects of thermal stresses, phase transformations and material property alterations also take place with temperature variations (American Welding Society, 1991; Rajad, 1992).

The level of tensile residual stresses in welds can be as high as the yield strength (Parlane, 1981). This high level of tensile stress may cause several problems such as cold cracks, stress corrosion cracking and faults due to fatigue (Bailey et al., 1993; Fessler and Krist, 2000; Nguyen and Wahab, 1995). Consequently, it becomes fundamentally important to understand the behavior of welding residual stresses to assure the integrity of industrial pipes. There is very little data published on residual stress due to manual welding, especially for the welding of pipes. This work aims to present the behavior of welding residual stress, determined experimentally by X-ray diffraction in pipes of small sizes and especially to evaluate the uniformity of the profile along the joint.

2. Experimental

ASTM A 106 Gr. B steel tubes with a 101.6 mm (4 in.) diameter and 6.6 mm thickness were used in this work. A semi-V joint with a 35°

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Table 1 – Chemical composition of base and filler metals (mass%)

Material	C	Mn	Si	P	S
ASTM A106 Gr. B steel (pipe)	0.19	0.96	0.20	0.016	0.006
Filler metal AWS ER 70 S3	0.18	0.95	0.18	0.09	0.04

Table 2 – Mechanical properties of the materials

Material	Yield strength, σ_y (MPa)	Tensile strength, σ_R (MPa)	Elongation (%)
Filler metal	420	516	30
Pipe/Ø4 in.	357	512	33
Standard of pipe (Min.)	241	415	23

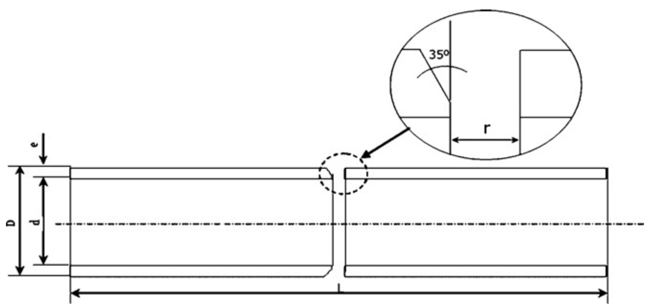

Fig. 1 – Schematic draw of test bodies and detail of the joint geometry.

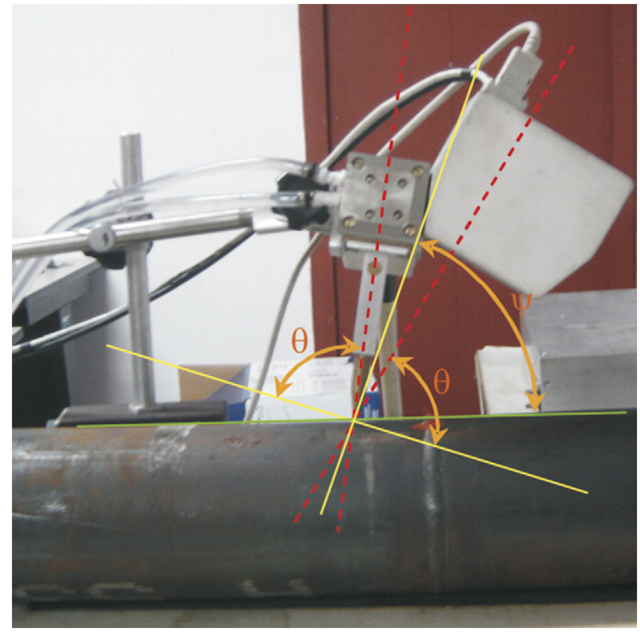

Fig. 2 – Geometry depicted by the pipe/detector set.

angle and root opening of 6 mm was employed. The filler metal used was a AWS E 70 S3 steel. The chemical composition and mechanical properties of the materials (pipe and filler metal) are presented in Tables 1 and 2. The joints were made by machining a bevel geometry of the semi-V type (Fig. 1), the dimensions of which are shown in Table 3.

The welds using the GTAW process were carried out manually, the parameters of which are presented in Table 4. The pipes were welded by three pass welding: root, filler and finishing. Four test samples were prepared under the same conditions and welding parameters (A1–A4), especially in the finishing pass. The idea is to check the repeatability of the behavior of the residual stresses for technically similar weld conditions from a parameter point of view.

The stress measurements were carried out using a portable X-ray mini-diffractometer for field measurements (Fig. 2) that was developed by IPRJ-Instituto Politécnico de Nova Friburgo (Polytechnic Institute of Nova Friburgo). This apparatus has been employed successfully for the measurement of residual stresses (Assis et al., 2003; Monin et al., 2004). A monochromatic beam with Cr Kα radiation ($\lambda = 2.2911$ Å) and the diffraction for the crystallographic planes family {2 1 1} were used in this work. Only the axial residual stresses were measured, not only because these are the most important in relation to the beginning and to the propagation of fatigue cracks and stress corrosion cracking (Hayashi et al., 2000), but also due to the physical limitations of the equipment. The measurements were carried out on the external surface previously prepared with electrolytic polishing. The region analyzed in all cases was a reference to the plane position of the weld. Adjustments on the curves using the analytical functions Pearson VII and Lorentz (Noyan and Cohen, 1987) were carried out for correct localization of the diffraction peak. The maximum X-ray measurement errors varied approximately ±30 MPa.

Table 3 – Test body dimensions and joint geometry

Dimensions (in.)	4
D (mm)	114.3
d (mm)	128.3
e (mm)	6.6
L (mm)	818.8
r (mm)	6

3. Results and discussion

In general the results of the stresses calculated as of the values of 2θ for the diffraction peak corrections, using the Pearson VII and Lorentz functions, presented a very similar behavior, with stress values very close to each other, indicating that both corrections are satisfactory.

The results of the four samples are presented in Fig. 3, for both corrections. The behavior of the residual stress profile was characterized by compressive stresses in the region of the weld (melted zone [MZ] and heat affected zone [HAZ]) and tensile stresses in the adjacent areas. This stress behavior is normally found on the external surface of welded pipes in butt joints.

In thin walled pipes, the cooling of the weld bead caused a contraction around the pipe, generating forces in the circumferential direction, an effect similar to a tourniquet around the pipe (Law et al., 2006; Brickstad and Josefson, 1998). The ASME XI code (ASME Section XI, 1986) assumes that the axial residual tensions vary linearly through the thickness and that on the internal surface of small diameter pipes the axial residual stresses are traction, with the same magnitude of the flow limit. Therefore, high levels of compressive residual stresses in the weld zone could represent a critical condition, since on the internal surface high levels of tensile stress would be developed, which, when in contact with a corrosive fluid can

Table 4 – Welding parameters

Test sample	Pass	Current (A)	Voltage (V)	Weld velocity (cm/min)	Weld heat input (kJ/cm)
A1	Root	98.2	10.9	3.9	10.6
	Filler	102.3	11.2	3.2	13.8
	Finishing	101.9	11.1	3.1	14.5
A2	Root	103.1	11.0	3.4	12.9
	Filler	105.5	11.3	3.2	14.7
	Finishing	104.2	11.2	3.1	14.8
A3	Root	102.1	10.9	3.6	12.2
	Filler	105.3	11.3	3.2	14.3
	Finishing	104.9	11.6	3.2	15.0
A4	Root	98.3	10.5	3.9	10.3
	Filler	105.1	11.3	3.3	14.2
	Finishing	105	11.5	3.2	14.7

produce stress corrosion cracking problems (Law et al., 2006; Brickstad and Josefson, 1998).

It should be noted that there is a significant difference in the stress values between the right and left side of the HAZ adjacent to the weld bead (Fig. 3). On the left side, the highest stress levels are noted in the joint and on the right side the stress values are less than −100 MPa, except for sample A4 that presents a very distinct behavior. Also it can be noted that three of the four curves (A1–A3) shown here become tensile around $X = -15$ mm. On the right side, there is a similar behavior between the A1 and A3 sample curves that become tensile when $X = 20$.

In general, the residual stress profiles for the samples analyzed were similar from the point of view that the compressive residual stresses were localized in the weld region (MZ and HAZ) and the tensile residual stresses further from the bead while the maximum stress in the HAZ was adjacent to the weld bead. However, from the point of view of the extension of regions under tension and under compression, and the degree of the maximum stress, the behavior was very distinct. The samples A1 and A3 presented very similar stress profiles,

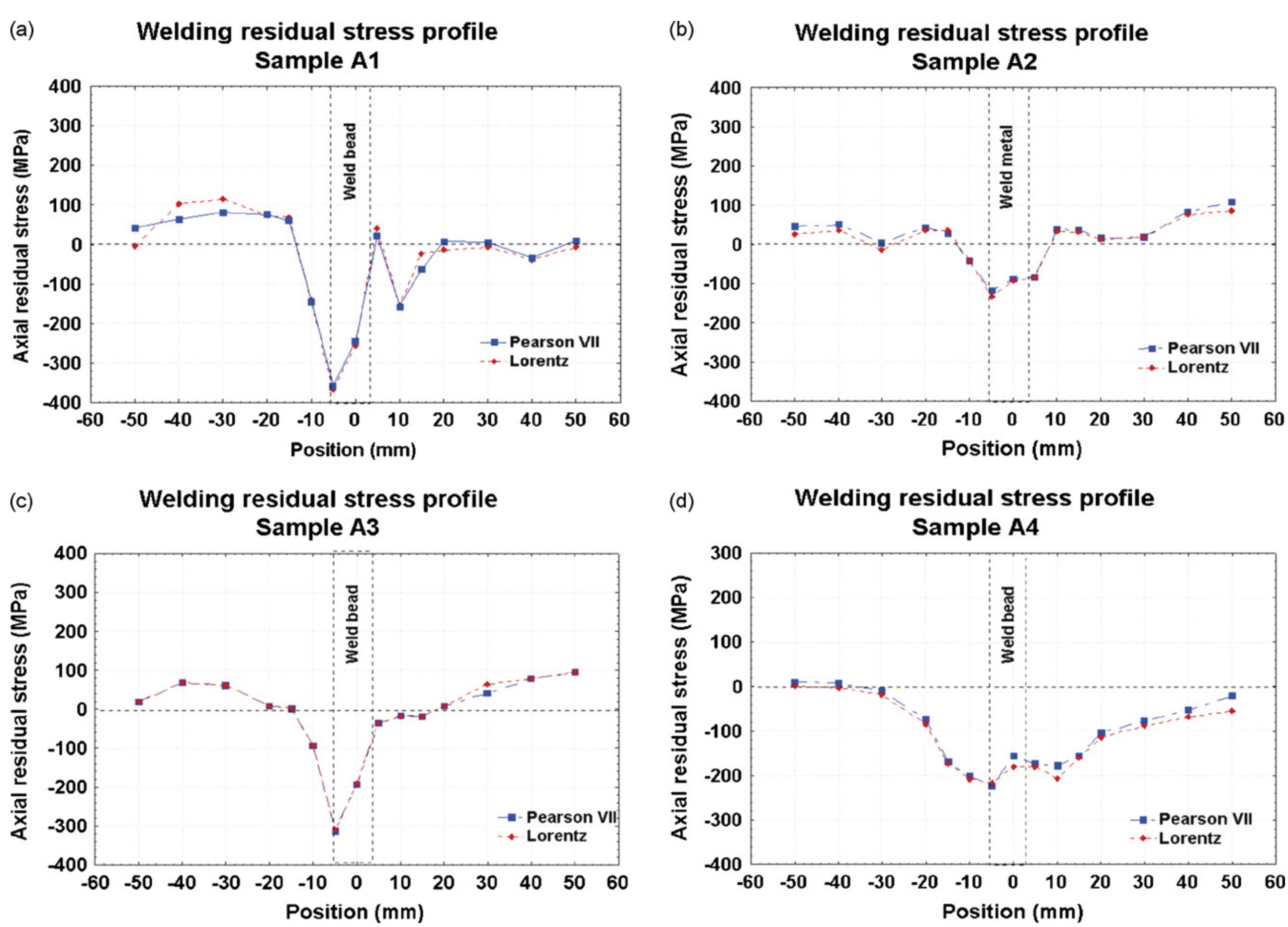

Fig. 3 – Profile of residual stresses in samples: (a) A1, (b) A2, (c) A3 and (d) A4.

showing very similar values for the extension zone under tension and the maximum residual stress. While the behavior of the A2 and A4 sample stress profiles was very particular with completely different maximum residual stress and extension of regions under compression.

This significant change in the behavior of residual stresses can, in this case, be attributed to the fact that the welding was carried out manually and perhaps more importantly to the deliberate choice of welding parameters that led to an especially critical condition, in which the thermal contribution was high and the operational conditions for the welder were not appropriate. However, it must be pointed out that the parameters used in this work are within the established range of conventional procedures for pipe welding.

This reveals an instability in the process of generating residual stresses, which inclusively makes it difficult to establish the relation between the thermal contribution of the weld and the residual stress level. This is because, during welding with a low current level, the weld velocity has to be much slower to ensure the correct filling of the joint, resulting in a high thermal contribution. These conditions were reported by the welder, who considers them more tiring and with more difficulty to control the weld pool, especially at the root and the finish pass.

Besides the welding parameters, various factors such as the geometry of the joint, number of passes, the quantity of weld metal deposited and even the dimensions of the pipes evaluated could act directly on the residual stress behaviors, thus generating serious difficulties to analyze the results and establish some direct relation between the variables and residual stress behaviors.

So it could be said that residual stress behavior and uniformity of the profiles along the manual weld joint could be directly related to better control of the arc and more appropriate operational conditions for the welder, which could be improved by correct adjustments of weld parameters.

However, the interference of so many variables brings certain difficulties in the interpretation of the results and making it impossible to reach more specific conclusions, even though a relevant contribution can be pointed out that in manual welding the adequate choice of the weld parameters can bring about a better stress profile behavior that is allied to greater comfort and control for the welder.

4. Conclusions

Based on the experimental results presented on the residual stress profile in welded pipes by the manual GTAW process and measured by X-ray diffraction, it is possible to conclude that the profile of residual stresses in manual welds can present significant variations causing non-uniformity of profiles. For apparently similar welding conditions the maximum stress can reach values as high as the yield strength, or much lower. Although it is not possible to conclude which variables have the most distinct effect on residual stresses, a part of this effect can be attributed to the adequate choice of weld parameters, which can bring about better stress profile behavior, due to greater comfort and control on part of the welder.

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