Atmospheric corrosion of ASTM A-242 and ASTM A-588 weathering steels in different types of atmosphere

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ABSTRACT

The work analyses the atmospheric corrosion resistance of two widely used weathering steels: ASTM A-242 and ASTM A-588. The steels were exposed for up to 5 years in different types of atmosphere: rural, urban, industrial and marine. The atmospheric corrosion resistance of the steels was evaluated and the rust layers formed on them were characterised by X-ray diffraction, optical microscopy and scanning electron microscopy. The most relevant conclusions reached include the following: (a) the visual appearance (colouring) of the rust, rust texture, nature of the corrosion products and compactness of the rust layers formed are similar in both types of weathering steel. (b) No great differences are observed in the corrosion resistance. Slight differences occur in the industrial atmosphere, where ASTM A-242 presents 10–13% less corrosion than ASTM A-588. (c) In the C2-C3 ISO corrosivity atmosphere both types of weathering steels are adequate for unpainted use. However, they are not suitable in higher ISO corrosivity atmosphere.

INTRODUCTION

Commonly weathering steels (WS) are often referred to as CORTEN steels, a term coined by US Steel in 1933 when the company launched the first commercial WS under the brand name USS Cor-Ten steel, a name that reflected the two properties differentiating it from plain carbon steel (CS), i.e. its higher corrosion resistance (Cor) and its superior mechanical properties (tensile strength, Ten).

In 1941 the first WS was standardised by ASTM A-242; a steel that is roughly comparable to USS Cor-Ten A steel. Its main characteristic is its high resistance to atmospheric corrosion, which is approximately 4 times greater than that of CS due to the presence of Cu, a high P content, and in general the presence of Ni (0.50–0.65 wt-%). In 1968 ASTM A-242 presented two specifications [1], one with a high P content (<0.15 wt-%) and the other with a lower P content (<0.04 wt-%), the latter ultimately replaced by ASTM A-588 [2], which is roughly comparable to USS Cor-Ten B steel. This steel possesses less resistance to atmospheric corrosion due to its lower P content but has better weldability.

Extensive information on the atmospheric corrosion of WS has been published in the literature, mostly concerning ASTM A-242 WS. A smaller amount of information is also available on the atmospheric corrosion resistance of ASTM A-588 WS. A bibliographic review on this topic has recently been published [3].

In order to get a broad understanding of the atmospheric corrosion resistance of these two steels it is desirable to test them in a wide range of typical atmospheres, from the least aggressive (rural) to those polluted with different amounts of SO₂ (urban, industrial) or chlorides (marine). Few studies of the atmospheric corrosion of commercial WS consider such a broad range of atmospheric aggressivities as the present study, which, besides evaluating the atmospheric corrosion resistance of these two WS in up to 5 years of exposure, also makes an in-depth analysis of the resulting rust properties (colouring, texture and composition) and rust layer structure.

EXPERIMENTAL

WEATHERING STEELS

Research has been carried out with two commercial WS, corresponding to specifications ASTM A-242 [1] and ASTM A-588 [2], whose chemical compositions are listed in Table 1. The composition of the steels was determined by glow discharge optical emission spectroscopy using a Leco model SA-2000 surface analyser. The carbon content was analysed with a Leco model CS230 unit by combustion of a 5 g shaving of the material in an induction furnace and subsequent determination of the carbon content by infrared absorption.

Microstructural analysis of the two types of WS was carried out by taking a representative sample of each steel and microscopic observation of the surface using an Olympus model PM3 optical microscope. Micrographs of these two steels are shown in Figure 1, revealing a characteristic equiaxial grain ferrite-pearlite type microstructure with a grain size of 14.1 µm. The presence of bainite was also observed.

Mechanical characterisation of the different steels was achieved through the performance of tensile tests and hardness tests. The former were performed in a MicroTest model EM2/100/FR 100 kN electromechanical testing unit, applying a transverse speed of 0.9 mm min⁻¹ until reaching the yield strength, subsequently increased up to 2 mm min⁻¹, according to EN ISO 6892-1 [4]. Three tensile tests were performed determining three different mechanical properties: (a) yield strength, (b) ultimate strength and (c) elongation. The yield strength was obtained from the stress–strain diagram,
adopting the conventional criterion of the stress above which the material experiences plastic deformation of 0.2%. Elongation was determined by means of the calibrated length, L= 25, using an extensometer with a base length of 10 mm. Hardness testing was carried out with a Zwick model 3203 Vickers hardness meter according to standard EN ISO 6507-1 [5].

The results obtained are presented in Table 2. From the mechanical point of view both steels comply with standard ASTM A-709/A-709M grade 50W [6]. The higher yield strength of ASTM A-588 WS is due to its higher Mn content, while the higher C content of ASTM A-242 WS confers it a higher ultimate strength and greater hardness [7]. With regard to the ductility of these steels, which can be evaluated by their elongation percentage, both are very similar.

### Atmospheric corrosion tests

Specimens of 100×50×3 mm were prepared by cutting and subjected to G-17/G-40 angular shot blasting in order to completely remove the oxide layer (millscale) formed during hot rolling and obtain a surface finish of ASa2½, in accordance with Swedish standard SIS 055900 [8], with a roughness profile of 75 µm. They were then subjected to cleaning in an ultrasonic bath, being submerged consecutively in distilled water, ethanol and acetone for 1 min in each solvent and then immediately dried with forced hot air and weighed in an analytical balance of 0.1 mg sensitivity.

Six different test sites have been considered: a rural atmosphere at Pardo (P), with very low SO2 and Cl− pollutant contents; an urban atmosphere in Madrid (C), with light SO2 pollution (0.80 mg m−2 d−1); two industrial atmosphere at Avilés (A) and Kopisty (K), with higher SO2 contents (4.64 and 14.20 mg m−2 d−1); and two pure marine atmosphere at Cabo Vilano-1 (X) and Cabo Vilano-2 (Y), with chloride deposition rates of 20.4 and 71.4 mg Cl− m−2 d−1, respectively. Atmospheres P, C, A, X and Y correspond to different exposure sites in Spain, while atmosphere K is a corrosion station operated by SVUOM Ltd. in the Czech Republic. Despite the limited space availability for specimen exposure in the Kopisty station, it was considered to be of great interest due to its relative space availability for specimen exposure in the Kopisty station.

All the steels were exposed on open-air racks at an angle of 45° from the horizontal plane. The corrosion stations were equipped with relative humidity (RH) and temperature (T) sensors along with the necessary instrumentation to measure atmospheric pollution in terms of SO2 and Cl− [9]. Table 3 sets out environmental and corrosivity category data [10] corresponding to the different test sites.

After 1, 2, 3 and 5 years of exposure four specimens were withdrawn from the testing stations in order to obtain data on mass loss due to corrosion following standard ISO 9226 [11] (three specimens) and for characterisation of the rusts and corrosion layers formed (one specimen). Unfortunately information is not available for Cabo Vilano-2 after two years of exposure due to an act of vandalism affecting the testing station.

### Characterisation of the corrosion products and corrosion layers formed

The colouring of the rusts formed in the different exposure conditions was evaluated by visual inspection, taking photographs of the skyward facing side of the exposed test specimens.

The rust texture (grain size) of the outermost surface of the rust layer was determined using the tape method [12], which consists of adhering a 2 cm × 2 cm piece of adhesive tape to the surface of the rust layer, pressing firmly and evenly on the surface, and lifting off to examine the size and density of rust particles.

The techniques used to characterise the corrosion products layers were polarised light microscopy (PLM) to study rust stratification, scanning electron microscopy (SEM) to study the morphology of the corrosion products on the outermost surface of the rust layer, and X-ray diffraction (XRD) to determine the phases present in the rust. To observe any possible stratification of the rust layers formed on the different WS, use was made of a Nikon EPIPI HOT 300 polarised light microscope coupled to an Infinity 2 camera. Analyses were performed on cross-sections of the specimens, always considering the skyward facing side. SEM studies were carried out on the skyward facing side of the exposed specimens using a JEOL JXA-840 electron microscope equipped with a Link System electron microprobe.

XRD measurements were carried out with a Bruker AXS D8 diffractometer equipped with a Cu X-ray tube (wavelength 1.79 Å) and parallel beam optic (Goebel mirror). A current of 30 mA and a voltage of 40 kV were employed as tube settings to perform 20 scans over a range from 10° to 80° in conventional Bragg–Brentano geometry, with a step width of 0.03° and a counting time of 3 s per step. Quantification of the different phases present in the rust samples has been carried out using

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**Table 1.** Chemical composition (wt-%) of the weathering steels.

|          | C  | Si | Mn | P   | S   | Cr | Ni | Cu | Al | Nb |
|----------|----|----|----|-----|-----|----|----|----|----|----|
| ASTM A-242 | 0.12 | 0.42 | 0.33 | 0.089 | <0.010 | 0.84 | 0.17 | 0.37 | 0.035 | <0.010 |
| ASTM A-588 | 0.057 | 0.39 | 0.91 | 0.027 | <0.010 | 0.57 | 0.30 | 0.35 | 0.025 | <0.010 |

**Table 2.** Yield strength, ultimate strength, elongation and hardness values of the weathering steels.

| WS         | Yield strength (MPa) | Ultimate strength (MPa) | Elongation (%) | Hardness (HV5) |
|------------|----------------------|-------------------------|----------------|----------------|
| ASTM A-242 | 396                  | 554                     | 38             | 185            |
| ASTM A-588 | 420                  | 519                     | 37             | 170            |
the Rietveld method. The analyses were performed directly on rusted sheet on the specimens of two WS. The appearance of the ferrite peak in the diffractogram indicated that the analysis had included the entire rust layer.

Results and discussion

Visual appearance (colour) of the rusts formed

Carbon steel exposed to the atmosphere develops ochre-coloured rust which becomes dull brown as exposure time increases. Figure 2 displays photographs showing the variation in the colour of the outermost rust formed on the two WS after 5 years of exposure in the rural (Pardo), industrial (Kopisty) and marine (Cabo Vilano-1) atmospheres. The rust colouring is similar in the rural and industrial atmospheres, while the patina formed in the marine atmosphere presents lighter tones. No significant differences in rust colouring are observed between the two tested WS.

Rust grain size

Figure 3 shows the variation in the granulometry of the outermost surface of the rust layer formed on the two steels exposed for 5 years in the rural (Pardo), urban (Madrid), industrial (Avilés and Kopisty) and marine (Cabo Vilano-1) atmospheres. The rust colouring is similar in the rural and industrial atmospheres, while the patina formed in the marine atmosphere presents lighter tones. No significant differences in rust colouring are observed between the two tested WS.

Corrosion resistance

Figure 4 displays the corrosion rates found for the two WS exposed in the six testing stations and their evolution with exposure time. The corrosion rates can be ordered (from lesser to greater) as follows:

\[
Pardo < Madrid < Avilés < Kopisty < Cabo Vilano-1 < Cabo Vilano-2.
\]

After 3–5 years of exposure in the various atmospheres no great differences can generally be seen between the corrosion resistance of the two types of WS, though a more rigorous comparison should take into account longer exposure times when a steady-state corrosion rate has been reached. The relationships \( R \) between the corrosion rates of ASTM A-242 WS and ASTM A-588 WS are relatively close to unity (Table 4). Perhaps the greatest differences in the behaviour of the two steels occur in the industrial atmospheres, where

**Table 3.** Environmental characteristics and corrosivity category [10] of atmospheric corrosion test stations.

| Atmosphere | Exposure site (code) | \( T \) (°C) | HR (%) | \( SO_2 \) (mg m\(^{-2}\) d\(^{-1}\)) | \( Cl^- \) (mg m\(^{-2}\) d\(^{-1}\)) | Corrosivity category | First year corrosion of mild steel (µm) |
|------------|----------------------|-------------|--------|-------------------------------|-------------------------|----------------------|---------------------------------|
| Rural      | Pardo (P)            | 15.3        | 69     | 0.28                          | 2.7                     | C2                   | 5.35                           |
| Urban      | Madrid (C)           | 14.2        | 63     | 0.80                          | 3.0                     | C2                   | 7.38                           |
| Industrial | Avilés (A)           | 14.5        | 78     | 4.64                          | 7.0                     | C3                   | 27.37                          |
| Industrial | Kopisty (K)          | 8.9         | 73     | 14.20                         | –                       | C3                   | 27.42                          |
| Marine     | Cabo Vilano-1 (X)    | 13.5        | 84     | 0.66                          | 20.4                    | C3                   | 34.20                          |
| Marine     | Cabo Vilano-2 (Y)    | 13.5        | 84     | 0.66                          | 71.4                    | C4                   | 63.40                          |

– Not available.

**Figure 2.** Photographs showing the variation in color of the outermost rust formed on the two WS after 5 years of exposure at different atmospheres.

**Figure 3.** Variation in the granulometry (grain size) of the outermost surface of the rust layer formed on the two WS after 5 years of exposure at different atmospheres.
ASTM A-242 WS presents 10–13% less corrosion rate than ASTM A-588 WS after 4–5 years of exposure.

A main feature that is claimed to WS is that it does not need to be coated (e.g. by means of a paint system) for atmospheric exposure. It is a matter of the greatest practical relevance to define what environmental conditions determine the applicability of unpainted WS in a given atmosphere. From a practical point of view, the most widely used criterion has been to limit the steady-state corrosion rate to $\leq 5–6 \text{µm y}^{-1}$ [13,14].

Figure 4. Corrosion rates of the two WS within each type of atmosphere after different times of exposure.
The results obtained in this study have been used to construct corrosion rate (CR) versus exposure time curves for each of the considered atmospheres (Figure 5). In this figure an indication is also given of the 5–6 µm/year band below which it is feasible to use the WS unpainted. In the atmospheres of lowest corrosivity, P and C, with corrosivity category C2 (see Table 3), it can be seen how the CR values of the two steels are ≤ 5–6 µm/year after only 3 years of atmospheric exposure. In the atmospheres of corrosivity category C3 (A, K, X) the CR is very close to the 5–6 µm/year band, and it is foreseeable that after exposure times of more than 5 years, when the corrosion rate reaches a steady state, the critical threshold for their use unpainted in atmospheric exposure may easily be reached. There is no doubt that in the marine atmosphere of corrosivity category C4 (Y), where despite information only being available for two years of exposure, the corrosion rates of the different steels are well higher than the threshold of 5–6 µm/year, so their use without a paint coating is not feasible. As is known, chloride ions degrade the protective ability of the rust layers [15], constituting the principal limitation for the use of conventional WS in marine atmospheres. The resulting rust layers formed are increasingly less protective the higher the atmospheric salinity at the exposure site.

**Corrosion products and corrosion layers**

Characterisation of the corrosion products formed on the two WS exposed during 5 years in the various atmospheres was carried out by means of XRD. With this technique the diffractograms of magnetite and maghemite are very similar, being very difficult to carry out their differentiation by XRD. For the sake of simplicity, both iron oxides are referred to in this paper as ‘spinel’.

The phases present in the recorded patterns were identified by the search-match technique using the DIFFRACplus EVA software by Bruker AXS and the JCPDS database [16]. This method shows that the main phases formed on steel under the selected atmospheric conditions are lepidocrocite (JCPDS pattern 44–1415), goethite (JCPDS pattern 29–0713), and in a smaller concentration spinel (JCPDS pattern 19–0629). In this work use has been made of version 4.2 of the TOPAS Rietveld analysis program (Bruker AXS) to model the full pattern with the crystallographic information obtained from Pearson’s Crystal Structure databases [17]. Although the Rietveld analysis including only a combination of lepidocrocite, goethite and spinel as the crystal structure model results in accurate peak fitting for most of the tested atmospheres, in the case of the rust layer formed in the marine atmosphere at Cabo Vilano-2 (Y) or the industrial test site at Kopisty (K) the existence of additional diffraction peaks is deduced. The simulated patterns can be improved when compared with the experimental findings if akaganeite (Cabo Vilano-2) or kornelite (Kopisty) are included in the refinement, respectively (Figure 6).

**Low corrosivity atmospheres (Pardo and Madrid)**

The corrosion products found were lepidocrocite (major), goethite and spinel (minor). Table 5 shows the contents found for these rust phases formed on the two WS after

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**Table 4. Values of relationship R between corrosion rates of ASTM A-242 and ASTM A-588 exposed during different times of exposure at various atmospheres.**

| Types of atmosphere | Time of exposure (years) | R   |
|---------------------|--------------------------|-----|
| Rural (Pardo)       | 1                        | 0.93|
|                     | 3                        | 0.96|
| Urban (Madrid)      | 1                        | 1.01|
|                     | 3                        | 1.00|
| Industrial (Avilés) | 1                        | 0.98|
|                     | 4                        | 0.90|
| Industrial (Kopisty)| 1                        | 0.96|
|                     | 5                        | 0.87|
| Marine (Cabo Vilano-1) | 1                  | 0.97|
|                     | 5                        | 0.94|
| Marine (Cabo Vilano-2) | 1                  | 1.00|
|                     | 2                        | 1.00|

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**Figure 5.** Corrosion rate (CR) versus exposure time graphs for ASTM A-242 and ASTM A-588 steels exposed up to 5 years in various atmospheres P (Pardo), C (Madrid), A (Avilés), K (Kopisty), X (Cabo Vilano-1) and Y (Cabo Vilano-2).

**Figure 6.** Comparison of the observed (blue circles) and calculated (solid line) XRD patterns obtained after Rietveld refinement for the rust layer formed on ASTM A-242 WS at Kopisty (a) and on ASTM A-588 WS at Cabo Vilano-2 (b), respectively.
5 years of exposure in Pardo test site. No great differences are seen between both WS.

It is well established that lepidocrocite is the crystalline product that forms initially on the surface of steel [18]. When the surface electrolyte layer generated on steel (condensed humidity, rainwater, etc.) is mildly acid, lepidocrocite is transformed into goethite. The spinel phase also forms by the reduction of lepidocrocite in the presence of a low oxygen concentration [19,20], according to the reaction:

\[ 2\gamma-\text{FeOOH} + \text{Fe}^{2+} \rightarrow \text{Fe}_3\text{O}_4 + 2\text{H}^+ \] (2)

for which reason it is usually found in the innermost zone of the rust layer, very close to the underlying steel, where the oxygen concentration is highly limited.

Figure 7 presents PLM views of cross-sections of the rust layers formed on both WS steels exposed for 5 years in the rural atmosphere of Pardo. The rust layer is relatively thin and fairly compact, which justifies the low corrosion rates of steels in this type of atmosphere. The outer surface of the rust layer presents the typical orangy colouring of the lepidocrocite phase [21]. SEM observation of this surface (Figure 8) reveals feather-like (Figure 8a) and bird’s
Oxidative hydrolysis of FeSO₄ leads to formation of oxyhydrates which is transformed into sulfate according to the cathodic reaction: 

$$\text{SO}_2 + \text{O}_2 + 2\text{e}^- \rightarrow \text{SO}_4^{2-}$$ (3)

balanced either by the dissolution of the metal

$$\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$$ (4)

or by the oxidation of Fe⁺² in the existing rust layer

$$2\text{Fe}^{2+} \rightarrow 2\text{Fe}^{3+} + 2\text{e}^-.$$ (5)

Oxidative hydrolysis of FeSO₄ leads to formation of oxyhydrates as the chief component of rust [24,25]

$$\text{FeSO}_4 + 2\text{H}_2\text{O} \rightarrow \text{FeOOH} + \text{SO}_4^{2-} + 3\text{H}^+ + \text{e}^-.$$ (6)

In the same way as in the rural and urban atmospheres, in the industrial atmospheres the corrosion products formed on the different steels were lepidocrocite (major), goethite and spinel (minor) (see Table 5). However, in the Kopisty atmosphere, with a higher SO₂ content (14.20 mg m⁻² d⁻¹), a significant kornelite [Fe₂(SO₄)₃·7H₂O] content was also found, of the order of 3 wt.-%. Also in this type of atmosphere, no great differences are observed between both WS. The proportions of goethite phase found in these atmospheres (33-36 wt-%) were higher than those found in the rural or urban atmospheres (25-28 wt-%). Atmospheric SO₂ facilitates the dissolution of lepidocrocite [26], accelerating the transformation of lepidocrocite to goethite.

Iron sulfates are water soluble (e.g. ferric sulfate has a water solubility of 440 g per 100 cm³ [27]) and rainwater will wash them from the corrosion product layers, so that any small remaining amounts may go undetected by the different analytical techniques used. The higher kornelite contents found in the rust formed at Kopisty indicates that in this case insufficient leaching has occurred for this compound to go unnoticed in the XRD analysis. The reverse should have been true in the Avilés atmosphere, with a lower SO₂ content (4.6 mg m⁻² d⁻¹), where leaching of the sulfate should have led to a residual content in the rust below the XRD detection limit.

Figure 9 presents PLM views of cross-sections of the rust layer formed on both WS in the industrial atmosphere of Avilés after 5 years of exposure. In comparison with Figure 7 obtained in the rural atmosphere of Madrid, it is seen that the rust layer presents greater thickness with the presence of abundant longitudinal and transversal cracks. The formation of lepidocrocite (orangey colour) as a consequence of the atmospheric corrosion process takes place both on the surface of the rust layer and in the cracks within it [28].

SEM observations of outermost surface of the rust layers (Figure 10) reveal the presence of globular and laminar formations of lepidocrocite [22] as well as a greater cracking of rust layers in comparison with the layers formed in less aggressive atmospheres (Figure 8). No great differences are seen between both WS. It is of interest to mention the existence of goethite needles or whiskers around the periphery of the lepidocrocite globules [29,30] in the rust formed in Kopisty (Figure 10a), not observed in the less SO₂ polluted atmosphere of Avilés (Figure 10b). As mentioned earlier, the SO₂ dissolved in the aqueous layer promotes dissolution of lepidocrocite and its transformation to goethite [26].

**Marine atmospheres (Cabo Vilano-1 and 2)**

The agent that stimulates the atmospheric corrosion of carbon steel in this type of atmosphere is the chloride ion which is present in marine aerosol and, like SO₂, promotes higher corrosion rates than those found in atmospheres with low pollution (Pardo, Madrid). The corrosion rate increases in line with the chloride deposition rate in the atmosphere [15] (Figure 5).

In this type of atmosphere, besides the formation of lepidocrocite, goethite and spinel, the presence of akaganeite is also detected in Cabo Vilano-2 of higher chloride deposition rate (71.4 mg m⁻² d⁻¹) (Table 5). In this case, the akaganeite contents of the rust are significant (though minor, as in the case of the spinel phase) of the order of 3 wt.-%. Also in this type of atmospheres, no great differences are observed between both WS. The proportions of lepidocrocite and goethite phases found were similar than those found in the low corrosivity atmospheres.
As is known, the oxyhydroxide akaganeite (β-FeOOH) forms in marine atmospheres [15]. The formation of akaganeite is preceded by the accumulation of chloride ions in the aqueous layer present on the metal, giving rise to the formation of ferrous chloride (FeCl₂), which hydrolyses water according to the reaction [31]:

\[
\text{FeCl}_2 + 2\text{H}_2\text{O} \rightarrow \text{Fe}(	ext{OH})_2 + 2\text{HCl} \quad (7)
\]

notably raising the acidity of the surface electrolyte.

At the steel/corrosion products interface, where Cl⁻ ions accumulate, high chloride concentrations and acidic conditions lead to the formation of ferrous hydroxychloride (β-Fe₂(OH)₃Cl). The oxidation process of the ferrous hydroxychloride which leads to the formation of akaganeite passes through different stages via the formation of an intermediate green rust compound GR(Cl). The complete oxidation process may be summarised as follows [32–36]:

\[
\text{FeCl}_2 \rightarrow \beta - \text{Fe}_2\text{(OH)}_3\text{Cl} \rightarrow \text{GR(Cl)} \rightarrow \beta - \text{FeOOH}. \quad (8)
\]

Figure 11 presents PLM views of cross-sections of the rust layers formed on both WS in the marine atmosphere of Cabo Vilano-1 after 5 years of exposure. The micrographs are similar to those corresponding to the Avilés atmosphere (see Figure 9), showing abundant cracking and the formation of lepidocrocite (orangy colouring) both on the surface and in bands inside the rust layer. However, unlike in the industrial atmosphere, in the marine atmosphere the underlying
steel presents notable pitting. In the SEM observations of the outermost surface of the rust layer (Figure 12) the typical lepidocrocite laminar formations can be seen, as occurred in the other types of atmosphere. The main difference lies in the higher porosity between the lepidocrocite formations (Figure 12a) as a consequence of the larger grain size of the rust formed in these atmospheres, aspect already mentioned above. Akaganeite formations are not observed on the outer surface of the rust layer as they occur preferentially in the innermost region of the rust layer, close to the base steel [29,30].

Conclusion

The following may be highlighted as the most relevant conclusions of this work:

(1) Both WS exposed to the atmosphere develops ochre-coloured rust which becomes dull brown as exposure time increases. In the marine atmospheres the colouring of the rust becomes lighter.

(2) The grain size of the rust formed on both WS increases with the corrosivity of the atmosphere. Patinas with smoother textures are found in less corrosive atmospheres (rural and urban), while higher atmospheric corrosivity (industrial and marine) give rise to rougher textures.
(3) In all the atmospheres considered in this study the rusts formed on both steels contain the following phases: lepidocrocite (major), goethite and spinel (minor). In the industrial atmosphere with the higher SO2 content (Kopisty) kornelite (Fe2(SO4)3·7H2O) is also formed as a minor phase, while in the more aggressive marine atmosphere (Cabo Vilano-2) akaganite is formed, also as a minor phase.

(4) The rust layers formed on both steels exposed in the least aggressive atmospheres (rural, urban) are fairly compact, but this is not the case in the more aggressive atmospheres (industrial, marine), where abundant cracking is observed. In the marine atmospheres also strong pitting of the underlying steel takes place.

(5) The corrosion rate of steel varies according to the type of atmosphere where it is exposed in the following order (from lesser to greater): rural < urban < industrial < marine. After 5 years of exposure in the various atmospheres no great differences can generally be seen between the corrosion resistance of the two types of WS, however some differences occur in the industrial atmospheres, where ASTM A-242 WS presents 10–13% less corrosion than ASTM A-588 WS.

(6) In the C2-C3 ISO corrosivity atmospheres (Pardo, Madrid, Avilés, Kopisty and Cabo Vilano-1), both types of WS are adequate for unpared use. However, are not suitable in the atmosphere of C4 corrosivity category (Cabo Vilano-2).

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Disclosure statement

No potential conflict of interest was reported by the authors.

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