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**IIW Doc II-2313-2024 (II-C-669-2024) (www.iiw2024.com)**

*Prevod: Bojan Gligorijević*

# ELECTROCHEMICAL CORROSION BEHAVIOUR OF STAINLESS STEEL GRADES 1.4404 AND 1.4435 BUTT WELDS BY AUTOGENOUS GTAW

# ELEKTROHEMIJSKO KOROZIONO PONAŠANJE SUČEONIH ZAVARA NERĐAJUĆIH ČELIKA 1.4404 I 1.4435 IZVEDENIH AUTOGENIM GTAW POSTUPKOM

**Professional paper / Stručni rad**

**Paper received / Rad primljen:**

*April 2026.*

**Paper accepted / Rad prihvaćen:**

*May 2026.*

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## Abstract

Prefabricated stainless steel welds are usually pickled. However, under certain conditions, the welds are left as-welded, due to the difficulty of implementing pickling. In such cases, the corrosion resistance in chloride environment is related to the heat tint on the root side. Coloration depends on the quality of the backing gas. For example, some specifications require maximum oxygen contamination of the backing gas, to guarantee a minimal oxidation layer on the root weld bead and adjacent heat affected zone.

In this work, grade 1.4404 and 1.4435 stainless steels pipes were welded with different backing gases, where oxygen contamination was set to 10, 50, 75 and 100 ppm. Corrosion behaviour was studied by determining the pitting potential in artificial seawater.

The major findings of this study are the following:

Beyond the backing gas quality, the polishing method of the pipe (mechanical or electrochemical) leads to a different level of coloration. The weld area of an electro-polished pipe is generally less tinted than that of a mechanically polished pipe. The root side surface roughness of the base material appears to be a key factor for service performance under severe corrosive conditions in as-welded state.

## Rezime

Prefabrikovani zavareni spojevi od nerđajućeg čelika obično se pasiviraju/pajcuju. Međutim, pod određenim uslovima, zavareni spojevi ostaju u zavarenom stanju zbog poteškoća u izvođenju pajcovanja. U takvim slučajevima, otpornost na koroziju u hloridnoj sredini povezana je sa termičkim obojenjem na strani korena zavara. Obojenost zavisi od kvaliteta zaštitnog gasa sa korene strane. Na primer, neke specifikacije zahtevaju maksimalno dozvoljenu kontaminaciju zaštitnog gasa kiseonikom kako bi se obezbedio minimalni oksidni sloj na korenom zavarnom prolazu i susednoj zoni uticaja toplote.

U ovom radu, cevi od nerđajućih čelika kvaliteta 1.4404 i 1.4435 zavarene su uz primenu različitih zaštitnih gasova sa korene strane, pri čemu je kontaminacija kiseonikom podešena na 10, 50, 75 i 100 ppm. Koroziono ponašanje ispitivano je određivanjem potencijala piting korozije u veštačkoj morskoj vodi.

Glavni zaključci ove studije su sledeći:

Pored kvaliteta zaštitnog gasa sa korene strane, metoda poliranja cevi, mehanička ili elektrohemijska, dovodi do različitog nivoa obojenosti. Oblast zavara kod elektropolirane cevi generalno je manje obojena nego kod mehanički polirane cevi. Hrapavost površine osnovnog materijala na strani korena izgleda da predstavlja ključni faktor za ponašanje u eksploataciji pod teškim korozionim uslovima u zavarenom stanju.

*This paper was originally presented at the 77th IIW Annual Assembly and International Conference on Welding and Joining, held from 7 to 12 July 2024 on the island of Rhodes, Greece.*

## 1. Introduction

Gas Tungsten Arc Welding (GTAW) of stainless steel pipes requires protection of the welding bath. Gas shielding on the weld face is achieved by a flow of argon provided by the welding torch. On the root side, backing gas is provided by argon purging, sometimes by nitrogen purging, or using a gas mixture that contains hydrogen.

For different technical reasons, in particular for welds produced on site, this protection is rarely perfect. The welds exhibit heat tint colours ranging from straw yellow to purple, indicative of surface oxidation of the weld metal and the heat affected zone.

When applied under such conditions, experience has shown that the welds are often preferred initiation sites for certain forms of localised corrosion, namely pitting corrosion and crevice corrosion [1,2].

The thickness of the oxide layer formed during the welding operation has an impact on the resistance to pitting corrosion. Turner *et al.* [3] have shown that this reduced resistance is linked to a depletion of the chromium content in the oxide layer and in the underlying substrate. This depletion increases as the thickness of the oxide layer formed and the temperature reached increase. In parallel with this chromium depletion, the oxide layer becomes enriched in iron [4-6].

Studies [7,8] have thus highlighted the need to limit the coloration on the root side of welds, and they even suggest a coloration chart. As a result, it has been proposed that, in the absence of pickling treatment, the coloration should not exceed a level of “shades of grey to slightly yellow”: this corresponds to a contamination level of 20 ppm to 30 ppm of oxygen in a pure Argon shielding gas (I1) or 100 ppm with an Argon-hydrogen mixture (R1) [8].

According to feedback from use, it seems that there are no established corrosion problems in the biopharmaceutical industry on welds left “as welded”, for a level of contamination of approximately 50 ppm of oxygen in pure argon gas (I1), with electropolished tubes [9].

The objective of this work is to obtain data on the gas shielding conditions in relation to the fitness for use of pipes, with a view to avoiding the need for a post-weld pickling treatment.

## 2. Experimental procedure

The study involved measuring the pitting potential by carrying out electrochemical tests on welds produced on tubes made of stainless steel grades 1.4404 (X2CrNiMo17-12-2) and 1.4435 (X2CrNiMo18-14-3) in accordance with standard NF EN 10088-1, by varying the level of oxygen contamination in the backing gas between 0 ppm and 100 ppm. Both stainless steel grades correspond to the AISI 316L designation, however the 1.4435 grade is slightly more alloyed than the 1.4404 grade, giving it a slightly higher pitting resistance equivalent number (PRE-N = $\%Cr$ + 3.3 × $\%Mo$ + 16 × $N$), but above all a lower δ-ferrite content. As a result, this grade is used in the agri-food and biopharmaceutical sectors, in areas considered critical or which have to operate in ultrapure water.

The welds were produced by automated GTAW, without filler material, on a rotating tube 50.8 mm in diameter and 1.65 mm thickness (refer to Figure 1), with the parameters defined in Table 1 below, and with the following backing gas mixtures:

- Pure argon (ISO 14175 – I1) with oxygen contents of 10, 50, 75, and 100 ppm,
- Argon+5 % H2 (ISO 14175 – R1 - ArH – 5) with oxygen contents of 10, 50, 75, and 100 ppm.



***Figure 1.*** *Inerting device and welding fixture on the weld face side.*

***Slika 1.*** *Uređaj za inertizaciju i zavarivačka stega na strani lica zavara.*

***Table 1.*** *GTAW parameters used in this study.*

***Tabela 1.*** *Parametri GTAW postupka korišćeni u ovom istraživanju.*

| | |
|---|---|
| Electrode | WLa 20, diameter 2.4 mm |
| Current | Ieff: 73 A (*pulsed mode*),<br>Time at 114 A: 20 ms,<br>Time at 40 A: 40 ms. |
| Voltage | 11 – 13 V |
| Polarity | DC- |
| Welding speed | 22.0 cm/min |
| Shielding gas flow rate | 12 l/min (*Ar100% - I1*), |
| Inerting gas flow rate | 6 l/min |
| Torch angle | 90° |
| Angle of attack | 75°, push |
| Electrode-to-workpiece distance | 2 – 3 mm |

Given the thicknesses, preparation was carried out by tack welding on straight edges, with no fit-up gap. Table 2 presents the different chemicals compositions from pipe. Note that the 1.4404 grade is available with two types of surface finishing:

- Mechanically polished tube, Ra < 0.51 µm,
- Electropolished tube, Ra < 0.38 µm.

***Table 2.*** *Chemical composition of the tubes used (wt.%).*

***Tabela 2.*** *Hemijski sastav korišćenih cevi (mas.%).*

| Material grade | Quality | %C | %Si | %Mn | %Cr | %Ni | %Mo | %N | $PRE_N$ |
|---|---|---|---|---|---|---|---|---|---|
| 1.4404 | Mechanically polished | 0.02 | 0.39 | 1.4 | 16.70 | 10.20 | 2.06 | 0.050 | 24.3 |
| 1.4404 | Mechanically polished | 0.02 | 0.54 | 1.5 | 17.4 | 10.1 | 2.03 | 0.04 | 24.7 |
| 1.4404 | Electropolished | 0.01 | 0.38 | 1.4 | 16.80 | 10.60 | 2.04 | 0.060 | 24.5 |
| 1.4435 | Electropolished | 0.02 | 0.42 | 1.4 | 17.16 | 12.62 | 2.52 | 0.031 | 26.0 |

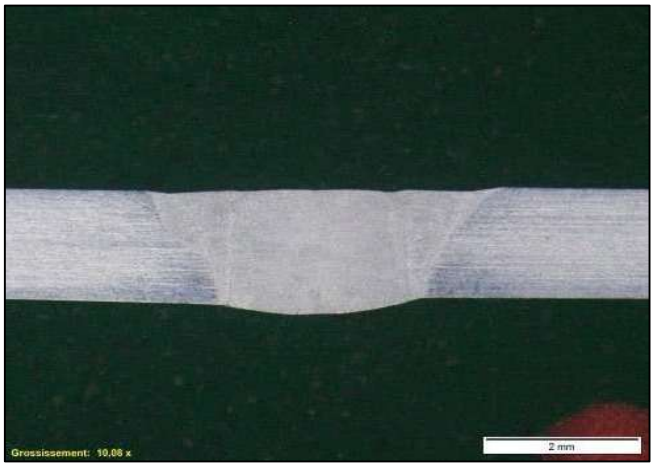



***Figure 2.*** *Metallographic section of the weld.*

***Slika 2.*** *Metalografski presek zavara.*

*2.1. Indirect visual examination*

Following the production of samples, indirect visual examinations were carried out to assess the ability to define the quality level of the backing gasg. The instruments used during this study are presented below:

- GE Mentor, refer to Figure 3,
- GE – XL Lv, refer to Figure 4,
- Olympus G Lite, refer to Figure 5.



***Figure 3.*** *GE Mentor.*

***Slika 3.*** *GE Mentor.*



***Figure 4.*** *GE – XL Lv.*

***Slika 4.*** *GE – XL Lv.*



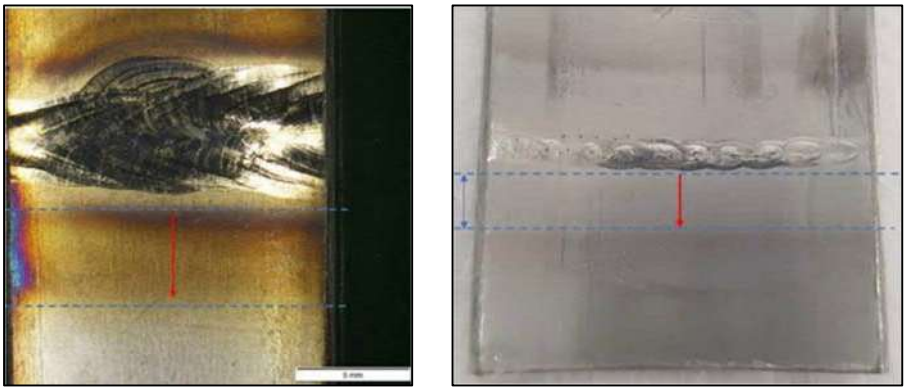
***Figure 5.*** *Olympus G Lite.*

***Slika 5.*** *Olympus G Lite.*

*2.2. Surface roughness measurement*

For each test specimen, a surface roughness measurement was carried out in the oxidation zones perpendicular to the bonding zone (Figure 6).

The measurements were acquired across the maximum height of the roughness profile ($R_z$) and the arithmetic mean deviation of the roughness profile ($R_a$).



As welded Pickled and passivated

***Figure 6.*** *Locations of the roughness measurements on the as-welded and pickled-passivated samples.*

***Slika 6.*** *Lokacije merenja hrapavosti na uzorcima u zavarenom i pajcovano-pasiviranom stanju.*

*2.3. Determination of the pitting potential*

The aim of these tests is to measure the pitting potential. Determining pitting potentials provides information on the susceptibility of materials to the initiation of pitting corrosion. The higher the value of this parameter, the better the behavior.

Three pitting potential measurements were carried out per configuration. To estimate the impact of the weld on the behavior, additional tests were also conducted on the base metal.

The experimental conditions are as follows:

- Immersion for 24 h in artificial seawater (in accordance with standard ASTM D1141-90) diluted 100 times, with a pH of 8.3.
- Deaeration of the test solution for 90 min by argon bubbling, then monitoring of the open circuit potential (free or mixed potential) for approximately 1 h in artificial seawater with a pH of 8.3, still under argon flow, in order to reach the equilibrium potential.

- Potentiodynamic scanning at a rate of 1 mV/s from the free potential to higher potentials and plotting of the current/potential curve up to a limit value corresponding to a current density of 100 μA/cm² (threshold value for pitting initiation). The pitting potential is associated with this current density (Figure 8).

The experimental setup is illustrated in Figure 7.

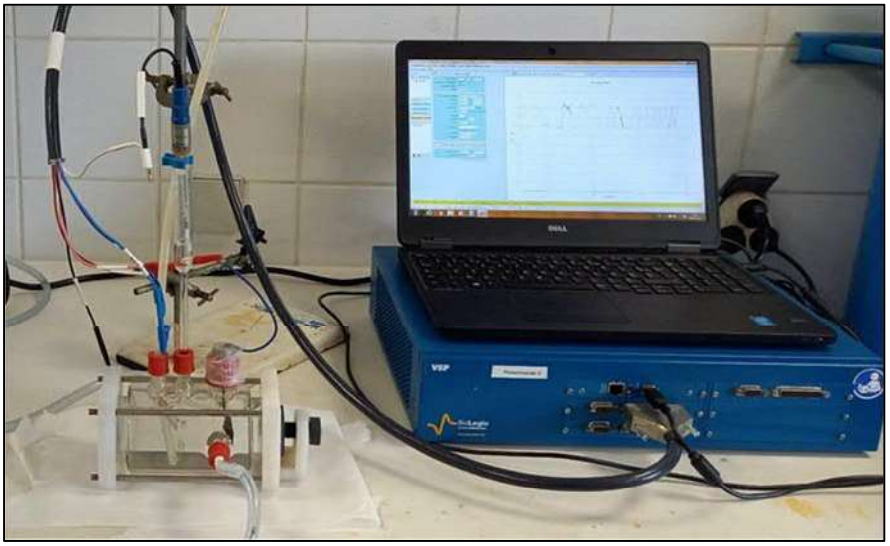


***Figure 7.*** *The experimental setup used in the pitting corrosion tests.*

***Slika 7.*** *Eksperimentalna postavka korišćena u ispitivanjima piting korozije.*

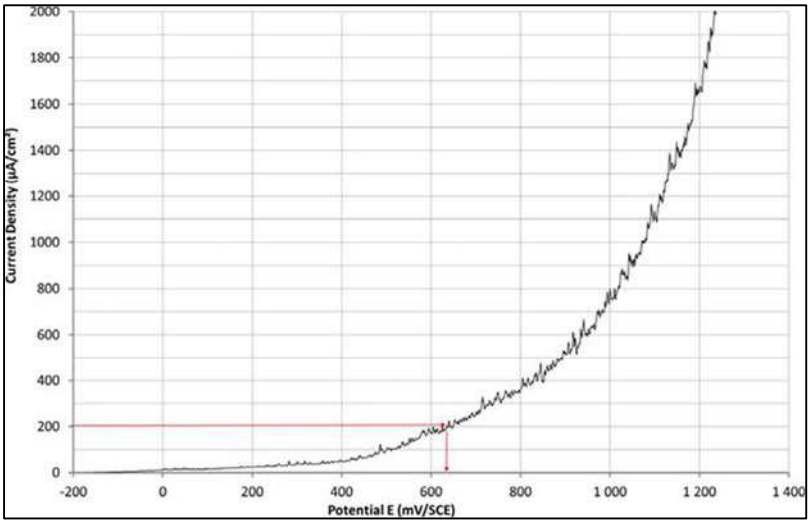



***Figure 8.*** *Example of a pitting potential measure on electropolished 1.4435 weld - after pickling and passivation – Backing gas: Ar 100% (I1) with $O_2$ pollution: 75 ppm.*

***Slika 8.*** *Primer merenja piting potencijala na elektropoliranom zavaru od čelika 1.4435 nakon dekapiranja i pasivacije – zaštitni gas sa zadnje strane: 100% Ar (I1) sa kontaminacijom $O_2$ od 75 ppm.*

All samples were tested in “as welded” and in “pickled and passivated” conditions. This pickling and passivation treatment consisted in immersing the samples for 2 h at room temperature in a solution of 20% nitric acid $HNO_3$ (69% vol. stock solution) and 2% hydrofluoric acid HF (40% vol. stock solution) for the pickling stage, followed by immersion for 30 min in a solution of 20% nitric acid HNO3 (69% vol. stock solution) at room temperature for the passivation stage.

The cutting faces are protected with varnish. The face side of the weld (outside of the tube) is also protected so that only the root side of the weld (inside of the tube) is exposed to the corrosive medium.

## 3. Results and discussion

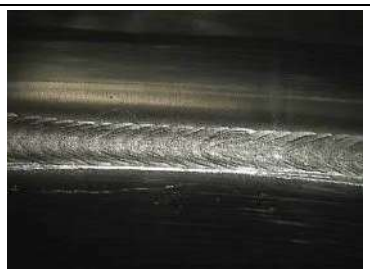
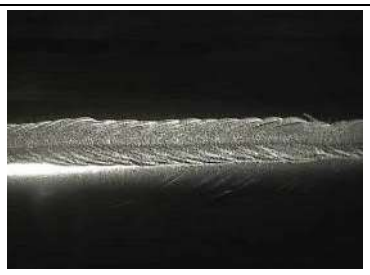
### *3.1. Effect of the quality of the backing gas and the pickling treatment on the oxidation of welds*

#### *3.1.1. Indirect visual examination*

The video borescope examinations were carried out with 3 instruments that are widely used for indirect visual examination: GE Mentor and XL Lv, and Olympus G Lite. Table 3 presents the results obtained for 4 configurations. The evaluation of these configurations can be used to infer the results of the intermediate configurations.

***Table 3.*** *Indirect visual examination of the roots of the TIG welds on grade 1.4435, as a function of the video borescope, the backing gas and the quality of the protection.*

***Tabela 3.*** *Indirektni vizuelni pregled korena TIG zavara na čeliku 1.4435, u funkciji video-boroskopa, zaštitnog gasa sa zadnje strane i kvaliteta zaštite.*

| Gas | $O_2$ contamination (ppm) | GE Mentor | GE XL Lv | Olympus G Lite |
|---|---|---|---|---|
| I1 | 10 |  |  |  |
| | 100 |  |  |  |
| R1 | 10 |  |  |  |
| | 100 |  |  |  |

As mentioned by other authors, although a video borescope inspection can highlight welding imperfections (lack of penetration, root porosity, inclusions, pores), it does not allow the quality of the gas backing to be determined. In fact, depending on the lighting conditions, which may

vary from one instrument to the other, proper root side colour discrimination cannot be achieved.

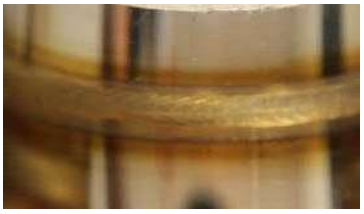
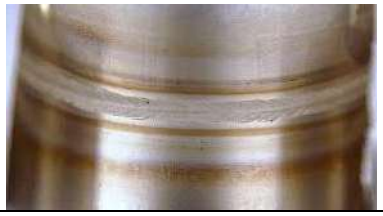
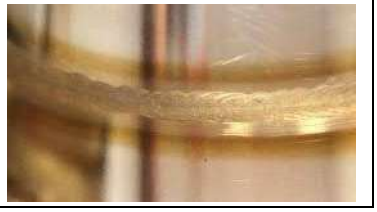
*3.1.2. Direct visual examination*

After opening of the tubes, the visual appearance of the iridescence was documented to compare it to colour charts, and in particular the chart defined in standard AWS D18-2 [7]. However, it should be noted that although the tested contamination level reached the lower threshold of 10 ppm oxygen in the argon gas backing, the coloration on the weld root side never dropped below number 2 (normally corresponding to 25 ppm of oxygen contamination) as defined in the AWS D18-2 chart. This is certainly due to the fact that, contrary to the AWS discoloration chart which is based on fusion lines, this study was conducted on tube joints. It should be noted that the coloration obtained with a 100 ppm contamination is in line with case No. 4 of the AWS D18-2 chart. The colorations obtained are in line with the guide published by Force Institute, namely levels B-C for the 10 ppm contamination, and level D for the 100 ppm contamination [8].

The present work confirms the assertions of standard AWS D18-2, namely that the addition of hydrogen to the backing gas results in a reduction in coloration and that the surface finish of the tube affects the appearance of the coloration. The visual appearance of the oxidation at the weld root highlights the reducing action induced by the addition of 5% hydrogen to the backing gas and confirms the reduction in coloration (refer to Table 4). A difference in surface coloration is rather clearly observed between a mechanically polished tube and an electropolished tube. A low initial tube roughness level (for the electropolished tube) results in lower iridescence in the heat affected zone than for the mechanically polished tube.

***Table 4.*** *Visual appearance of the TIG weld roots as a function of the material grade, the finish, the backing gas and the quality of the protection.*

***Tabela 4.*** *Vizuelni izgled korena TIG zavara u funkciji vrste materijala, završne obrade, zaštitnog gasa sa zadnje strane i kvaliteta zaštite.*

| Gas | $O_2$ contamination (ppm) | Grade 1.4404 Mechanically polished | Grade 1.4404 Electropolished | Grade 1.4435 Electropolished |
|---|---|---|---|---|
| I1 | 10 |  |  |  |
| | 100 |  |  |  |
| R1 | 10 |  |  |  |
| | 100 |  |  |  |

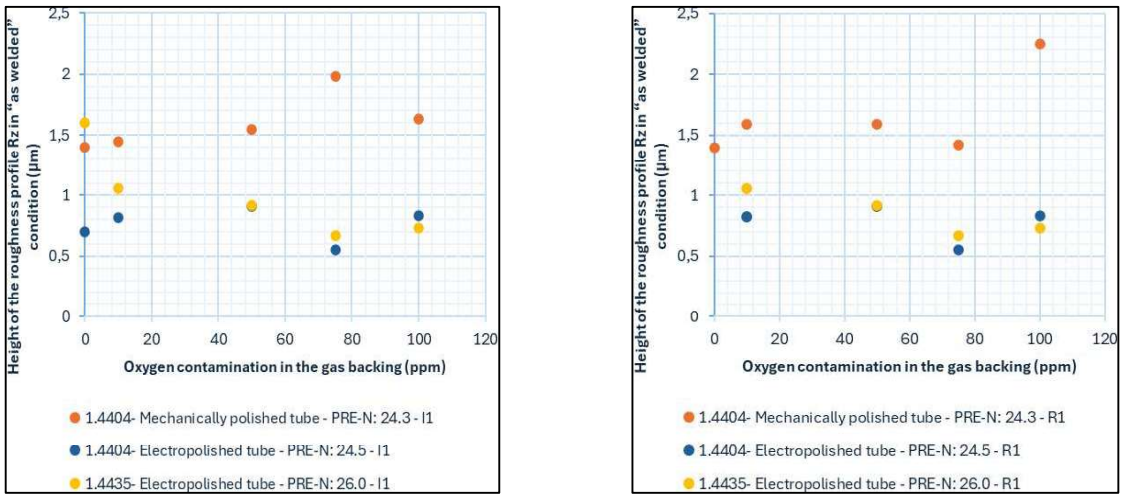
*3.2. Effect of the quality of the gas backing and the pickling treatment on roughness*

For the studied oxygen contents, the increase in contamination does not result in an increase in the arithmetic mean roughness ($R_z$), refer Figure 9, or an increase in the maximum height of the roughness profile ($R_z$). The only noticeable impact is a rise in the scattering of results as the oxygen content in the welding gas increases. The pickling operation does not cause any significant change in the roughness level: in particular, there is no peak clipping effect which could have resulted in a reduction of the $R_z$ value.

***Table 5.*** *Arithmetic mean deviation of the roughness profile ($R_a$) and maximum height of the roughness profile ($R_z$) as a function of the quality of the gas backing and the condition.*

***Tabela 5.*** *Srednje aritmetičko odstupanje profila hrapavosti ($R_a$) i maksimalna visina profila hrapavosti ($R_z$) u funkciji kvaliteta zaštite gasom sa zadnje strane i stanja površine.*

| Roughness $R_a$ / $R_z$ (µm) | | As-welded | | After pickling and passivation | |
|---|---|---|---|---|---|
| Backing gas | $O_2$ content (ppm) | I1 | R1 | I1 | R1 |
| 1.4404 – Mechanically polished tube – PRE-N: 24.3 | As received: 0.21 / 1.43 | | | | |
| | 10 | 0.20 / 1.45 | 0.25 / 1.59 | 0.20 / 1.37 | 0.19 / 1.70 |
| | 50 | 0.22 / 1.55 | 0.31 / 1.59 | 0.19 / 1.36 | 0.30 / 2.37 |
| | 75 | 0.21 / 1.98 | 0.24 / 1.42 | 0.34 / 1.40 | 0.31 / 1.47 |
| | 100 | 0.27 / 1.63 | 0.41 / 2.25 | 0.26 / 1.67 | 0.36 / 1.88 |
| 1.4404 – Mechanically polished tube – PRE-N: 24.7 | As received: 0.14 / 1.51 | | | | |
| | 10 | 0.17 / 1.65 | | 0.17 / 1.167 | |
| | 50 | 0.19 / 2.17 | | 0.15 / 1.73 | |
| | 75 | 0.17 / 1.57 | | 0.23 / 2.34 | |
| 1.4404 – Electropolished tube – PRE-N: 24.5 | As received: 0.11 / 0.69 | | | | |
| | 10 | 0.13 / 0.82 | 0.15 / 0.92 | 0.13 / 0.58 | 0.15 / 0.74 |
| | 50 | 0.20 / 0.91 | 0.16 / 1.24 | 0.16 / 0.95 | 0.17 / 1.01 |
| | 75 | 0.12 / 0.55 | 0.20 / 1.34 | 0.17 / 0.65 | 0.11 / 0.99 |
| | 100 | 0.18 / 0.83 | 0.18 / 0.96 | 0.23 / 0.76 | 0.17 / 1.44 |
| 1.4435 – Electropolished tube – PRE-N: 26.0 | As received: 0.2 / 1.6 | | | | |
| | 10 | 0.15 / 1.06 | 0.16 / 1.09 | 0.12 / 0.80 | 0.13 / 0.97 |
| | 50 | 0.12 / 0.92 | 0.14 / 1.30 | 0.26 / 1.72 | 0.14 / 0.87 |
| | 75 | 0.10 / 0.67 | 0.12 / 0.93 | 0.16 / 1.08 | 0.18 / 1.51 |
| | 100 | 0.12 / 0.73 | 0.12 / 0.92 | 0.15 / 1.15 | 0.13 / 1.01 |




Backing gas I1 Backing gas R1

***Figure 9.*** *Change in roughness vs. oxygen content in the backing gas.*

***Slika 9.*** *Promena hrapavosti u zavisnosti od sadržaja kiseonika u zaštitnom gasu sa zadnje strane.*

### *3.3. Corrosion tests*

The measurements carried out on the base materials upon receipt revealed that the type of surface finish is of little importance. In fact, the pitting potential is markedly lower for finishes with a higher roughness level. It is therefore the roughness of the tube that leads to good corrosion resistance. The tube with the lowest roughness value exhibits the highest pitting potentials. As the roughness increases, these values decrease (refer to Figure 10). This is confirmed by the results obtained on the 1.4435 grade, which features a slightly higher PRE-N but has a pitting potential that is very close to that of the mechanically polished 1.4404 grade and an equivalent roughness level.

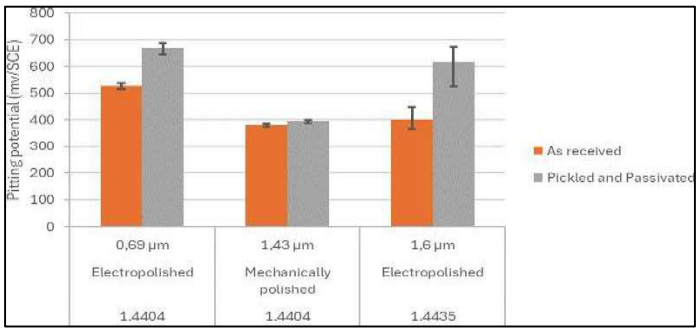



***Figure 10.*** *Pitting potential on base materials, depending on the material grade, the finishing method and the maximum height of the roughness profile $R_z$.*

***Slika 10.*** *Piting potencijal osnovnih materijala u zavisnosti od vrste materijala, metode završne obrade i maksimalne visine profila hrapavosti $R_z$.*

On the other hand, after a pickling and passivation treatment, the type of surface finish seems to play a more important role. Electropolished materials are more resistant to corrosion. Therefore, the pickling and passivation treatment seems to be more effective for electropolished surface finishes.

The pitting potential results for the different configurations are given in Table 6. In "as welded" condition, whatever the oxygen contamination levels may be, the pitting potentials are higher overall for the grade 1.4404 electropolished tube, which featured the lowest initial roughness and whose base material's pitting potential was higher by almost 150 mV/SCE compared to the other tested materials. If we consider the initial roughness as the main factor, the corrosion resistance of the "as welded" 1.4435 grade is

greater than that of the 1.4404 grade with the same roughness level. After pickling and passivation, the performance of the tubes becomes fairly the same again for all material grades, i.e. around 400/500 mV/SCE for all tested contamination levels.

In the welded zones, the results of the pitting potential measurements are much more scattered that those obtained on the base metal. This scattering stems from the fact that a welded zone is never completely identical at all its points and that pitting corrosion is a local phenomenon.

In the mechanically polished tubes, the pitting potentials, measured at the root of the welded joints, decrease sharply even from an oxygen contamination level of 10 ppm, and the higher this level, the lower the pitting potential. The other two tubes with equivalent roughness levels show fairly similar behaviours in line with their pitting resistance equivalent numbers PRE-N. (Refer to Figure 11 and Figure 12).

In all configurations, the pitting potentials are very similar for the different oxygen concentrations tested. As a result, the improvement in the quality of the gas backing has very little to no impact on the corrosion resistance.

However, contrary to what could be expected in view of the visual examinations, the hydrogen-containing gas mixture does not lead to superior behaviour compared to argon gas (I1). The pitting potential is reduced by approximately 100 mV/SCE for the R1 mixture compared to the I1 gas mixture (refer to Figure 11 and Figure 12).

***Table 6.*** *Results of the pitting potentials (mV/SCE) measured for a current density of 100 µA/cm²d.*

***Tabela 6.*** *Rezultati piting potencijala (mV/SCE) izmerenih pri gustini struje od 100 µA/cm².*

| Material grade, Surface finish, PRE-N, Roughness $R_a$ / $R_z$ (µm) | | As-welded | | Pickled and passivated | |
|---|---|---|---|---|---|
| Backing gas | $O_2$ content | I1: Pure Ar | R1: Ar + 5% $H_2$ | I1: Pure Ar | R1: Ar + 5% $H_2$ |
| 1.4404 – Mechanically polished tube – PRE-N: 24.3 – Ra = 0.2 µm / Rz = 1.42 µm | Base metal | 380 ±5 | | 394 ±5 | |
| | 10 | 97 ± 4 | 19 ± 11 | 548 ± 11 | 424 ± 20 |
| | 50 | 56 ± 14 | 93 ± 36 | 547 ± 18 | 424 ± 36 |
| | 75 | 47 ± 17 | 114 ± 13 | 384 ± 9 | 486 ± 36 |
| | 100 | 41 ± 12 | 136 ± 29 | 416 ± 30 | 364 ± 17 |
| 1.4404 – Mechanically polished tube – PRE-N: 24.7 – Ra = 0.14 µm / Rz = 1.51 µm | Base metal | | | | |
| | 10 | 103 ± 26 | | 162 ± 52 | |
| | 50 | 130 ± 42 | | 309 ± 43 | |
| | 75 | 70 ± 41 | | 302 ± 47 | |
| 1.4404 – Electropolished tube – PRE-N: 24.5 – Ra = 0.1 µm / Rz = 0.69 µm | Base metal | 41 ± 12 | | 669 ± 22 | |
| | 10 | | | | |
| | 50 | 476 ± 5 | 168 ± 18 | 383 ± 40 | 469 ± 57 |
| | 75 | 428 ± 4 | 183 ± 21 | 477 ± 42 | 542 ± 45 |
| | 100 | 374 ± 24 | 237 ± 18 | 474 ± 31 | 464 ± 49 |
| 1.4435 – Electropolished tube – PRE-N: 26.0 – Ra = 0.2 µm / Rz = 1.6 µm | Base metal | 401 ± 41 | | 617 ± 80 | |
| | 10 | 210 ± 74 | 93 ± 32 | 462 ± 101 | 242 ± 96 |
| | 50 | 198 ± 2 | 209 ± 76 | 295 ± 78 | 458 ± 49 |
| | 75 | 166 ± 73 | 148 ± 2 | 592 ± 65 | 232 ± 80 |
| | 100 | 96 ± 16 | 81 ± 50 | 637 ± 109 | 418 ± 51 |

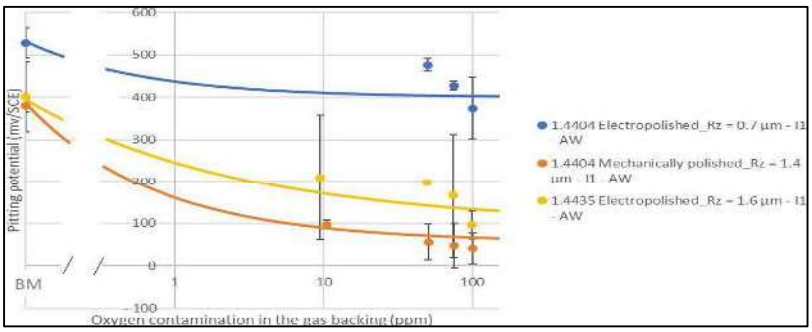



***Figure 11.*** *Effect of gas contamination in the backing gas (I1) on the pitting potential for grades 1.4404 and 1.4435.*

***Slika 11.*** *Uticaj kontaminacije zaštitnog gasa sa zadnje strane (I1) na piting potencijal čelika 1.4404 i 1.4435.*

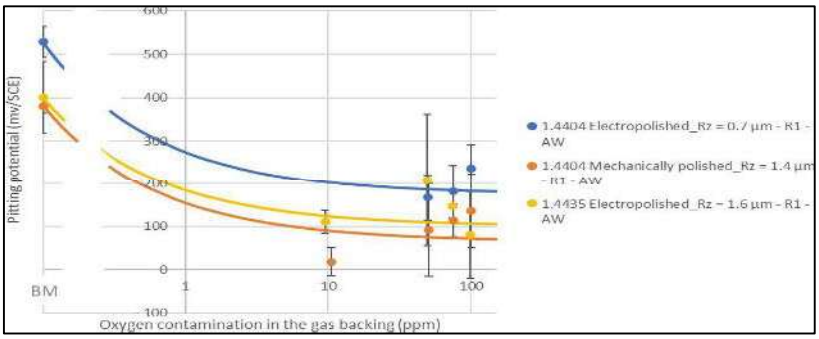



***Figure 12.*** *Effect of gas contamination in the backing gas mixture (R1) on the pitting potential for grades 1.4404 and 1.4435.*

***Slika 12.*** *Uticaj kontaminacije smeše zaštitnog gasa sa zadnje strane (R1) na piting potencijal čelika 1.4404 i 1.4435.*

In the pickled and passivated condition, on mechanically polished tubes, the pitting potentials remain equivalent to those of the base metal for all configurations. On electropolished tubes, the pitting potentials are lower than those of the base metal in "as received" condition, but the level obtained is of the same order as that of the mechanically polished tubes. These results are in line with the previous studies where the corrosion resistance was restored with contamination levels reaching approximately 1% (10,000 ppm) [10-12].

Although the roughness measurements are relatively scattered, it appears that the roughness level has an impact on the resistance to pitting corrosion in the "as welded" condition (refer to Figure 13). This impact is particularly visible above a maximum roughness Rz of 1.5 µm, where no values can reach values closed to those of the base metal. Nevertheless, it should be noted that, in the pickled and passivated condition, the roughness level has less effect on corrosion resistance. The close relationship evidenced in the "as welded" condition is undoubtedly more closely related to the relationship between roughness and contamination.

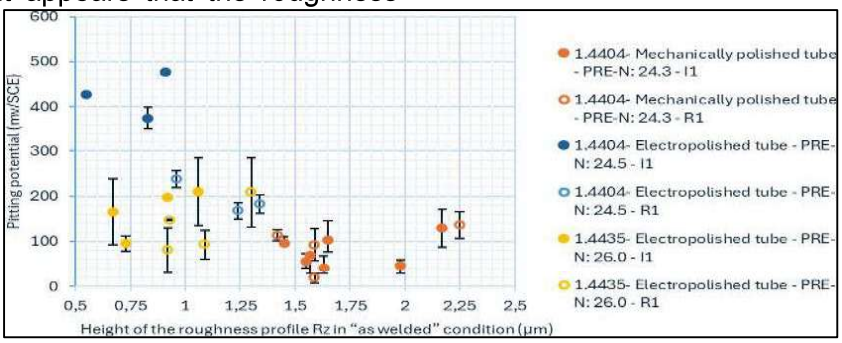



**Figure 13.** Effect of the maximum height of the roughness profile ($R_z$) on corrosion resistance, irrespective of the backing gas and nature of the tube.

**Slika 13.** Uticaj maksimalne visine profila hrapavosti ($R_z$) na otpornost prema koroziji, nezavisno od zaštitnog gasa sa zadnje strane i vrste cevi.

## 4. Conclusions

As expected, the addition of hydrogen limits the coloration of the welded zones, in particular at the lowest contamination levels. Beyond the level of backing gas, the quality of the tube (mechanically polished or electropolished) leads to a different level of coloration. The weld seams of the electropolished tubes generally feature a lower level of coloration than those of the mechanically polished tubes.

In terms of corrosion resistance, it appears that the initial quality of the tube is important in order to avoid the need for a pickling and passivation treatment. Therefore, to achieve optimum corrosion resistance, the use of an electropolished tube with a low level of roughness is essential. On the other hand, this study shows that although the argon backing could allow the tube to be left as-is in the event the oxygen contamination remained below 50 ppm or 75 ppm, the behaviour of the hydrogen-containing gas is not at the expected level. In “as welded” condition, such an Ar+5%H2 mixture would not make it possible to avoid the need for a pickling and passivation treatment, irrespective of the contamination level, contrary to what the colourless appearance of the welds might have suggested. This unexpected behaviour has led to further work which will form the subject of a forthcoming study.

It is worth noting that, for the tested contamination levels, the relationship between the coloration of the oxide layers and the corrosion resistance of the material is less obvious than it would seem at first sight, and it depends on many factors (surface condition, nature of the backing gas). Moreover, this study shows that an indirect visual examination with a borescope can in no case be used to determine the quality of the gas backing.

## 4. Zaključak

Kao što se i očekivalo, dodatak vodonika ograničava obojenost zavarenih zona, naročito pri najnižim nivoima kontaminacije. Pored kvaliteta zaštitnog gasa sa zadnje strane, kvalitet cevi (mehanički polirana ili elektropolirana) dovodi do različitog stepena obojenosti. Zavareni spojevi elektropoliranih cevi generalno pokazuju niži stepen obojenosti od zavarenih spojeva mehanički poliranih cevi.

U pogledu otpornosti prema koroziji, pokazuje se da je početni kvalitet cevi važan kako bi se izbegla potreba za tretmanom dekapiranja i pasivacije. Stoga je, za postizanje optimalne otpornosti prema koroziji, neophodna upotreba elektropolirane cevi sa niskim nivoom hrapavosti. S druge strane, ova studija pokazuje da, iako bi zaštita argonom sa zadnje strane mogla omogućiti da se cev ostavi u stanju nakon zavarivanja ukoliko kontaminacija kiseonikom ostane ispod 50 ppm ili 75 ppm, ponašanje gasa koji sadrži vodonik nije na očekivanom nivou. U stanju „nakon zavarivanja“, smeša Ar + 5% $H_2$ ne bi omogućila izbegavanje tretmana dekapiranja i pasivacije, nezavisno od nivoa kontaminacije, suprotno onome što bi bezbojni izgled zavara mogao da sugeriše. Ovo neočekivano ponašanje dovelo je do daljih istraživanja, koja će biti predmet naredne studije.

Vredno je napomenuti da je, za ispitane nivoe kontaminacije, odnos između obojenosti oksidnih slojeva i otpornosti materijala prema koroziji manje očigledan nego što bi se na prvi pogled moglo činiti i da zavisi od mnogih faktora, kao što su stanje površine i vrsta zaštitnog gasa sa zadnje strane. Pored toga, ova studija pokazuje da se indirektni vizuelni pregled pomoću boroskopa ni u kom slučaju ne može koristiti za određivanje kvaliteta zaštite gasom sa zadnje strane.

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