The Journal of Adhesion

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gadh20

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To cite this article: M.J. Oliveira, F.F. Enne, J.M.L. Reis & H.S. da Costa Mattos (2021): Alternative surface treatments for the repair of through-wall corrosion damage in metallic pipes with bonded plates, The Journal of Adhesion, DOI: 10.1080/00218464.2021.1986395

To link to this article: https://doi.org/10.1080/00218464.2021.1986395

Published online: 06 Oct 2021.

THE JOURNAL OF ADHESION
https://doi.org/10.1080/00218464.2021.1986395

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Alternative surface treatments for the repair of through-wall corrosion damage in metallic pipes with bonded plates

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ABSTRACT

Through-wall corrosion damage in pipelines can be repaired using a bonded metallic patch. Several parameters influence the repair performance, such as the surface preparation. Offshore oil platforms are restricted areas, and sparkling derived from surface preparation can have drastic consequences. Additionally, an industrial climber is required to access some areas that are difficult in the repairing process. In this work, the influence of alternative, easy to apply in the field, surface preparation methods on the burst pressure in pipes with defects repaired by a bonded metallic patch is investigated. Three different methods were considered: treatment with an abrasive-free rotating bristle machine and the application of a special primer directly on the oxidized surface without any additional mechanical treatment; and wet abrasive blasting. Initially, to verify the difference between these different systems, bonded single-lap joints are analyzed and then, hydrostatic tests in 6″ diameter specimens with a circular hole of 1″. Although the use of a rotating bristle machine gives the best roughness and strength results, the other alternative methods are less time-consuming, assure reasonable strength, and are easier to be used in the field.

ARTICLE HISTORY

Received 19 Aug 2021
Revised 11 Set 2021
Accepted 21 Set 2021

KEYWORDS

Metallic pipes; through wall corrosion damage; bonded metallic patches; in field surface preparation

1. Introduction

One of the major challenges in the industrial environment is the maintenance of pipes and equipment that suffer wear and tear by corrosive processes. Pipes are essential for transporting liquids and gases in many industrial processes, and their failure can compromise the entire system, causing huge losses.[1] Even with the gradual growth in the number of engineering solutions, the poor maintenance pipes and equipment can cause great damage, lowering the rate and raising the cost of production .[2]

Periodically, production is shut down, whether scheduled or not, for maintenance, such as temporary repairs or replacement of defective equipment sections .[2,3]

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The conventional mechanisms employed, such as hot work, require a complete interruption of the system, since it is necessary to drain the line and completely remove the hydrocarbons and other contaminants present on the substrate surface.[2] On the other hand, the use of bonded joints has gradually grown for the maintenance of pipes and equipment, as well as other types of applications in industries (automotive, aerospace, among others), successfully replacing conventional means of repair .[4–7]

When compared with conventional processes (welding, riveting, and bolting), these joints have more uniform distribution of stresses, do not require heat intake, and have good fatigue and shear resistance, excellent weight/resistance ratio, good weather resistance, and simplicity of application. It is considered a totally cold process and can be performed with the presence of contaminants and, in some cases, while in operation, without the need for loss of production.[8,9]

Several studies have been carried out to better understand the processes, mechanical requirements, and variables involved when using bonded joints.[10–13] Fundamentally, the joints mechanical behavior depends on adhesion at the interface between the substrate and the adhesive, so surface treatment prior to bonding is often used to improve the bond strength .[13–16]

Da Silva et al.[13] conducted experimental studies in single-lap joints (SLJ) to investigate the effect of three surface treatments (one mechanical and two chemical conversion coatings) on joint strength. For the three adhesives used, the authors concluded that the surface treatments did not result in increased joint strength. Spaggiari and Dragoni[14] studied joints with aluminum and steel substrates bonded with epoxy and acrylic adhesives using four common surface treatments and concluded that although knurling caused the highest surface roughness, the shear strength of joints was not the best. Similar to Ref. [14] Rudawska[15] analyzed adhesive joint strength of steel sheets whose surfaces were subjected to various methods of mechanical pretreatment.

They concluded that surface treatment influences adhesive joint strength, where lapping displayed the highest strength and the joint with no treatment, just degreasing, the lowest. The influence of grooves in the preparation of bonded surfaces was studied by Da Silva .[16] The results showed that the surface pattern had an influence on the joint's mechanical strength, and this effect was more pronounced on test specimens without surface treatment. The grooved specimens showed mixed (cohesive and adhesive) ruptures, while those without grooves showed adhesive ruptures (at the interface).

This paper investigates surface adhesion through mechanical and non-mechanical treatment of metallic adherends and pipelines with defects repaired by patching (curved plate), with the goal of ensuring the adhesive bond will carry the load until failure and therefore prevent leakage. Through-wall corrosion damage in pipelines can be repaired using a bonded metallic patch. Several parameters influence the repair performance, such as the surface preparation. The surface treatment is carried out in field. It is well known that the bonding conditions are very different if the repair is taking place in an indoor shop setting or outdoors in the field. One of the main shortcomings for the application of such a kind of repair in offshore oil platforms is the restriction to surface treatments that can cause sparking and the difficulty in access to some areas requiring an industrial climber. In this work, the influence of surface preparation methods on the burst pressure in pipes with defects repaired by a bonded metallic patch is investigated. The focus is to analyze alternative surface treatments that are easy to be applied in the field. Three different methods were considered: treatment with an abrasive-free rotating bristle machine; the application of a special primer directly on the oxidized surface without any additional mechanical treatment; and wet abrasive blasting. Initially, to verify the difference between these different systems, bonded single-lap joints are analyzed and then, hydrostatic tests in 6" diameter specimens with a circular hole of 1". Although the use of a rotating bristle machine gives the best roughness and strength results, the other alternative methods are less time-consuming, assure reasonable strength, and are easier to be used in the field.

2. Experimental program

2.1. Materials and methods

Three kinds of surface treatments suggested for use in oil platforms are Bristle blaster machine (BBM), Wet abrasive blasting (WAB), and Oxidized surface primer (OSP).

The first step to analyze the influence of the suggested surface treatments in metallic adhesive bonding was to test single-lap joints (SLJ), in accordance with the parameters of ASTM D 1002–10.[17] The second step was to perform hydrostatic tests in metallic pipes with a through-wall defect repaired with bonded patches.

The SLJs were manufactured with ASTM A1020 steel as adherend and bonded with Syntho-SubseaLV® Epoxy. It is a two-part blend of liquid epoxy, including Kevlar, polymer, and aliphatic polyamine curing agents, which are able to repel water from wet surfaces in order to form a permanent bond. The formulation is solvent-free to ensure safety and maximum technical performance. This adhesive is used to restore the geometry of corroded pipelines and ensure an even load transfer in composite repair applications. The properties of the adhesive provided by the manufacturer Nepture Research Inc, (NRI), USA, are presented in Table 1. This epoxy system is conceived to repair localized through-thickness corrosion defects in produced water pipelines.

Table 1. Properties of the adhesive.

Property	Syntho-Subsea®LV Epoxy
Flexural strength (MPa)	31.4
Tensile strength (MPa)	41
Compressive strength (MPa)	50.9
Flexural modulus (MPa)	980
Shear strength (MPa)	12.3
Abrasion resistance	34 mg/1000 cy

The SLJs had an overlap of 12.5 mm and a width of 25 mm. The adherend thickness was 1.6 mm. The SLJs were manufactured individually in a mold, and the adhesive thickness was controlled by 2 mm packing shims. The adhesive thickness was 0.4 mm. Five specimens per type of surface preparation were tested. The SLJ tests were carried out with a Shimadzu AGX-100 universal testing machine with a test speed of 1.3 mm/min.

The patch repair was performed in pipe specimens made from ASTM A106 Gr. B carbon steel, with a nominal diameter of 4”, schedule 40, and an axial length of 1200 mm. The “defect” is a 1” diameter hole. A ¼” thick, 100 mm x 100 mm steel plate was bonded over the hole. The adhesive was the same used to bond the SLJs. The plate has the same curvature than the pipe. The pipe and plate can be seen in Figure 1. The thickness used for the adhesive was 3 mm, and it was applied to the two bonding surfaces, i.e., pipe and curved plate.

To access the effectiveness of the patch repair in the surface-treated pipes, hydrostatic testing was performed in 9 specimens, 3 per type of surface preparation, according to ASTM 1599–18, [18] which requires an increase of 1 bar per second pressure ramp. The tests were performed until leakage occurred (this pressure being considered the rupture pressure). The acceptance criterion was no visible leakage, according to ISO 24817–17 .[19] The hydrostatic testing machine has a maximum test capacity of 15,000 bar. All specimens were filled with water at room temperature. The necessary caution was taken to prevent air particles from being mixed with the water before pressurization.

2.2. Surface treatment

Three different surface preparation methods were used to perform this study. The first was to use a bristle blaster machine (BBM) without employment of abrasive (which is the most usual procedure so far). The second one was a wet abrasive blasting and, finally, the direct application of a primer on the surface that already presented oxidation, without any machining or other mechanical procedure.

Figure 1. Curved plate and pipe used in the test (a) and curved plate bonded to the pipe (b).

2.2.1. Bristle blaster machine (BBM)

To perform the surface preparation without any abrasive, a device commercially known as Monti® was used. Initially, this equipment was developed for carbon steel surface treatment in the automotive industry. Subsequently, the technology was improved to treat carbon steel within the factory with the Bristle Blaster® machine.

Surface preparation is carried out with this device in a fully manual process. The machine is responsible for cleaning the region, that is, removing any existing coating, impurities, and other contaminants, making the metal surface almost white, and producing a roughness profile between 40 μm and 120 μm for better anchoring of the polymer to the substrate. The treatment is the result of bristling without abrasive, having an intelligent blasting system with bristles that impact the surface through kinetic force after receiving an impulse from the accelerator bar.

2.2.2. Wet abrasive blasting (WAB)

The second surface treatment method was wet abrasive blasting, with a machine called Ecorestauradora®. It was developed to perform cleaning and preparation of surfaces using a low-pressure jet of water containing inert abrasives that do not harm the environment. This type of blasting can be applied to any substrate (wood, fiberglass, carbon steel, stainless steel, plastic, glass, among others). It is used for the removal of paints and other contaminants, inspection of surfaces and welds, preparation of surfaces, cleaning of tanks, removal of rust and fouling, and maintenance in general, in civil construction and offshore and onshore oil and gas operations. One of the main advantages of this equipment is safety of the operator, since the wet blasting works at an average pressure of 125 psi, while other hydrojet equipment used in the oil industry works with pressures up to 40.000 psi.

The machine mixes water/abrasive, with the proportions pre-defined by the operator. After cleaning through blasting with the machine, washing is performed to remove the abrasive and other contaminants from the surface and finally drying is performed with the same device, to avoiding long exposure of the metal to water.

In this surface treatment method, blasting occurred for about 30 seconds on each test specimen. The distance from the nozzle of the equipment to the surface was 50 centimeters, and the blasting angle was 45º. Glass sphere particles with a diameter of 50 μm were used as abrasive. These are inert and have no ferrous components that could oxidize in contact with water. Both the joints and tubes were blasted. The pressure used in the blasting was 125 psi.

2.2.3. Oxidized surface primer (OSP)

To perform the non-mechanical surface treatment, a primer called Rust Grip® was used. It is a rigid monocomponent polyurethane coating that cures by absorption of atmospheric moisture, being highly resistant to abrasion and impact. This material can be used as a primer or as single-layer coating and can be applied directly on pre-washed and fully dried surfaces, surfaces with rust and surfaces with firmly adhered commercial paints. In most cases, conventional blasting to obtain white metal is not necessary, as this primer is indicated for surfaces that have oxidation. Thus, this primer would facilitate the adhesion of the adhesive to the metal substrate without the need for mechanical adhesion. The idea of using this material was to simulate the condition where it is not possible to perform any form of mechanical treatment, such as in highly explosive atmospheres (Zone 0). Since the manufacturer reported it forms a good connection between the oxidized layer and the product, the joints were prepared in such a way as to present a considerable degree of oxidation. No mechanical treatment was performed before the surface oxidation.

Before applying the primer, acetone was used on the oxidized substrate to remove any type of contaminant. Then, two coats of primer were applied using a roller. The application interval was about 30 minutes. The relative humidity was less than 85%, as recommended by the manufacturer.

2.3. Surface analysis

2.3.1. Surface analysis on SLJ adherends

After surface preparation, surface analysis was carried out to identify the changes introduced to the steel substrate by the different pretreatments. A Talysurf® CCI MP-Lite (Taylor Hobson®) profilometer was used to perform the analysis.

Table 2 displays the mean roughness and standard deviations measured by the three surface treatment methods performed in the SLJ steel adherends, considering roughness St and Sa, respectively. St is the maximum height from the highest point to the deepest valley of the measured surface, and Sa (arithmetic mean height of a surface) expresses the difference (in absolute value) in the height of each point compared to the arithmetic mean of the surface. Roughness Sa was obtained according to ISO 25178: 2012[20] and roughness St, according to ASME B46.1: 2019 .[21] Equation 1 displays the Sa equation used to calculate surface roughness.

$$Sa = 1A \iint_A |Z(x,y)| dxdy, \tag{1}$$

where A is the measured area and Z(x,y) is the function representing the height of the surface relative to the best fitting plane, cylinder, or sphere.

From Table 2, it can be seen that BBM presented the highest value for both roughness St and Sa. The WAB surface preparation produced average roughness between OSP and BBM values. Of course, OSP displayed the worst value for both roughness St and Sa (since there is no surface preparation at all).

Figure 2 shows a typical surface scan of the SLJ adherend surface prepared by all surface preparation methods.

It can be seen that OSP presented a uniform trend on the measured surface. The steel surface prepared by the wet abrasive blasting (WAB)(c) presented similar surface roughness distribution as OSP. However, unlike the other

Table 2. Average roughness St and Sa values of bonded joints.

Surface treatment	Average roughness St (μm)	Average roughness Sa (μm)
OSP	24.6 ± 1.6	3.1 ± 1.1
BBM	118.7 ± 10.1	24.4 ± 3.9
WAB	75.1 ± 6.6	10.3 ± 1.8

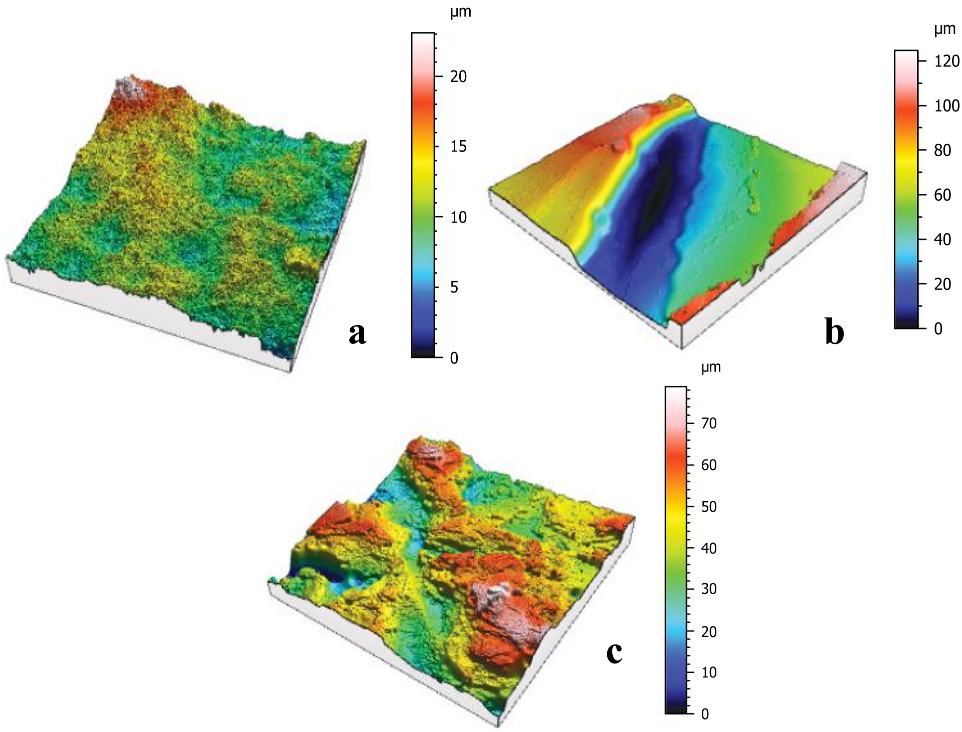

Figure 2. Profilometer images of SLJ adherends: (a) OSP, (b) BBM and (c) WAB.

surfaces, in the surface prepared with BBM, there was no such uniformity. There were regions with high roughness values, but neighboring regions with virtually no measured roughness.

Figure 3 presents the visual appearance of the steel adherends after surface preparation.

2.3.2. Surface analysis of pipes and patches

Pipes and curved plates were also submitted to the same three surface treatments used on the SLJ adherends. Again, no mechanical treatment, oxidized surface primer (OSP), (Rust Grip®), mechanical treatment process using bristle blasting without the use of abrasive (BBM, Monti®), and wet abrasive blasting (WAB, Ecorestauradora®) were performed.

Table 3 summarizes the mean roughness and standard deviations found for the three surface treatment methods, considering roughness St and Sa, respectively.

It can be seen from Table 3, that OSP again had the worst value for both roughness St and Sa, while BBM produced the highest value. The surface prepared by WAB displayed a result similar to the average roughness value of BBM treatment.

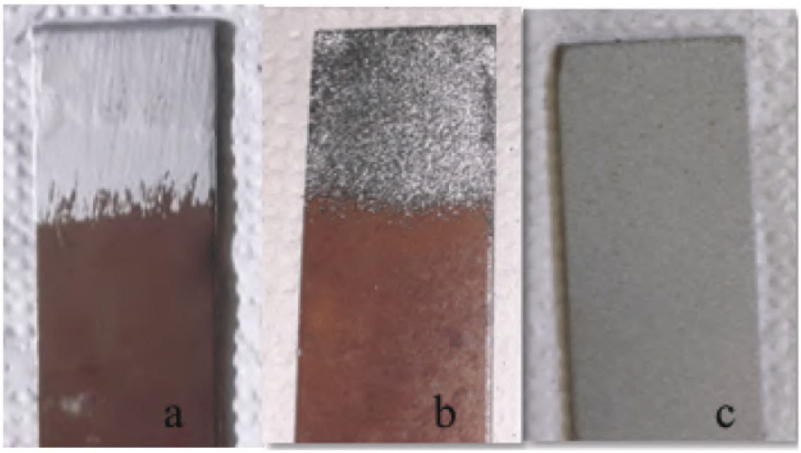

Figure 3. Visual appearance of SLJ adherends: (a) OSP, (b) BBM and (c) WAB.

Table 3. Average roughness St and Sa for pipes and curved plates.

Surface treatment	Average roughness St (μm)	Average roughness Sa (μm)
OSP	34.8 ± 7.5	5.8 ± 2.7
BBM	92.570 ± 17.2	12.9 ± 3.2
WAB	74.030 ± 7.2	10.3 ± 0.1

Figure 4 presents the profilometer images of all surface treatment methods used in the pipes and in curved plates: (a) OSP, (b) BBM, and (c) WAB.

The surface images of all treatments presented a similar profile to the surfaces analyzed for SLJ adherends.

3. Results and discussion

3.1. Single-lap bonded joints

Table 4 summarizes the single-lap test results of specimens prepared with different surface treatments.

According to Table 4, the SLJ adherend surface prepared by BBM displayed higher values of Sa and St, which can lead to a higher failure force, and the specimens prepared by WAB presented the maximum measured failure force of 4662.6 N. Comparing WAB SLJ results with SLJ surface prepared with OSP, an increase of 71.4% is calculated and an increment of 22.2% on joints prepared with BBM is observed. SLJ prepared with BBM presented a 40.3% higher failure force than SLJ prepared with OSP.

Figure 5 displays the force vs. displacement test results for SLJ prepared with different surface treatments.

Figure 5 shows that WAB surface treatment produced the highest value tested, followed by BBM and then OSP. All specimens presented brittle failure. Considering that the force divided by the bonded area can represent stress and

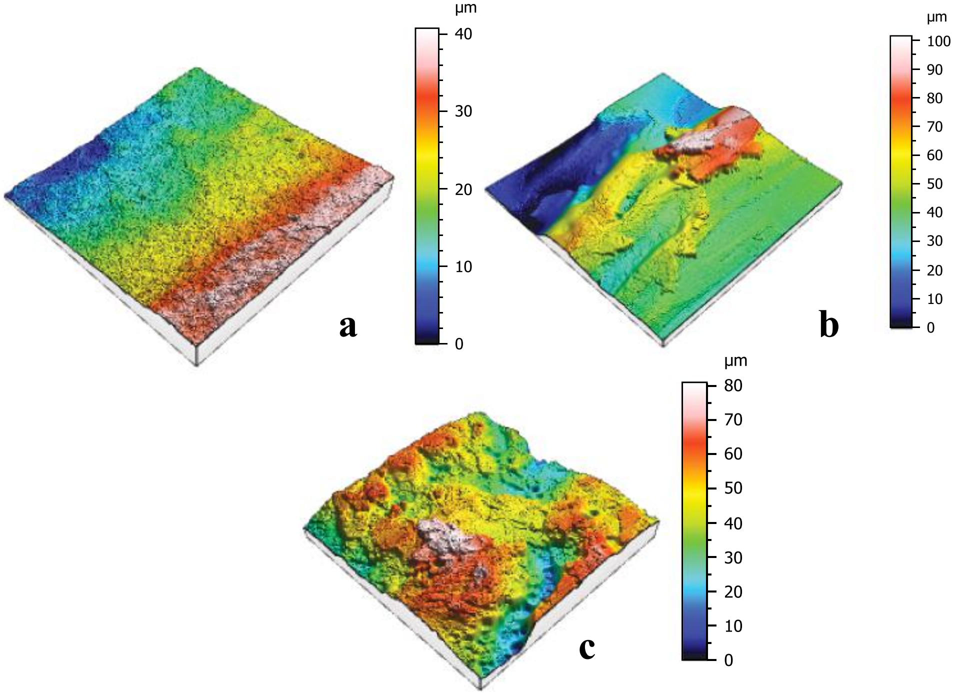

Figure 4. Profilometer images of pipes and curved plates: (a) OSP, (b) BBM and (c) AWB.

Table 4. SLJ failure force (N) of all surface preparations.

Surface Treatment	OSP	BBM	WAB
Failure Force (N)	2720.7 ± 49.1	3816.2 ± 313.9	4662.6 ± 49.5

strain, the displacement divided by the adhesive thickness, the slope of force vs. displacement can represent the SLJ stiffness considering Hooke's law. Therefore, despite presenting higher failure load, SLJ prepared by WAB displayed lower stiffness compared to SLJ prepared with other surface treatments. SLJ adherends prepared BBM presents high stiffness.

The tested joints failed predominantly adhesively, while in some cases, a mixed failure mode (adhesive/cohesive) was observed. Failure type is not relevant in such adhesive joints. Although cohesive failure is preferable, the oil industry is mainly focused on the result rather than the failure mode. Figure 6 presents SLJ failure modes.

In a variety of field applications, the methods that use abrasive blasting have the advantages of producing good productivity in extensive areas, by treating the surface evenly and triggering good anchoring of the adhesives near the substrate. The BBM treatment is known for practicality and easy handling by the operator, allowing obtaining high roughness profile on the substrate, but it depends largely on the operator's ability. The method that used the primer is

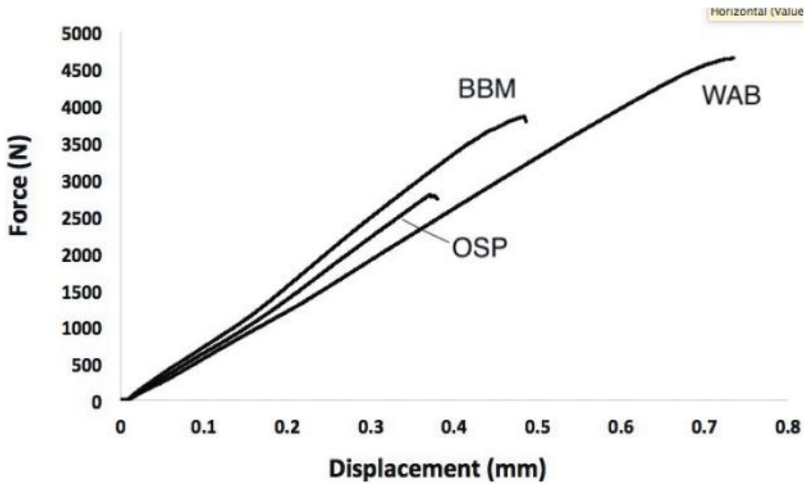

Figure 5. Typical force vs. displacement curves for SLJ.

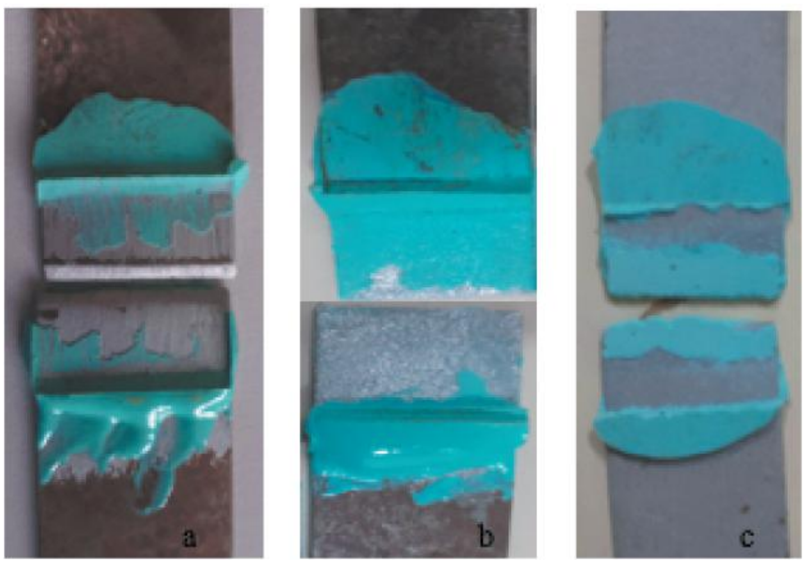

Figure 6. Joints failure mode: (a) OSP, (b) BBM and (c) AWB.

indicated in situations where it is not possible to perform any type of mechanical treatment, due to either advanced degradation of the substrate or the impossibility of working in environments with high explosion potential (Zone 0). It also does not require high mechanical bonding strength. Therefore, according to our results, the best method for bonded joints submitted to shear loading is the use of the WAB machine.

3.2. Hydrostatic burst tests in specimens repaired with bonded metallic patches

Table 5 presents the failure pressure of the hydrostatic tests performed in the pipes with a 1” through-wall defect repaired with the curved plate.

According to Table 5, preparation of pipes and curved plates with the bristle blaster without abrasive (BBM) produced the highest average failure pressure. Wet abrasive blasting (WAB) produced failure pressure 14.4% lower than BBM, while the failure pressure of application of the primer on the oxidized surface without treatment was 53.5% lower. Note that unlike the result obtained in the SLJ, surface preparation by BBM had a slight advantage over preparation by WAB, but statically, considering the standard deviation, there was no significant difference. Figure 7 presents the pipes after testing (a) OSP, (b) BBM, and (c) WAB.

From Figure 7 it can be seen that the specimen prepared by OSP presented adhesive failure and specimens prepared with BBM and WAB displayed mixed failure mode (adhesive/cohesive).

Although the measured roughness value of the specimens prepared by BBM for both tests, SLJ, and pipes bonded with curved plate surfaces is higher, the measured area also presented points with very low values, that is, oscillating quite from one region to another. The BBM method is known for practicality and easy handling, allowing obtaining high roughness profile on the substrate, but it depends heavily on the operator’s ability. WAB presented uniform roughness values, a characteristic of methods involving wet blasting.

In summary, as expected, the type of surface treatment of metal substrates had a considerable influence on the resistance of the materials bonded with polymeric adhesives, both in the shear stress of bonded joints and the failure pressure of the curved pipe/plate assembly. In addition to a good roughness profile, it is highly desirable to obtain uniformity in the treatment so as not to cause discrepancies between one region and another along the bonded surface. However, it is important to remark that the average failure pressure obtained without any mechanical surface treatment is quite amazing, mainly considering that such kind of repair is usually applied in combination with a composite glove.

Table 5. Summary of failure pressures obtained in the hydrostatic tests according to surface treatment.

Surface treatment	Failure Pressure (MPa)
OSP	9.18 ± 1.69
WAB	16.92 ± 1.26
BBM	19.77 ± 3.40

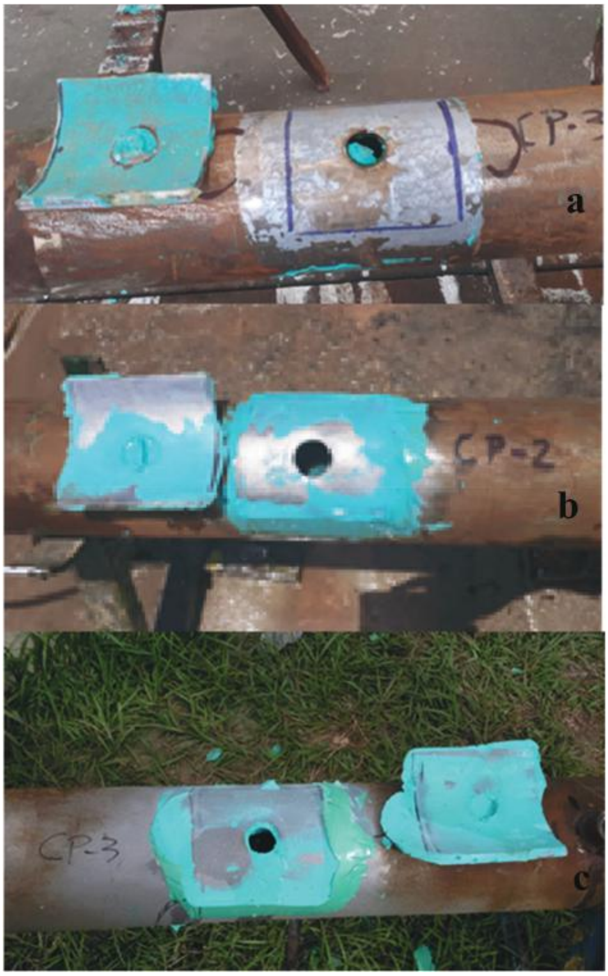

Figure 7. Pipes after surface preparation by (a) OSP, (b) BBM and (c) WAB.

Both the BBM and the WAB treatments provided satisfactory values. In general, we recommend using OSP where the surface is oxidized, and it is not possible to perform mechanical treatment. The BBM is easier to handle and to transport and is recommended in mechanical treatments with smaller application areas but requires greater operator skill. WAB is indicated when large regions need to be treated, because it has excellent productivity and produces more uniform surface treatment and lower dispersion values in the results. However, due to the dimensions of the equipment, it requires more complexity in transportation and allocation in the region where the treatment will be carried out.

3.3 Towards a simple criterion for the effect of surface treatment on the failure pressure or damaged pipes repaired with metallic patches. Critical energy criterion

In this section, a preliminary failure criterion, based on the principles of linear elastic fracture mechanics, is summarized. The idea is to obtain a simple parameter – a critical energy release rate – able to account all the main information about a given surface treatment. Besides, an algebraic expression to obtain a lower estimate for the failure pressure is also derived. The main features of the theoretical aspects of such a criterion can be found in Refs [22] and [23]. The main simplifying assumptions are similar to those used in ISO 24817[19] or ASME PCC-2[24] standards to obtain a lower limit for the failure pressure of a pipe with a hole, repaired with a composite glove.

The main simplifying assumption is to consider the hole at the pipe "small enough" to model the metallic patch bonded over the pipe as a pressurized circular delamination between a rigid substrate and an elastic plate (like the classic blister test), see Figure 8. The curvature of the pipe wall is assumed small enough, to not influence the critical energy release rate, and it is neglected in the analysis.

The energy criterion for unstable propagation of the delamination is basically an extension of Griffith's criterion for quasi-static crack growth. Considering W as the work of the external forces, $U$the elastic energy, A the crack area, and γ_{cr} the critical energy release rate, the propagation will be stable provided

$$\gamma = \partial(W - U)\partial A < \gamma_{cr}. \tag{2}$$

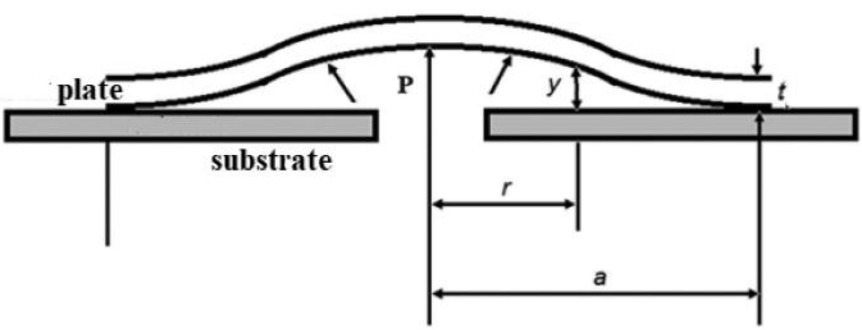

Figure 8. Pressurized circular delamination between a rigid substrate and an elastic plate.

The surface free energy γ includes all energy losses around the crack tip and can be described as the energy required to increase the crack area $A$by an amount ∂A. The term $(W - U)$ in the problem depicted in Figure 6, considering a plate exhibiting bulk linear elastic behavior away from the vicinity of the crack tip, can be expressed as follows:

$$(W - U) = 12PV, \tag{3}$$

where V is the volume under the delamination. The volume V is estimated by obtaining the vertical displacement $y$of the (circular) plate under internal pressure P,

$$(W - U) = \frac{1}{2}PV = \frac{1}{2}P\pi \int_{r=0}^{r=a} y(r)rdr \tag{4}$$

Where $a$is the radius of the delamination surface. Considering the first order Mindlin theory of plates and an isotropic elastic behavior, it comes that vertical displacement $y$of the circular plate under uniform pressure P, clamped at the extremities is given by[25,26]

$$y(r) = P[3(1 - v^2)16Et_i^3(a^2 - r^2)^2] + P[38Gt(a^2 - r^2)]. \tag{5}$$

In fact, the "circular plate" is not really clamped at the extremities and it is necessary to consider the stress at the crack tip. In Ref. [27], ithe stored energy for this case was calculated (a penny-shaped crack under internal pressure). Combining this additional term with Equation (4), the total difference between the external work done and the elastic energy stored within the patch can be obtained,

$$(W - U) = 12PV + \underbrace{P^2[4(1 - v^2)a^3 3E]}_{additional} = \pi P \int_0^a y(r)rdr + P^2[4(1 - v^2)a^3 3E]. \tag{6}$$

Thus,

$$(W - U) = \pi P^2[(1 - v^2)32Et^3a^6 + 332Gta^4 + 4(1 - v^2)3\pi Ea^3], \tag{7}$$

ith E being Young's modulus, v Poisson's ratio, and $G$the shear modulus given by

$$G = E2(1 + v). \tag{8}$$

Combining Equations (1) and (6), it comes that the propagation is stable, provided

$$\frac{\partial(W - U)}{\partial A} = \frac{1}{4\pi a}\frac{\partial(W - U)}{\partial a} < \gamma_{cr} \Rightarrow$$

$$\underbrace{P^2\left[\frac{1-\nu^2}{E}\left\{\frac{3}{32t^3}\left(\frac{d}{2}\right)^4+\frac{2}{\pi}\left(\frac{d}{2}\right)\right\}\right]+P^2}_{MODE\ I} \tag{9}$$

where $d = 2a$. The first term on the right side of Equation (8) represents the parcel of the energy rate related to the mode I and the second is the parcel related to the mode II. Thus, the critical value of the pressure is given by the following expression:

$$P_{cr}^2\left[\left\{\frac{3}{512t^3}d^4+\frac{1}{\pi}d\right\}+\left[\frac{3}{64Gt}d^2\right]\right]=\gamma_{cr} \tag{10}$$

or

$$P_{cr}=\sqrt{\{\gamma_{cr}(1-\nu^2)E\{3512t^3d^4+1\pi d\}+364Gtd^2\}}. \tag{11}$$

The last expression is similar to the ones presented in ISO 24817[19] or ASME PCC-2[24] standards to obtain a lower limit for the failure pressure of a pipe with a hole, repaired with a composite glove. From now on, we consider the following expression:

$$P_{cr}=\sqrt{\{0.001\gamma_{cr}(1-\nu^2)E\{3512t^3d^4+1\pi d\}+364Gt_id^2\}}, \tag{12}$$

where the following units are considered: E and G (MPa), d and t (mm), γ_{cr} (J/m^2), and P_{cr} (MPa). For the steel patches, the following values are adopted: E = 200000 MPa, ν = 0.3, t = 6.35 mm, and d = 25.4 mm.

It is important to make two important observations: The expression (11) does not depend on the pipe diameter and the only parameter that accounts for the surface is the critical energy γ_{cr}. It is not the goal of the present paper to discuss the experimental statistic identification of this parameter, and the reader is invited to look at the detailed discussion in Refs.[19,24]. The critical energy γ_{cr} is different depending on the surface treatment (for a fixed adhesive and adhesive thickness). Thus, the critical energy can be used as a good preliminary index of the effectiveness of an alternative surface treatment, since it is not dependent of the size of the defect nor of the diameter of the pipe. Table 6 presents the values obtained for the three surface treatments.

Table 6. Critical energy release rate γ_{cr} obtained from the failure pressure.

Surface treatment	Failure Pressure (MPa)	γ_{cr} (J/m^2)
OSP	9.18 ± 1.69	11.64 ± 4.30
BBM	19.77 ± 3.40	53.99 ± 18.05
WAB	16.92 ± 1.26	38.91 ± 5.65

According to Table 6 it can be seen that pipes surface prepared with BBM method presented the highest failure pressure and therefore the highest critical energy release rate (γ_{cr}). Critical energy release rate from BBM surface treated pipes is 363.8% higher than OSP surface treated pipe and 38.8% over WAB surface preparation system. Although the critical energy release rate from pipes surface treated with BBM system is higher than WAB, it is not statistically significant in analyzing standard deviation's lowest and highest values.

Although the value of the critical energy rate is smaller for the OSP treatment, the results are promising (since it requires practically no surface treatment) and may be enhanced if a peel ply is laid upon the outer surface of the polyurethane coating after it is applied. This layer should be peeled off at some future time prior to bonding. When the bonding is to be done, the peel ply is removed, fracturing the coating surface. This could leave a roughened surface to which the adhesive is applied. However, future studies must be performed to verify the effectiveness of such a procedure to enhance the critical energy release rate in the OSP surface treatment.

4. Conclusions

The aim of the tests was to analyze steel surfaces subjected to three treatment methods: application of a primer directly on the oxidized surface without any special surface treatment, cleaning with an abrasive-free rotating bristle machine, and wet abrasive blasting. The highest failure force was obtained for the adhesive joints whose surfaces were subjected to wet abrasive blasting. The lowest strength was achieved by application of primer on the oxidized surface. In terms of hydrostatic testing of pipes bonded with curved plates, the most advantageous surface treatment was wet abrasive blasting, although the abrasive-free rotating bristle machine presented a better result. A simplified fracture analysis allows introducing a scalar variable that characterizes the bonding surface between the plate and the pipe. This parameter can be used as a preliminary index to classify the bonding effectiveness. Although the use of a rotating bristle machine gives the best roughness and strength results, the other alternative methods are less time-consuming, assure reasonable strength, and are easier to be used in the field. The use of a primer directly on the oxidized surface without any special surface treatment is a simple procedure and brings an excellent perspective. It can be a good alternative for emergency repairs, since the repair of through-wall corrosion damage in pipelines with bonded metallic patches does not allow an adequate surface preparation. In general, it is supposed to be used only until a next planned maintenance stop (short period).

Acknowledgements

We thank the Rio de Janeiro State Research Foundation (FAPERJ), the Brazilian National Council for Scientific and Technological Development (CNPq), and Office for Coordination for the Improvement of Higher Education Personnel (CAPES) for supporting part of the work presented here.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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