Original article

Toughness properties of a friction hydro pillar processed offshore mooring chain steel

Diogo Trento Buzzatti\textsuperscript{a}, Mariane Chludzinki\textsuperscript{b}, Rafael Eugenio dos Santos\textsuperscript{a}, Jonas Trento Buzzatti\textsuperscript{a}, Guilherme Vieira Braga Lemos\textsuperscript{a,}*, Fabiano Mattei\textsuperscript{a}, Ricardo Reppold Marinho\textsuperscript{c}, Marcelo Torres Piza Paes\textsuperscript{c}, Afonso Reguly\textsuperscript{a}

\textsuperscript{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
\textsuperscript{b} Department of Materials Science and Metallurgical Engineering and Inorganic Chemistry, LABCYP, University of Cadiz, Faculty of Engineering, University of Cádiz, Av. Universidad de Cádiz 10, E-11519 Puerto Real - Cádiz, Spain
\textsuperscript{c} Centro de Pesquisa da Petrobras (CENPES), Petróleo Brasileiro S.A., Rio de Janeiro, RJ, Brazil

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A B S T R A C T

In the past few years, solid-state welding has been a great alternative in comparison to the conventional fusion welding technologies. Solid-state welds are usually processed in lower temperatures than the other common fusion joints, tending to avoid problems such as hydrogen embrittlement, brittle microstructures and porosity. Therefore, these advantages can be useful to industrial applications which do not allow fusion welding. Offshore mooring components, which are fabricated under restricted standard requirements to ensure the floating marine integrity, is one of these applications. Thus, defects in links of mooring chains cannot be repaired by traditional welding, resulting in high operational costs. In this context, this study aims to characterize the Friction Hydro-Pillar Processing (FHP) application to a mooring chain steel IACS UR W22 grade R4. The main process parameter studied was an axial force ranging from 30 to 60 kN. The welded joints were evaluated by metallography (macro and microstructure) and microhardness mapping. Furthermore, the toughness properties were assessed by Charpy and Crack Tip Opening Displacement (CTOD) tests, and the fractures were afterwards observed by scanning electron microscopy (SEM). The results showed that an increase in the axial force enhances the Charpy and CTOD values.

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1. Introduction

As part of floating structures, mooring systems are a combination of the long length of chain, rope, and wire. The mooring lines have the primary function to keep the floating structures movements, having to withstand the loads working on the structure as well as to loads acting directly on the mooring components. The mooring line components are exposed to adverse environmental conditions such as low temperatures, sour corrosion fields, and fatigue. Therefore, defects may be generated at the chains surface affecting their service-life. In this sense, if a mooring line failure occurs, the floating structure may lose its stability causing problems to the structures

* Corresponding author.
E-mail: guilherme.lemos@ufrgs.br (G.V. Lemos).
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and environment as well as to human lives and impacting in economic losses [1,2]. The International Association of Classification Societies (IACS) has unified requirements applied to offshore mooring chain with specified mechanical properties of high hardenability Q&T (quench and tempered) for high strength steels used in mooring lines (IACS UR W22) [3]. However, it should be noted that any fusion welding applied to these materials may generate hydrogen induced cracking (HIC) and its resulting problems. Thus, due to this characteristic, repairs and maintenances of mooring chains are forbidden, leading to the chain replacement in case of a defect is encountered (i.e. at flash butt weld) [4]. In addition, these steels may be classified as high strength materials with their chemical composition corresponding to low and medium carbon alloy steels. Moreover, the components manufactured with these steel grades are joined by flash butt welding electrical resistance (FBW) process and heat treated to reach the final mechanical properties requested [5].

In the recent years, much effort on research for friction based welding processes has been made. In such method, in general, the heat is occasioned by friction between two surfaces, with relative motion in contact under load. Hence, the requested plasticity is produced by addition compressive load, and the joints are formed [6]. In this context, the FHPP technology was patented by The Welding Institute (TWI) [7] and developed as a valuable tool for repairing and maintenance. However, this solid-state process has some specific characteristics such as a rotating consumable rod which is thermo-mechanically processed inside of a hole where defects would have taken place. During this process, the axial force is maintained over the rotated rod, and the increase in the friction energy between rod and hole is dissipated as heat. The strength of the rod decreases as the heat increases and the pressure applied by axial force generated hydrostatic forces, plasticising the rod until filling the hole [8]. Finally, the compression force is maintained for achieving suitable mechanical properties.

Sound joints can be obtained by applying a specific combination of welding parameters. In friction welding process, the rotating speed, burn-off, axial and forging force are usually set up. Other parameters such as time, energy, torque, and temperature are a consequence of the process, and they can be used as a comparative performance evaluation. In the FHPP process, it is also important to consider the rod tip and hole geometry as well as the chemical and physical properties of the rod and base materials. Several studies had been carried out to identify the effect of welding parameters on the processed joints. In this sense, investigations recognized that with increasing axial force, the process time is decreased and also heat affected zone (HAZ) size is reduced [6–9]. The increase of rotational speed implies in the rise of energy. Studies of rod tip geometries demonstrated that the flat, conical, and rounded tip forms could be applied [8–11]. Hence, Fig. 1 shows the FHPP process sequence schematically [12].

FHPP joint structural integrity may be related to toughness properties that can be a quantitative representation of how the material is resistant to brittle fracture in the presence of a crack [6]. In this context, the fracture toughness of C-Mn steel processed by FHPP was investigated. From their available findings, it was observed that the weld toughness was lower than that of the base material [6]. Recently, the application of FHPP to duplex stainless steels (UNS S31803) was investigated by mechanical and metallurgical properties [13]. The results indicated that the FHPP duplex joint presented suitable microstructural, corrosion and toughness results according to the specifications requested in the oil and gas industry. Moreover, this friction repair process can be an alternative to underwater welding and restoration of marine structures or undersea oil pipelines [14]. In such cases, special equipment is designed for working in unusual environments,
allowing the repair of high-cost components in their production line.

Another example of FHPP industrial application can be of offshore mooring chain manufacturing, which is composed of successive production steps and intermediate stages of quality inspections. As a reminder, defects repair of the link are not allowed by international codes, and during the inspection, the non-compliance links are scrapped, adding cost to production and reprocessing. Thus, this work aims at investigating the welds produced by FHPP application to a mooring chain steel IACS UR W22 grade R4. In this sense, macro and microstructural features and microhardness mapping were performed. Finally, the toughness properties were evaluated by Charpy and CTOD tests, and the fracture surfaces were analyzed by SEM.

2. Experimental procedure

The material used in this study was IACS UR W22 steel grade R4 supplied by Gerdau SA, which is applied in the manufacturing of mooring chains and accessories. The material was received as bars of 120 mm diameter, and 300 mm length and it was further used to produce the rods and base material (BM). The steel chemical composition can be seen in Table 1. The heat treatments were made in rods and plates, before machining, consisted in austenitizing at 850 °C, quenching and subsequent tempering at 650 °C, 1 h/inch, in agreement with IACS UR W22 [3]. Finally, the parts were air-cooled. The average rod microhardness was 346HV0.3, and for the plates, it was of 331HV0.3.

Meyer [8] showed that the rods and holes geometry have significant influence in the joint results. The geometry used in the current study can be seen in Fig. 2A. The rods were manufactured with 28.6 mm diameter and BM with 25.4 mm thickness where the holes were machined. The welded joints were processed by an MPF 1000 machine which was developed at LAMEF. It has a hydraulic actuator of 1000 kN axial force, an electrical motor of 1500 rpm and displacement sensor with 150 mm of range (Fig. 3B). As can be seen in Table 2, the welding parameters considered three levels of axial force, where the rotational speed and burn-off were kept constant. Post weld heat treatment (PWHT) was immediately executed after welding was ended, which consisted of tempering at 650 °C for 4 h and air cooling.

Micro and macrostructural features were analyzed in the cross-sectioned sample prepared according to standard metallographic procedures. The microstructural observation considered the following regions: BM, heat affected zone (HAZ), and thermomechanical affected zone (TMAZ) regions. Mechanical properties were analyzed regarding microhardness mapping, using HV0.3 (300 g) and 0.3 mm of distance between indentations.

Charpy impact tests were executed at −20 °C according to DNV OS E302. The samples and tests were carried out according to ASTM E 23 [15] with the notch located in the weld interface (Fig. 3). Therefore, six welds were produced to obtain all the Charpy specimens. In this context, two specimens were collected obtained from each weld (F30, F45, and F60 conditions), and a third sample was cut from other weld made with the same parameters.

Besides, the compact tension (CT) specimens of CTOD tests were cut from the weld interface as well as the BM and
Fig. 3 – Positions of Charpy impact specimens (A) and dimensions according to ASTM E 23 [15] (B).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Axial force (kN)</th>
<th>Forging force (kN)</th>
<th>Rotational speed (rpm)</th>
<th>Burn-off (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F30</td>
<td>30</td>
<td>30</td>
<td>1500</td>
<td>7</td>
</tr>
<tr>
<td>F45</td>
<td>45</td>
<td>45</td>
<td>1500</td>
<td>7</td>
</tr>
<tr>
<td>F60</td>
<td>60</td>
<td>60</td>
<td>1500</td>
<td>7</td>
</tr>
</tbody>
</table>

Fig. 4 – CT dimensions as recommended by BS EN ISO 15653 (A). Regions of CTOD specimens (B and C).

Further tested at −20°C. As this process produces weld region with the conical shape, sub-size geometry was used to be able to position the notch at the weld interface. The CT specimens configured with W = 13 mm were chosen (Fig. 4) with the dimensions as suggested by BS EN ISO 15653 [16]. SEM was used for the fracture observation, and the local chemical compositions were verified by Energy Dispersive Spectroscopy (EDS).

3. Results and discussions

3.1. Microstructural features

Figs. 5–7 present the micro and macrostructures of the three process parameters evaluated (F30, F45, and F60, respectively). The weld microstructural features were characterized and defined as: region (1) the rod heat affected zone (HAZ); region (2) the rod thermomechanical affected zone (TMAZ); region (3) the bottom thermomechanical affected zone (TMAZ); regions (4) and (5) lateral and bottom weld interface between rod and BM, respectively.

Defect-free joints were obtained, showing sound weld interfaces between rod TMAZ and BM, these were observed in lateral and bottom interfaces (Figs. 5–7, regions 4 and 5). The macrostructures showed that an increase in the axial force reduced the area of rod affected by the heating and, consequently, the F60 condition displayed narrow welding zones.

In the region 1, the same microstructure was found in all conditions, which was presented to be of tempered martensite (TM). Region 2 displayed a particular microstructure for each joint, where the F30 introduced TM and upper bainite (UB), while F45 showed UB and allotriomorphic ferrite (ATF), and the F60 joint mainly TM. In the regions 3, 4 and 5, the F30 condition microstructure was composed by idiomorphic ferrite (IF) and intergranular Widmanstätten ferrite (WF), whereas the F45 weld has presented mainly upper bainite (UB) and the F60 joint showed lower bainite (LB) as well as retained austenite (RA). In all the welds, dispersed carbides were verified (C). In addition, finer grains were observed in the melting line (WL).

All these modifications observed in the microstructure are related to different conditions of plastic deformation, heat input, and recrystallization degree imposed by FHPP process. The higher was the force applied, the more plastic
3.2. **Hardness mapping**

Figs. 8–10 present the microhardness mapping for each welding condition. It is possible to notice the variation of hardness according to the welding zones, as observed in the macrostructural features. The dimensions of HAZ and TMAZ of the F60 condition were minor than the other welds.

The hardness of the rods TMAZ enhanced as the level of force was increased. The minimum value found was of around 300HV$_{0.3}$ (located in the TMAZ of the F30 condition) and the highest value (approximately 350HV$_{0.3}$) was found in the F60 situation. Therefore, it was caused by increasing the plastic deformation state, welding time reduction and heat input. Furthermore, the tempering promoted by the PWHT occasioned a hardness decrease on the base material, around the welded region on the higher force applied. This softening effect is a consequence of the tempering on the material exposed to the highest deformation level [17].

3.3. **Charpy impact test**

Fig. 11 shows the macrographs of the fracture surfaces and their corresponding Charpy impact results. The F30 condition reached the lower absorbed energy (8 J). On the other hand, the F45 condition presented the intermediate absorbed energy values (ranging from 18 to 28 J). The best result was achieved by the weld produced with F60 condition (44 and 42 J). However, it has to be mentioned that one specimen of F60 condition was rejected because the surface has not advanced through the notch. Fig. 12 presents the average and minimum values compared to the Charpy results for FBW process and the base material (indicated by DNV OS E302 [4] and IACS UR W22 [3]). This comparison is significant since the mooring chains
usually employ this method (FBW) for joining the free extremities of chains [4].

Fig. 13 displays the fracture surface features of the F30 and F45 conditions, respectively. It was possible to observe brittle fracture surface with cleavage and intergranular characteristics (A and B). Besides, non-metallic inclusions with different shapes inside of dimples were also found, as can be seen in (D) and (C). On the other hand, for the F60 condition, the SEM images displayed the mixed fracture behavior with brittle and ductile regions. These ductile regions appeared to be larger than the ones found in the other welds, although cleavage regions surrounded by dimples as well as larger and elongated inclusions were observed in Fig. 14. From these findings, it is evident that the changes in the welding parameters led to modifications in the inclusions size and morphology, and a definite improvement in the energy absorbed by the welds produced with higher axial forces (F60) was noted.

3.4. Fracture toughness

Fig. 15 shows the CTOD values calculated with the maximum load of welds and BM specimens. The measured values indicated that an increase of toughness is associated with increased axial force. The welds corresponding to the F30 and F45 conditions resulted in the lowest main CTOD values (0.015 and 0.020 mm, respectively). Here, the F60 condition also displayed the best performance with the main CTOD of 0.04 mm, which is the closest value of the BM (0.1 mm). Furthermore,
the minimum CTOD measured for F60 represents 40% of the minimum of BM CTOD value.

As can be seen in Fig. 16, the BM fractographs showed a surface with the ductile aspect, which further revealed the presence of fragmented inclusions. Still, elongated inclusions were observed in the direction of the rolling process.

The three welding conditions presented a mixed aspect of brittle and ductile fracture and distinct influence of inclusions size and morphology. The F45 condition was noted as an intermediary behavior of absorbed energy and inclusions and, therefore, these results were not reported here. Thus, the F30 and F60 conditions were displayed here due to the more significant differences between them (Figs. 17 and 18, respectively).

Moreover, the F30 condition presented less incidence of brittle features and inclusions like thin films (Fig. 17(D)) which are likely a consequence of higher peak temperatures and longer welding time, leading to their dissolution and even melting [18]. On the other hand, the inclusions observed in the F60 condition were elongated and with a spherical morphology similar to the ones seen in BM. The chemical compositions of these inclusions were verified by EDS analysis, which confirmed the presence of MnS.

As indicated, the FHPP process has not led to enhanced toughness in the weld interface. In this sense, all the fractures revealed inclusions in this region. The influence of welding conditions was reflected in distinct morphologies
of these inclusions, which were caused by different plastic deformation levels and temperatures reached by them. The specimen properties response for each welding condition can be related to the inclusions characteristics, and according to previous works [5,19], these inclusions influence the fracture toughness. Therefore, inclusions morphologies like thin films were observed in F30 welds, where the larger contact surface between inclusions and matrix generated a preferred way to the propagation of cracks. Furthermore, this inclusions-shape adversely affected the F30 weld toughness properties and occasioned the lowest CTOD and Charpy values. On the other hand, the inclusions verified in F60 condition were better for its toughness results.

Post-tempering hardness mapping (Figs. 8–10) revealed that the increase in the axial force resulted in highest hardness values on the rod, as observed in F60 weld. The metallography showed diversified microstructural features in each welded
Fig. 13 – SEM fractographs showing brittle fracture regions with cleavage and intergranular aspect of the F30 (A) and F45 (B) specimens. In (C) and (D) inclusions with different format inside of dimples (arrows).

Fig. 14 – SEM fractographs of F60 specimens showing regions with brittle and ductile aspect (A) and (B). In (C) and (D) elongated inclusions (arrows).
joint and, especially in F60 condition, it was mostly composed of LB. The increment of axial force decreases the welding time and the peak temperature achieved, so this microstructure can be associated with the short welding thermal cycle and lower temperature providing the situation for generating LB [20]. Moreover, the greater plastic deformation produced in F60 condition also allowed to an increase in the dynamic recrystallization rate and probably lowered its prior austenite grain size, providing a higher density of sites to LB formation [21,22]. Finally, it is also known that the LB presence is
recommended for enhanced toughness due to its ability to hinder the propagation of cracks [23–26], a fact here reflected in increased F60 toughness values.

The IACS UR W22 standard [3] suggests that the CTOD values for FBW process in the weld interface shall meet the minimum of 0.16 mm (65% of the BM) in the stud less link and 0.12 mm (50% of the BM) in stud link of R4 steel grade. However, these values were obtained from bend specimens with a dimension of W = 80 mm. In the present study, the minimum measured CTOD values were of 0.09 mm (BM) and 0.03 mm for the F60 condition (33% of the BM). In this sense, these results obtained with CT specimens (W = 13 mm) showed particular properties of WL with more conservative values than the ones achieved by bend specimens. This difference in the results is suggested to be a consequence of the specimen’s size and geometry, and imperfections [27]. The CT specimen with small cross section was chosen as a possibility to evaluate the toughness of WL, even though the CT geometry has higher constraint at the crack tip, and the geometry and size of inclusions and defects show more effect on small specimens, both likely lead to lowest fractures toughness. In this context, the methods of fracture test published by some institutions and standards have had showed the size and geometry of CTOD specimens with propose to avoid the designing of over-dimensioned structures [27].

A recent study [28] of offshore mooring steel joint produced by FBW has revealed similar outcomes. A single link of the R4S steel grade was extracted from an offshore mooring chain after years of service life, and it was analyzed by toughness properties. The results of CTOD tests performed using CT specimen with W = 25 mm showed reduced values, 0.17 mm of BM and 0.06 mm of WL (35% of BM). As mentioned, the recommended CTOD values for the R4S grade [3], are a minimum of 0.26 mm for BM and of 0.17 mm for WL (65% of BM). The difference in the values was associated with the sample’s characteristics, CT specimen (W = 25 mm) versus bend specimen (W = 80 mm) [3], besides the service life effect.

In general, the results of this study indicate that FHPP technology has great potential for repairing structures in the offshore industrial field. However, further investigations shall be carried out to evaluate the hydrogen effects, other welding process parameters such as even higher forces, fatigue properties, and full-scale tests in the FHPP joints.

4. Conclusions

This work aimed to evaluate an offshore mooring steel IACS RU W22 grade R4 processed by FHPP in three different welding conditions. The findings of the current study are summarized as follows:

- Defect-free welds were obtained, and an increase in the axial force produced narrow welding zones. Furthermore, the F60 condition promoted lower bainite microstructures, which were beneficial for its toughness properties.
- The microhardness mapping presented a distinct hardness distribution for each weld condition. Also, maximum microhardness of 350HV0.3 was observed in the F60 condition.
As the axial force increased, the Charpy and CTOD tests presented higher values. The F60 condition reached an average absorbed value of 43 J in Charpy and a minimum of 0.03 mm in CTOD, both results were 50% superior of F45 and F30 conditions. Therefore, the best toughness properties occurred with higher axial forces (60 KN).

The presence of inclusions (MnS) affected the Charpy and CTOD tests results. Therefore, the fracture behavior of each weld condition had a specific inclusions morphology and dispersion. Furthermore, these inclusions seemed to be originated from the BM, but their presence in the weld interface can be a consequence of FHPP application.

Conflicts of interest

The authors declare no conflicts of interest.

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References

[19] Chludzinski M. Avaliação da Tenacidade à Fratura em Juntas Soldadas por Fricção com Pino Consumível. Porto Alegre, RS, Brazil: Federal University of Rio Grande do Sul (UFRGS); Post-graduation Program in Mining, Metallurgical and Materials Engineering (PPGEM3); 2013 [PhD thesis].

[28] Santos RE. Caracterização Mecânica e Metalúrgica de um Elo de Corrente de Amarrar em Aço para Aplicação Naval na Indústria do Petróleo. Porto Alegre, RS, Brazil: Federal University of Rio Grande do Sul (UFRGS); Post-graduation Program in Mining, Metallurgical and Materials Engineering (PPGE3M); 2017 [Master dissertation].