Numerical-experimental analysis of a modified G-BOP test to evaluate cracks in weld beads in thin sheets

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Abstract
One of the most critical problems related to welding is the occurrence of Hydrogen-Induced Cracking (HIC), and despite all the efforts made to mitigate this defect, it remains present in the modern welding industry. Although the Gapped Bead-on-Plate (G-BOP) test is one of the most practical methods for assessing susceptibility to HIC, the use of a thick plate as the base metal (BM) restricts its application. Considering that many materials, such as the High-Strength-Low-Alloy (HSLA) steels, are difficult to find commercially in the required thickness, and also the fundamental need to appropriately represent the relationship between BM and electrode, da Silva, Fals and Trevisan developed a modified G-BOP test that uses a thinner sheet as the BM. Thus, the present paper aims to evaluate the ability of the Finite Element Method (FEM) to represent the thermomechanical aspects of the G-BOP test and to analyze its modified version using a numerical-experimental approach. In addition to consolidating the modified G-BOP test, the results corroborate the FEM as an important ally in HIC studies.

Keywords Hydrogen-induced cracking · Finite element method · Thermal cycle · Welding residual stresses

1 Introduction
The development of the so-called High-Strength-Low-Alloy (HSLA) steels allowed, among many benefits, the fabrication of slenderer and lighter structural elements, with a still remarkable capacity to appropriately resist the service loads. These steels, particularly the API 5L Class X standard, find great relevance in the oil and gas industry for such characteristics.

Nonetheless, welding such materials is often related to various challenges, especially Hydrogen-Induced Cracking (HIC). This welding defect is also known as Delayed Cracking or Cold Cracking because it generally occurs many hours, days, or even weeks after the welding, at room temperature. Although it is one of the most studied defects related to welding, it is one of the less comprehended [1]. However, it is consent that three fundamental elements must be present for HIC to occur: hydrogen dissolved in the weld bead, susceptible material microstructure, and tensile stresses acting on the welded element [2].

The hydrogen will always be present in welds, whether due to the flow used by the welding process, the atmosphere itself, the electrode coating, or from contamination on the workpiece surface. Its dissolved molecules in the weld bead present a tendency to accumulate in the existent crystalline defects in brittle microstructures, very common in welded components [3]. Regarding the tensile stresses, even though they may arise from mechanical solicitations in service, welding residual stresses are also likely to cause the problem as they are the first to act in the component after the welding [4, 5], therefore, playing an essential role in the HIC.

As for the need to evaluate the susceptibility of a welded joint to HIC, many tests have been developed. The Gapped Bead-on-Plate test (G-BOP), proposed by Graville and McParlan [6] in 1974, is one of the most employed ones for its versatility and simplicity in quantifying the HIC effect.
Even though its benefits are many, using 50.8 mm (2\(\text{"}\)) thickness plates as Base Metal (BM) is a considerable disadvantage once a given electrode needs to be evaluated with the BM for which its application is recommended. Also, many materials, such as the HSLA steels, are most commonly found in considerably smaller thicknesses to be commercially viable [7]. Then, to overcome such inconvenience, da Silva, Fals and Trevisan [7] proposed a modified G-BOP test configuration to be applied for small thickness HSLA steels as BM and to properly investigate its weld metal (WM) susceptibility to HIC in a practical, less expensive, and yet reliable way, using more common steel as a complement plate bolted to the BM to achieve the standard thickness of the test specimen.

The improvement of computational capabilities has made numerical methods, particularly the Finite Element Method (FEM), a strong ally for engineers to understand phenomena of various engineering areas. It has been successfully applied in the simulation of welding regarding its thermal [9–12] and structural [13–17] aspects, with several commercial packages, but less frequently in the simulation of the G-BOP test [18]. The present paper aims to apply this tool in the context of welding simulation, using the commercial software ANSYS\textsuperscript{®} to assist in evaluating the modified G-BOP test. For such, numerical-experimental analyses of three cases are performed: case 1, a standard G-BOP test with AISI 1020 steel as BM; case 2, a modified G-BOP test with AISI 1020 as small thickness BM and the same steel as complement plate; and case 3, a modified G-BOP test with the API 5L X70 HSLA steel as small thickness BM and AISI 1020 as the complement plate.

In the experimental part, six specimens for each case, totaling 18 specimens, were welded using two different shielding gases: three specimens with 75\% argon and 25\% carbon dioxide mixture (“C25 gas”), which provides lower hydrogen levels to the weld bead, and three specimens with 73\% argon, 25\% carbon dioxide and 2\% hydrogen (called here of “H2 gas”). This difference is set to highlight the hydrogen level significance for HIC, both in standard and modified G-BOP arrangement. Also, metallography determined the microstructure for all three cases, showing its susceptibility to HIC. Finally, the numerical part of the analyses involved FEM simulations of the welding in the three cases to obtain the residual stress distribution, the third main point in HIC.

As cases 1 and 2 use the same material as BM, they allow to assessing the ability of the modified G-BOP test to maintain the thermomechanical characteristics of the standard test by observing the isothermals and residual stress profiles, which will be made with the aid of the FEM and validated with experimental measurements of temperature and the HIC effect. Case 3 complements the study by applying the tool to a dissimilar metal pair, consolidating that the interface impact in the behavior of the test is minimal and providing relevant information in the matter of HIC and its structural aspect. With the G-BOP tests results in quantifying the HIC for all situations, the analysis put up a panoramic evaluation of all main elements involved in the phenomena.

2 Theoretical and practical review

2.1 Hydrogen-induced cracking

According to Maoref et al. [3], the HIC dynamic starts with the atoms, ions, and molecules of hydrogen present in the atmosphere, material surface, gas, or material flux involved in the welding, dissolving into the weld bead during the operation. It establishes the first essential element for HIC, which is the hydrogen presence itself.

Then, the WM becomes supersaturated with hydrogen during the subsequent cooling and solidification, which tends to migrate to the Heat Affected Zone (HAZ) to balance the dilution. If the HAZ microstructure is austenitic, which may hold much more hydrogen, it will be diffused across its fusion line. Otherwise, it will remain in the WM. Independently of the region in which the hydrogen is present, brittle microstructures, the second main element for HIC, appear during the quick cooling after welding, making the trapped hydrogen to be in a high energy level. Then, this hydrogen migrates for the defects and discontinuities in the crystalline structure, accumulating in these “traps”.

From that point on, the welding residual stresses, representing the third essential element for HIC, act in the traps, already weakened by the presence of the high state energy hydrogen, starting the crack formation. The hydrogen is then released in the crack, accelerating its growth to points far from the traps, and consolidating the HIC.

2.2 Standard and modified G-BOP test

Developed by Graville and McParlan [6] em 1974, the G-BOP test has the purpose of evaluating the WM susceptibility to HIC in welded structural steel and consists basically of a material deposition across a gap, typically of 0.75–1 mm in length and 100 mm wide, between two thick blocks of 100 mm × 125 mm × 50.8 mm. Figure 1 shows the schematic representation of this test.

After the welding and being held in position by the C-clamp for at least 48 h, the weld in the gap vicinity is heated to cause a heat tint in the affected area, highlighting the HIC [7, 18]. After 24 h more, the specimen is broken in the Gap area, its cross section is analyzed, and calculated the HIC percentage. The geometrical modification proposed by de...
Silva, Fals and Trevisan [7] is also displayed in Fig. 1, with emphasis on the complement plates under the BM sheets, so the whole specimen reaches the standard test thickness, and on the 12.5 mm bolts attaching the assembly. The standard test dynamics, as described above, is the same for the modified test.

For the appropriated characterization of the HIC phenomenon through the G-BOP test, the appropriated electrode for a given BM must be employed to take the dilution of the BM in the WM into account [7]. Also, the establishment of the welding residual stresses, crucial to the occurrence of HIC, depends, beyond the geometry and restraining conditions, on the thermomechanical properties of the materials [9–17].

2.3 Welding simulation by FEM

The correct characterization of the multiphysics is the first key point to attend in the simulation of welding processes. There is the thermal aspect inherent to the localized heating from the electric arc, fundamentally governed by the Heat Equation as it is shown in Eq. 1 in which \( \rho \) is the density, \( c \) is the specific heat, \( k \) is the thermal conductivity, and \( q_g \) is the internal heat generation.

\[
\rho c \frac{\partial T}{\partial t} = \nabla^2 (kT) + q_g
\]

The amount of heat input \( Q \) is ruled by Eq. 2, in which \( \eta \) is the efficiency of the process, \( U \) is the welding voltage, \( I \) is the welding current, is distributed along the workpiece according to a mathematical model to be chosen. The heat dissipation to the environment by convection and radiation are ruled by Eqs. 3 and 4, respectively, and for them \( h \) is the convective coefficient, \( A \) is the external area, \( T_s \) is the temperature of the external surface, \( T_\infty \) is the temperature of the external flow, \( \varepsilon \) is the emissivity of the surface, \( \sigma \) is the Stefan-Boltzmann constant and \( T_{env} \) represents the temperature of the surrounding environment.

\[
Q = \eta UI
\]
\[
Q = hA (T_s - T_\infty)
\]
\[
Q = \varepsilon \sigma A \left( T_s^4 - T_{env}^4 \right)
\]

The structural aspect is represented by the stresses related to the deformations in the component during the thermal cycle, which remain even after the whole process takes place and are, therefore, called “residual stresses” [13–17]. This part of the phenomenon is modeled by Eq. 5, in which the total strain is computed as the addition of the elastic strain, taken by isotropic Hooke’s law and its related properties, the plastic strain, described by a linear isotropic hardening rule, and the thermal strain, calculated with the thermal expansion coefficient. As it is a time-dependent phenomenon, the software calculates...
Table 1  Welding parameters

| Parameter          | Value |
|--------------------|-------|
| Voltage (V)        | 28    |
| Current (A)        | 211   |
| Wire feed speed (m/min) | 7   |
| CTWD (mm)          | 19    |
| Velocity (mm/min)  | 223.6 |
| C25/H2 gas flow (l/min) | 20  |

The microstructural aspect of the problem may be considered by appropriately including temperature-dependent thermal and structural properties influenced by the internal changes in the material, such as thermal conductivity, thermal expansion coefficient, Young’s modulus, yield strength, and tangent modulus.

\[
d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p + d\varepsilon_{ij}^{th}
\]  

(5)

The second central point is the appropriated definition of the simulation goals, which allows applying the most indicated approach regarding the relationship between the physics: the one-way or two-way coupling. In the first one, the simulations are carried out sequentially for each physic, according to the dependency of results, which has to be very strong in one way, and weak in the other. In the second one, only one simulation, with degrees of freedom in the element nodes involving all the physics, is performed, being indicated to a strong dependency in all ways between the physics.

Finally, the correct representation of geometry, materials, boundary, and loading conditions must be considered. The CAD geometry must include all essential parts in the workpiece, which is the simulation domain, and a FEM mesh with enough refinement to capture results convergence. The materials must have their thermomechanical properties well defined, with their non-linearities in temperature and deformation, making possible an accurate numerical solution of the differential equations defining the problem. The boundary conditions are represented in the thermal and structural aspects, respectively, by heat transfer modes in the workpiece external surfaces and its imposed mechanical restrictions to displacement. The loads are a heat source model representing the electric arc for the thermal analysis, and the node displacements, calculated by the FEM from...
the material properties and thermal results, for the structural analysis.

3 Materials and methods

3.1 Experimental analysis

Figure 2 shows the schematic representation of the three cases: case 1, applying the standard G-BOP test with AISI 1020 steel plates; the modified G-BOP test in case 2, with AISI 1020 steel in both small thickness BM and complement plates; and case 3, the same as case 2, but with API 5L X70 as small thickness BM. For cases 2 and 3, the contact surfaces were machined to the roughness of 0.65 μm. The tightening torque of 146.5 Nm was applied to the 12.5 mm diameter bolts, as suggested by the manufacturer.

For each case, it was performed an automatic Flux-Cored Arc Welding (FCAW) to the test steps described in [6] and [7], the latter one for the modified approach, in 6 specimens, totaling 18 test bodies. The welding parameters are shown in Table 1, and the two shielding gases used were the C25, with 75% of argon gas and 25% of carbon dioxide, and 73% of argon gas, 23% of carbon dioxide and 2% of hydrogen, which is called here of H2. After welding, metallography analysis determined the microstructures present.

The thermal cycle in the specimens was measured with a K type thermocouple positioned at 1.5 mm under the weld bead, as displayed in Fig. 3, which also shows images of the welding apparatus and procedure.

After the determined time interval, the components were submitted to heating to highlight HIC, broken through a bending moment, and the HIC was measured.

3.2 Numerical analysis

In the present paper, the FEM simulations were performed using ANSYS® to obtain the thermal cycle in the same spots.
observed in the experimental analyses, making it possible to validate the modeling procedure for this application. Afterward, the FEM was used to estimate the level and distribution of the welding residual stresses in the weld bead of the G-BOP specimens, which is an essential condition to the HIC phenomenon. Figure 4 shows the FEM meshes used, highlighting that cases 2 and 3 had the same mesh, the refinement option applied in the weld bead, and its verification through convergence tests.

Concerning the multiphysics of the problem, the one-way coupling method was employed. The strong dependency from the thermal cycle on the welding residual stress, with minimal reverse dependency, explains this choice. The microstructural effects are represented by the accurate description of the thermomechanical properties and its variations with temperature, as illustrated in Fig. 5 for the AISI 1020 steel [19] and Fig. 6 for the API 5L X70 [20], which are fundamentally ruled by microstructural transformations. This approach was used in many other studies [13–17].

The electrode used was the AWS E81T1 flux-cored wire, suitable for API 5L X70 steel welding. The mechanical properties described by the manufacturer were implemented, with a yield strength of 566 MPa, an ultimate strength of 635 MPa, an elongation of 22 %, and the thermal properties were replicated from API 5L X70 steel.

In the thermal analysis, the heat source model utilized was the hemispheric [17, 21], implementing the welding parameters of Table 1, an efficiency of 0.75 and geometric parameters gathered by measurements of the weld bead in the experimental analysis, as done in [4]. Boundary conditions were convection and radiation applied to the external surfaces of the specimen, except for those restrained by the C-clamp. Convective coefficient \( h \) and emissivity \( \varepsilon \) were, respectively, 25 W/mm\(^2\) °C and 0.5, following the described by [22].

To estimate the average interface thermal contact conductance for cases 2 and 3, a simplified test that approximates the modified G-BOP test specimen to a composed wall, with a known thermal power source acting in the upper surface of the specimen, and a heat sink, kept at the water fusion temperature, in the lower surface, was realized. Temperatures in surfaces were monitored and, with the known geometric and thermal properties of the materials, allowed the calculation of the property. The scheme is presented in Fig. 7, and the values of 3.64 kW/m\(^2\) °C for case 2 and 7.03 kW/m\(^2\) °C for case 3 were obtained, and implemented in the simulations of the respective cases. For the structural analysis, the consideration of an equal friction coefficient of 0.15 for thread and collar surfaces, as suggested in [23], makes it possible to calculate the bolts preloads by Eq. 6. Therefore, the referred assembling torque of 146.5 Nm in cases 2 and 3 produces a load of 58.6 kN in the bolted assembly.

\[
F_i = \frac{\tau}{0.2d} \quad (6)
\]

One static structural analysis with the bolts preloads was performed to get the resultant stress distribution in all specimen, as shown in Fig. 8 for its cross section and its variation in a center line of the interface between BM and the complement plate. The results for cases 2 and 3, as an additional verification of the model, are presented in the graphic. After that, the C-clamp restrictions to any free body movement were imposed in the model, and a transient...
Fig. 9  Numerical-experimental comparison of the thermal cycle in the thermocouple position (i) and of the weld bead cross section (ii) for standard G-BOP test in case 1

Fig. 10  Numerical-experimental comparison of the thermal cycle in the thermocouple position (i) and of the weld bead cross section (ii) for the modified G-BOP test in case 2

Fig. 11  Numerical-experimental comparison of the thermal cycle in the thermocouple position (i) and of the weld bead cross section (ii) for modified G-BOP test in case 3
4 Results and discussion

4.1 Thermal cycle and microstructure

The thermal cycles obtained in the experimental analysis using the thermocouple, as described by Fig. 3, is presented with its numerical counterparts in Figs. 9, 10 and 11.

It is possible to observe a good agreement between experimental and numerical analysis results regarding the thermal aspect of welding. The higher discrepancy between peak temperatures is in case 2, with AISI 1020 steel as BM and complement plate in the modified G-BOP test, with a deviation of 4.9% for less. The isothermal line tendency is also well captured by simulations in all cases.

Figure 12 shows examples of the obtained microstructures in the WM for specimens in cases 1 and 2, with a 500x zoom after a nital attack 2%. According to the International Institute of Welding (IIW) classification, the primary ferrite in grain boundaries (PF(G)), susceptible to brittle fracture, and the ferrite with the aligned second phase (FS(A)), which has a similar aspect to bainite, are identified as HIC facilitators among those identified [24].

4.2 Welding residual stresses estimation and HIC quantification

The welding residual stresses, as one of the central elements for the HIC, were estimated by the numerical simulation. Figure 13 exhibits the general panorama of the transverse residual stresses, most commonly analyzed in similar papers [13–17], for the three cases, highlighting that the greatest stress levels, along with its steeper variations, are concentrated in the weld bead area.

Figure 14, in its item (i), shows the variation of the normal stress in the three-axis of the system that appears in Fig. 13, in the length the heat source had traveled to produce the longitudinal extension of the weld bead, in a line that passes through the geometric center of the WM cross section, respectively. These normal stresses are the...
Fig. 14  Triaxial residual stresses across the weld bead length in its geometric center for the three cases (i), transverse residual stress profile through a transverse line crossing the BM and the WM on the gap area (ii), and transverse residual stress across the WM thickness in the middle of the gap, following the ascending sense (iii)

most critical for the HIC phenomenon, as they promote the appearance and propagation of cracks during hydrogen infiltration in the crystalline discontinuities. According to the observed stresses, it is clear that the G-BOP specimen geometric configuration, be it on the standard or in the modified test, concentrates the peak stresses and its main variations in the gap area of interest where the specimen is broken.

In its item (ii), it is portrayed the transverse residual stresses crossing the BM and WM through a transverse line in the upper surface of the BM, next to the interface between the left and right parts of the specimens, also featuring the high-level stresses in the weld bead area. Finally, the graphic (iii) in Fig. 13 displays the variation of the transverse residual stresses through WM thickness in the gap area, being possible to observe that the residual stresses levels decrease from the bottom to the top of the WM, which agrees with the fact that the HIC generally occurs in the bottom region of the WM, as shown in Fig. 15. Additionally, it is crucial to notice that the curves between cases 1 and 2

Fig. 15  HIC representation
Table 2  Percentage results of HIC for six specimens of each one of the three observed cases, with two different shielding gases

| Case 1 (C25) | Case 2 (C25) | Case 3 (C25) |
|--------------|--------------|--------------|
| Test 1 (%)   | Test 2 (%)   | Test 3 (%)   |
| 30.8         | 20.0         | 41.7         |
| Avg. value (%)| Avg. value (%)| Avg. value (%)|
| 30.8         | 23.2         | 17.2         |
| Std. dev. (%)| Std. dev. (%)| Std. dev. (%)|
| 10.9         | 17.6         | 9.0          |

| Case 1 (H2) | Case 2 (H2) | Case 3 (H2) |
|--------------|--------------|--------------|
| Test 1 (%)   | Test 2 (%)   | Test 3 (%)   |
| 80.0         | 99.3         | 96.3         |
| Avg. value (%)| Avg. value (%)| Avg. value (%)|
| 91.9         | 85.2         | 87.3         |
| Std. dev. (%)| Std. dev. (%)| Std. dev. (%)|
| 10.4         | 89.2         | 5.3          |

are alike in shape and behavior for all presented graphics, which corroborates that the modified configuration for the G-BOP test maintains most characteristics of the standard test regarding the welding residual stresses.

Figure 15 also represents the analysis process of the HIC through the heat tint produced during the test in one of the specimens. The image vectorization makes it possible to quantify this effect, as shown in Table 2, which brings results in the percentage of the HIC for all situations observed, the average and standard deviation values. The results show how the hydrogen level effect, from the different values between C25 and H2 gases, is as noticeable in the modified test as in the standard for all three cases. Compared with the stress levels in Fig. 14, the Table 2 values show agreement between the tests in cases 1 and 2, with comparable levels of residual stresses in all graphics exhibited and no substantial variation between the HIC percentage results, even with different G-BOP test configuration.

Concerning case 3, the obtained results show significant agreement with the expected for the modified G-BOP test and observed for the previous cases, even though BM and complement plates are dissimilar metals. Therefore, it solidifies the capability of the FEM to provide relevant information for the study of HIC, primarily allied to the G-BOP test, and such results may eventually be extended to put up a correlation between the residual stresses and their influence in the HIC phenomena for this specific BM-electrode pair, and any other.

In summary, the present study results are:

- FEM simulation and experimental measurements agreed in thermal cycles, both in standard and in modified G-BOP test;
- Microstructure analysis showed the presence of brittle constituents in all cases;
- The FEM residual stress simulation captured the expected high levels in the notch area of all specimens;
- The estimated residual stress levels are in accordance with the HIC results;
- The hydrogen levels effect are expressed as expected in the HIC results for both gases used.

5 Conclusion

For its inherent simplicity and practicality in HIC susceptibility evaluation, the G-BOP test stands up as a fundamental tool for the referred phenomenon investigation. The need to appropriately observe the WM behavior by using an electrode to its indicated BM, added to the difficulty to find viable commercial plates of HSLA steels in the necessary thickness for the test, brought up the need for a test modification, as proposed by da Silva, Fals and Trevisan [7]. Their results, together with the presented numerical-experimental results in this paper, establish that the modified version allows a proper representation of the fundamental characteristics that confer the standard G-BOP test the capacity to provide relevant information regarding HIC.

Among these characteristics, the similar thermal cycle and the concentration of stresses in the gap area, with similar behavior, are crucial, even though the levels depend, obviously, on the BM and WM material properties. As the differences between the observed in cases 1 and 2, especially regarding the Normal Y stress component, are not very significant, it indicates that the load in the bolts of the modified version of the test, in the levels indicated by the bolt manufacturer, exerts low interference for the modified test results. Beyond that, according to the numerical-experimental thermal results comparison, the contact thermal resistance is little expressive for the heat flux during welding, showing a low influence on the test accuracy.

For future work, simulations to determine the optimal thickness for the BM in the modified G-BOP test and
investigate the effects of excessive torque in the assembly are interesting issues to be addressed.

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**Declarations**

**Conflict of interest** The authors declare that they have no conflict of interest.

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