Original Article

Residual stress evaluation in API 5L X65 girth welded pipes joined by friction welding and gas tungsten arc welding

Carlos Alexandre Pereira de Moraes a, Mariane Chludzinski b,*, Rafael Menezes Nunes a, Guilherme Vieira Braga Lemos a, c, Afonso Reguly a

a Laboratório de Metalurgia Física (LAMEF), Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e de Materiais (PPGE3M), Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
b Department of Materials Science and Metallurgical Engineering and Inorganic Chemistry, LABCYP, University of Cádiz, Faculty of Engineering, University of Cádiz, Av. Universidad de Cádiz 10, E-11519 Puerto Real – Cádiz, Spain
c Universidade Regional Integrada (URI), Erechim, Brazil

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A B S T R A C T

The present study compared the residual stress states in friction welded pipes of API 5L X65 to those achieved by gas tungsten arc welding (GTAW). X-ray diffraction (XRD) was used to assess residual stresses. In addition, microstructural and microhardness were analyzed for both welding processes. As expected, results showed that each welding method led to different residual stress states. The friction technology led to coarser microstructure, increased microhardness and lower residual stress states at the weld centreline. On the other hand, fusion welding was responsible for higher heterogeneity microhardness at the weld centerline, greater residual stress distributions and porosity formation in the joint cross section.

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1. Introduction

Welding processes are widely used in various industrial sectors, especially in the oil and gas industry [1]. In general, pipeline joining is produced by conventional fusion welding process. Among the several methods available, the gas tungsten arc welding (henceforth, GTAW) process is one of the most frequently used for its ability to promote high quality joints. To achieve high thicknesses, financial aspects need to be considered due to equipment costs and consumables as well as the productivity that may be relatively low [2]. These challenges have prompted the development of alternative welding methods such as solid-state joining process, also known as friction welding. The production of quality joints at relatively low temperatures and fast welding speeds makes these friction methods increasingly attractive for API steels.

Some studies have reported pipes joined by friction welding with a rotating ring, a process typically referred to as Friex [3–5]. In this method, a ring is placed between two pipes and
it is further rotated. The pipes are then axial pressed against the ring until a given force is reached. The friction produced thus generates the necessary heat to plasticize the materials and produce a sound weld without reaching the melting point.

In other words, a process of a solid state nature is achieved (Fig. 1). It has been recognized that friction welding with a rotating ring is a process similar to radial friction welding [6,7]. Therefore, numerous advantages can also be obtained such as low distortion, absence of liquid phase and porosity, no solidification cracking and hydrogen embrittlement, among others [8–11]. The extent literature also claims that other friction based process such as Friction Stir Welding (FSW) might be an alternative to help lower costs in pipeline welding projects [12]. It is therefore expected that interest in high quality of welding methods to API steels will continue to rise.

API 5L and supermartensitic stainless steel pipes have been reported to be joined by friction welding [13–15]. Faes et al. evaluated different pipeline steels such as API 5L X42, X52 and X70 with relatively small thickness (from 3 to 5 in. in diameter) [3–5]. Other studies have involved a welding machine suitable to higher diameters (from 8 to 16 in. for API 5L X46 as well as Duplex Stainless Steel (SAF 2205)) [16,17]. Moreover, the forging force effect was also investigated in API 5L X42 pipeline with a diameter of 4 in. [3]. However, their findings showed that there was no significant influence of the forging force on the weld mechanical properties and microstructural features. As far as optimization of the process conditions, the ring heat affected zone (HAZ) microstructure was evaluated and found to consist of fine-grained ferrite, pearlite and small amounts of bainitic. In addition, in the pipe HAZ microstructure fine-grained ferrite and pearlite was observed [4].

Several factors can affect the pipeline weld structural integrity and, therefore, an understanding of the microstructure, mechanical properties, and residual stress states must be achieved. A rarely-studied issue in pipeline joining is the residual stresses distribution. However, it has been broadly established that the residual stress states can be beneficial or detrimental to fatigue properties. In this context, the residual tensile stresses found in welded joints can lead to a higher effective stress and, consequently, negatively affect the fatigue life. Still, compressive residual stresses are usually recognized to decrease the resulting stress and may be beneficial to fatigue [18]. Both solid state and fusion welding generate residual stress states due to non-uniform temperature gradients and/or plastic deformations and the resulting microstructural changes. These would affect the material properties. In this sense, the residual stresses in the welds produced by friction based process such as FSW have been widely reported [19–24]. Finally, residual stresses in welded pipes have not yet been analyzed in detail for the welding process selected here. Therefore, the present work aims to evaluate the residual stress states in API 5L X65 girth welded pipes joined by two different methods: friction welding and the GTAW process.

2. Materials and methods

The welded pipes considered in the current study were made of API 5L X65 steel with an outer diameter of 219 mm and a wall thickness of 22.5 mm. The base material chemical composition is presented in Table 1. The pipe was made by Mannesmann process, which is a process of making seamless pipes from metal billets by piercing.

The friction weld was produced in the MASF 1500 equipment [16]. The intermediated ring was made with the same pipe material. The rotation speed applied to the ring was 500 rpm, axial and forge forces were 420 kN and the welding time was 280 s. No cooling system was considered.

GTAW was also carried out with a filler rod made of ER70S of 3.2 mm. The filler chemical composition is provided in Table 1. Standard V-butt configurations (single V-groove having a root gap of 2 mm, land size of 1 mm, and an angle of 60°) were adopted on the base material before welding. The fusion welding parameters adopted were arc distance of 1.7 mm, argon flow of 9.0 l/min, welding current of 40 A and welding speed of 13.5 cm/min. Multi-pass welding was made with a temperature between the passes of around 200°C. The welds were subsequently air cooled.

The microstructural analysis of the joints was performed by optical microscopy (OM). Basic metallography procedures were adopted and the samples were then etched with a 5% Nital reagent. Vickers microhardness profiles were set at a distance of 0.5 from the top surface of the joint.

The evaluation of residual stresses of the welded API 5L X65 pipes joined by different welding methods (friction and GTAW) was performed using a GE-Seifert-Charon-M X-ray diffractometer (research edition) with Bragg-Brentano geometry and an X-ray tube with Cr-Kα radiation. The voltage and current applied to the X-ray tube were 30 kV and 45 mA, respectively. Both welding processes resulted in welds that needed surface finishing. To that end, the samples were cut by

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<th>Table 1 – Chemical composition (wt.%)</th>
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<td>Material</td>
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electrical discharge machining, a method that tends to do not cause significant changes in the residual stress distributions. A diffracted beam was used from a collimator with a 2 mm primary aperture and a 20° GE-Meteor-1D linear detector. Evaluation of the residual stresses considered the sin 2θ method. The diffraction peaks in the direction (211) at 2θ = 156.08° were evaluated. The 2θ measuring range was 147°–166° in steps of 0.1° with measurement times of 20 s for each step. The standard deviation of the residual stress measurements is derived from X-ray deviations of the diffraction line positions in 11 different angular positions for the calculated regression line. Finally, for the calculation of the residual stresses, values of the elastic constants \( \frac{1}{2} \) of 5.80 × 10⁻⁶ MPa⁻¹ and 1.27 × 10⁻⁶ MPa⁻¹ were used respectively, with a modulus of elasticity of 220 GPa and Poisson’s ratio of 0.28 [25].

3. Results and discussion

3.1. Weld macrostructure

Fig. 2 presents a cross section macrograph of the friction welded pipe. As expected, the microstructure of the parent material was transformed into variable microstructures according to different regions. These resulting microstructures are related to the material flow, severe plastic deformation and thermal cycle imposed on the API steel. Similar to other friction processes, the regions can be divided into base material (A) (characterized as the pipe material that was not exposed to the welding process), the heat affected zone (HAZ) (B), interface of the pipe and ring material (C) and the ring zone (D), which can also be characterized as the thermo-mechanically affected zone (TMAZ). The microstructural features present at the base metal, HAZ and weld interface were evaluated in Figs. 4 and 5.

Concerning the fusion welded pipe, Fig. 3 shows the cross section macrograph of the GTAW process. In this context, the solidification macrostructure of multipass welding with depositing filler metal is apparent. The regions A and B selected here were later analyzed with respect to the microstructure (Figs. 6 and 7). Although the surface appearance was relatively adequate, some dispersed porosities were found. The amount of porosity is acceptable according to API 1104 standard [26], however this may exert an influence in the fatigue properties.

3.2. Weld microstructure

The microstructural features were classified with respect to both welding processes according to the guidelines proposed by IIW [27]. As can be seen, different joining processes achieved a particular microstructure. Because GTAW usually involves higher temperatures, its corresponding microstructures are formed according to the specific thermal cycle and heat input reached. Therefore, the multipass fusion welding
Fig. 4 – In (a) the base material with irregular and polygonal ferrite, FC, FS(NA) and FS(A). In (b) the HAZ with PF and FC microstructures.

Fig. 5 – Interface zone (a) with FS(NA), PF(G), PF(I), AF microstructures. In the center of the ring (b) PF, FS(NA) and AF microstructures.

Fig. 6 – Fusion zone with columnar grains (a) and network of AF and FS(A) microstructures (b).

Fig. 7 – HAZ with fine PF, FC and constituent M-A (a) and porosity of the middle of the FZ (b).

presents a solidified structure. On the other hand, friction welding is a relatively fast joining process which occurs in a solid state manner and is often used due to the possibility of achieving lower distortion and residual stress, enhanced mechanical and corrosion properties.

The original pipe material (Fig. 4a) is composed of complex microstructural constituents such as irregular and polygonal ferrite, ferrite carbide aggregate (FC), ferrite with aligned second phase (FS(A)) and ferrite with non-aligned second phase (FS(NA)). The presence of dispersed fine A-M constituents (retained austenite + martensite) characterizes a mixed microstructure.

The friction weld microstructure evaluation is shown in Figs. 4 and 5. The HAZ region (indicated as region B)
displayed a polygonal ferrite (PF) matrix and dispersed FC microstructure. Fig. 5a exhibited the pipe interface and the ring material (region C) with coarser microstructures where high amounts of FS(NA), grain boundary ferrite (PF(I)), polygonal ferrite intergranular (PF(I)), acicular ferrite (AF) and FC were found. As the ring material was rotated during the weld, it was probably subjected to compressive stresses by the pipes as well as substantially exposed to thermomechanical effects from friction welding. The microstructure found at the weld centerline of the ring (region D) exhibited mainly PF, AF, FS(NA) and FC (Fig. 5b).

Based on the metallography presented above, it can be assumed that the friction welding process affected the base material microstructure and, as a result, the microstructures appeared to be coarser. Here, upon approaching the higher heat and deformation regions involved, the predominance of PF and FC was observed. The region that corresponds to the ring zone displayed coarser microstructures consisting chiefly of PF.

Unsurprisingly, the GTAW process produced distinct microstructural features in comparison to the friction welding process. The microstructure found near the weld centerline, at the center of the FZ, displayed coarse columnar grains (Fig. 6a). This feature is a recognized characteristic of the weld metal deposited by an arc process. The microstructures observed were a network of AF with FS(A), some PF(I) and grain boundary ferrite PF(G) (Fig. 6b). Due to the thermal cycle achieved, the HAZ region presented polygonal grains of ferrite with FC, as well as constituents M-A (Fig. 7a). In a multiple-pass process, each weld pass may affect the previous one and changes its microstructure. It promotes the grain refining of the coarse-grained fusion zone and, the transformation into acicular ferrite, may also contribute to an enhanced toughness [23]. The porosities were then observed in the middle of the FZ. The Fig. 7b detailed displays this porosity with a crack. In fact, depending on the external stress acting on this welded pipe in a real-world application, the porosities can act as stress concentrators and lead to a catastrophic fracture.

3.3. Microhardness

Figs. 8 and 9 show the microhardness profiles for friction welding and GTAW, respectively. In general, as can be seen in Fig. 8, it is noted that the friction welding was conducive to a more symmetrical microhardness profile along the measurements. There is also a clear hardness increase at the weld centerline (ring material) caused by the local microstructure developed. From the −10 mm to 10 mm distance, at the weld centerline and adjacent areas, the microhardness profile appeared to be more homogenous. Moreover, the decreased microhardness found in the HAZ is consistent with the PF matrix microstructure.

As can be observed in Fig. 9, the GTAW joint presented a more dispersive microhardness profile and therefore certain heterogeneity along the joint cross section. In addition, at −14 mm and 14 mm, the GTAW joint presented the highest microhardness values. However, at the positions around 5 and −10 mm, there was a reduction in these values. This can be linked to the thermal cycle effect of the last filling pass in the surrounding area, which resulted in a microstructural modification. That might also account for the scatter in hardness values observed at the weld centerline.

4. Residual stress distributions

The residual stress and FWHM (full width at half maximum) results for API 5L X65 girth welded pipes are shown in Figs. 10–12.

![Fig. 8 - Microhardness profile of the friction weld.](image1)

![Fig. 9 - Microhardness profile of the GTAW joint.](image2)

![Fig. 10 - Circumferential residual stresses of the friction weld and GTAW joint.](image3)
Circumferential residual stress distributions after friction welding and GTAW process are shown in Fig. 10. For the solid state joining method, it was observed values up to 70 MPa at the weld centerline, while at +10 mm the residual stress increased to +110 MPa. At distances between −5 and −20 mm and +10 and +15 mm from the weld centerline, the residual stresses change the behavior, presenting values of −100 MPa and −70 MPa in the −20 mm and +15 mm positions, respectively. In the direction of the base material, at distances between approximately ±20 and ±25 mm, residual stress distributions were modified with a trend toward values of 70 MPa. On the other hand, the circumferential residual stresses for the GTAW joint presented a tensile behavior at weld centerline. At distances of ±25 mm, a different residual stresses behavior with −300 MPa can be seen.

The comparison between friction weld and GTAW joint shows that in the friction based process, the circumferential residual stresses are more homogeneous. In this regard, the maximum tensile residual stresses take place at different circumferential positions. Low tensile values, at the weld centerline, were also observed. The calculated standard deviation of the circumferential surface residual stresses shows values of 65 MPa for friction weld and 196 MPa for GTAW process. The mean surface residual stress levels for the friction weld as well as GTAW joint was calculated and the values were of −5 MPa −72 MPa, respectively. However, although the circumferential mean value is more compressive for the GTAW process, the maximum tensile residual stress is greater than that of the friction process. As reported by Kumar et al. [28], circumferential stresses are tensile in nature in the welded region and this behavior is consistent with the present results. In addition, a comparison between the macrostructures observed (Figs. 2 and 3) shows that the circumferential tensile stresses seemed to occur in the HAZ or surrounding regions. Moreover, in general, it is clearly noted that the residual stress states in the friction welded pipe are less heterogeneous than those observed in the fusion welded pipe. This is in a good agreement with the microhardness profile, which presented a lower gradient for the weld zone.

Fig. 11 shows the transverse residual stress values for all the welds produced. For the friction weld, it was observed that the residual stress is of +70 MPa at the weld centerline. At the −10 and +10 mm positions, relative to the weld centerline, the residual stresses were found to be −50 MPa and +100 MPa, respectively. Moreover, residual stresses values of −150 MPa (at −20 mm distance) and −80 MPa (at +20 mm distance) were reached. In the direction of the base material, at distances between ±20 to ±40, residual stress of around −190 MPa was found. Transverse residual stresses of the GTAW joint are also shown in Fig. 11. In this context, residual stresses exhibited a tensile behavior with a peak of 300 MPa (at −10 mm distance). For distances between ±15 and ±40 mm, in relation to the weld centerline, there is a residual stress behavior change with a tendency toward compressive values, with residual stress in the order of −400 MPa (at positions ±25 mm).

The comparison between the two welded pipes revealed that residual stresses in the GTAW joint are more tensile at the weld centerline, but on the other hand, they are also compressive in adjacent regions. In the friction method, the residual stress differences over the weld were minimized due to the nature of the process. The calculated standard deviation for the transverse surface residual stresses shows values of 82 MPa for friction welding and 270 MPa for GTAW process. Still, the mean surface residual stress for friction welding and GTAW was calculated and presented values of −54 MPa −110 MPa, respectively. Finally, as can be seen, the residual stress states in the friction weld are more homogeneous. This may be somehow related to the lower microhardness gradient found in the friction joint (at the weld centerline or closest regions).

Fig. 12 shows the circumferential FWHM (full width at half maximum) values from the pipeline welded conditions evaluated. The width of diffraction lines at 50% of the intensity after background correction (FWHM) can be used to estimate the state of materials within the penetration depth of the X-ray radiation. FWHM values were determined by mean values of all ψ-angles for each measurement position. The FWHM data present an indication of plastic deformation. A scatter of about 0.1° seems to be realistic for stress relieved steels, but higher differences are observed in Fig. 12 for both welds. It appears that the fusion/solidification phenomena that occur in the GTAW process generate a more homogeneous FWHM distribution. On the other hand, the friction weld FWHM values were affected by the thermo-mechanical process characteristic.
Residual stress distributions in welded pipes may be very complex and vary according to each process mainly due to the welding heat, deformation imposed and restraint conditions. Hence, residual stress in a weld component needs to be evaluated for each material in relation to different welding processes [29]. In other words, previous manufacturing processes may introduce or modify the material residual stress states prior to the joining process. For example, considering the Mannesmann process used to make the pipes, it is obvious that the plastic deformation manufacturing process may have a certain influence on the pipe residual stress distributions. Therefore, the pipeline joining process would likely change the initial material residual stress states and/or even impose certain residual stresses. From the findings observed in the current study, it is evident that depending on the joining process selected, distinct residual stress distributions and levels will be achieved. Finally, the friction welded pipe exhibited a more homogeneous residual stress state, lower microhardness heterogeneity and a more uniform microstructure at the weld centerline. This suggests an enhanced fatigue life. However, fatigue properties would have to be carefully studied. On the other hand, the fusion welded pipe presented higher residual stress states, microstructural gradient features and microhardness at the weld centerline.

5. Conclusions

The results of the present study presented important differences related to the microstructure, microhardness and residual stress states for each welding process adopted. The findings of the current investigation can be summarized as follow:

- The friction welding process promoted coarser microstructures which may be related to a slow cooling rate. By contrast, the fusion welding process (GTAW) was responsible for porosity formation.
- The friction weld microhardness analysis revealed an enhanced hardness in the welded joint. On the other hand, the GTAW process led to scattering microhardness at the weld centreline.
- The residual stresses evaluation showed that the friction welded pipe achieved a more homogeneous residual stress distribution in comparison to that observed in the fusion welded pipe.

Conflicts of interest

The authors declare no conflicts of interest.

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