

FAILURE ANALYSIS AND CORROSION MECHANISM INVESTIGATION OF HEAT EXCHANGER PLATES FROM AN OIL REFINERY

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This paper presents research conducted on four plates from a heat exchanger located in an oil refinery, aiming to identify the causes leading to their severe corrosion. The chemical composition, macro- and microstructural analysis, and hardness characteristics of the material were analyzed. Results obtained were compared with material standard specifications outlined in the equipment documentation. A separate chapter details optical and electron microscopy analyses of corrosion developed on plate surfaces. Finally, the probable causes of premature plate failure caused by severe corrosion are discussed.

Keywords: corrosion, heat exchanger, industrial equipment, oil refinery, austenitic steel

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1. Introduction

The scope of this paper is the assessment of the quality of the material used in heat exchanger plates and the analysis of corrosion processes leading to their deterioration. For the purpose of this study, four plates exhibiting corrosion damage up to wall perforation were selected.

The analyzed plate heat exchanger is located on the site of a refinery and is part of the installation associated with a gas compressor. The circulating fluids consist of demineralized water containing hydrocarbon traces at a working pressure of 2.5 bar and temperatures of 50°C at inlet and 43°C at outlet, respectively cooling water at a working pressure of 5 bar and temperatures of 28°C at inlet and 38°C at outlet.

During operation within nominal parameter limits, after approximately 2640 operating hours, the heat exchanger failed due to loss of structural integrity of the plates. Multiple corrosion processes were identified, leading to perforation of numerous plate walls.

This paper includes the following analyses and determinations:

- analysis of the quality of the material from samples taken from heat exchanger plates, namely chemical composition analysis, microstructure, and hardness characteristics;
- comparison of obtained results with the provisions of the material standard specified in the equipment documentation;
- analysis of the corrosion process developed on plate surfaces through optical or electron microscopy methods;
- evaluation of the probable causes of premature plate failure.

The paper presents data concerning the development of the corrosion process responsible for the premature failure of stainless steel plates, as well as recommendations for measures that may enhance the operational safety of the analyzed heat exchanger.

2. Experimental research

The heat exchanger consists of 20 stainless steel plates of grade 1.4404 EN 10028-7 (SS 316 L), with overall dimensions of approximately $300 \times 850 \text{ mm}^2$. Four of these plates were selected for analysis and are shown in Figure 1. All analyzed plates exhibit perforations with dimensions of up to 4 mm.

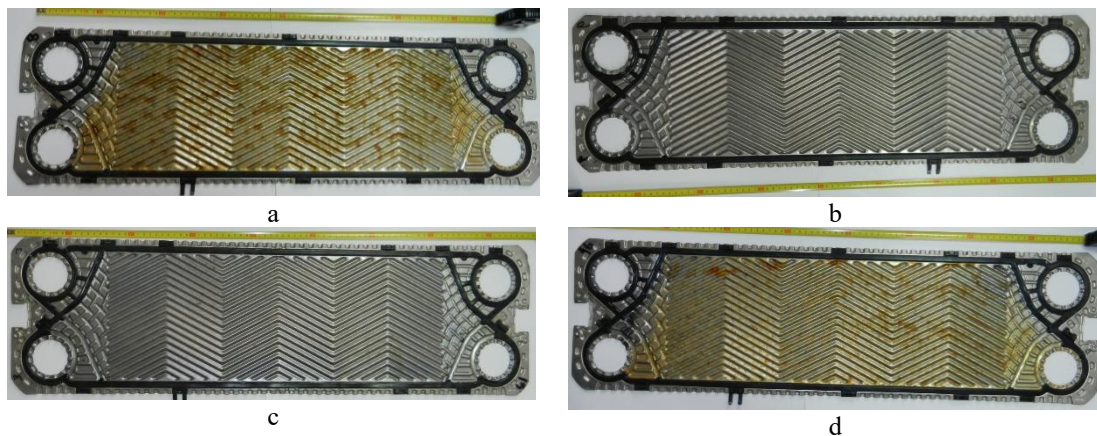


Figure 1. Plates for the analyzed heat exchanger

2.1 Analysis of the quality of the heat exchanger plates' material

2.1.1 Chemical Composition

The technical specification of heat exchanger E-01 indicates that its plates are manufactured from steel grade 1.4404 according to EN 10028. Verification of the chemical composition was carried out on a material sample taken from plate marked 2. The analysis was performed using the LECO GDS 500 A optical emission spectrometer, and the obtained results are presented in Table 1.

Table 1. Material chemical composition

	in %								
	C	Si	Mn	P	S	N	Cr	Mo	Ni
X2CrNiMo 17-12-2 (1.4404) EN10028	max. 0,030	max. 1,00	max. 2,00	max. 0,045	max. 0,015	max. 0,11	16,50... 18,50	2,00 ... 2,50	10,00... 13,00
Plate 2 ¹⁾	0,025	0,36	0,84	0,033	0,003	0,035	16,62	2,07	10,25

¹⁾ Other elements: 0,28% Cu; 0,08% V; 0,025% Al; 0,20% Co

It is observed that the material meets the chemical composition conditions of the EN10028 standard corresponding to the prescribed mark. The material is an austenitic type stainless steel with low carbon content and molybdenum addition [1, 2, 3].

2.1.2 Microstructural analysis

The analysis was performed with an optical microscope OLYMPUS Model: BX 51 M, in several cross sections of the slices, both in flat areas, located close to the contour, and in contoured areas belonging to the heat exchange surfaces.



Figure 2. Microstructure of the material in the contour zones of the plates; etched with Marble's reagent

In the flat areas, the microstructure is γ -solid solution (austenitic), with maced polyedra. The grain size is very fine, corresponding to ASTM grain size score 8 (Figure 2).

In areas profiled by embossing process (Figure 3), the microstructure is textured, typical of a cold plastically deformed material.



Figure 3. Material microstructure of cold-formed plate areas etched with Marble's reagent

2.1.3 Microhardness determinations

Microhardness determinations were carried out with an INNOVATEST microhardness tester Model: FALCON 500 both in areas of apparently undeformed material near the contour of the slabs, and on areas of embossed profiled material placed near the points where corrosion perforation occurred. The results of the determinations are given in Table 2.

Table 2. Material hardness determined in different areas of the plates

Examined area	$\mu\text{HV}_{200\text{ gf}}$
Undeformed	144; 145; 150; 152
Cold formed / Embossed area	270; 271

The results indicate a significant increase in hardness in the profiled areas of the heat exchanger plates.

2.2 Surface analysis of the corrosion damage process of heat exchanger plates

2.1.1 Macroscopic analysis

The macroscopic appearance of the heat exchanger plates results from the overview images given in Figure 1, as well as from the detail images given in Figure 4 ÷ 7.

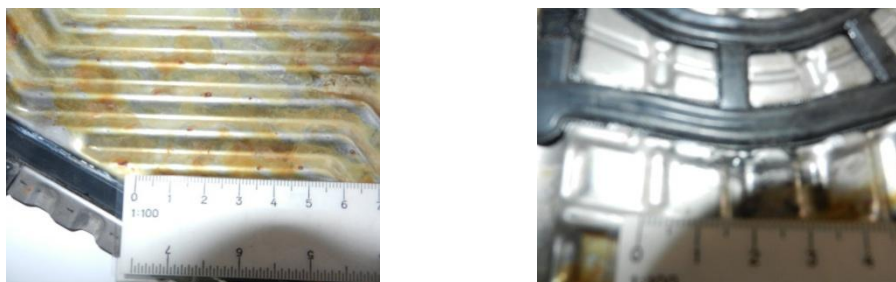


Figure 4. Macroscopic appearance of the mark 1 sample

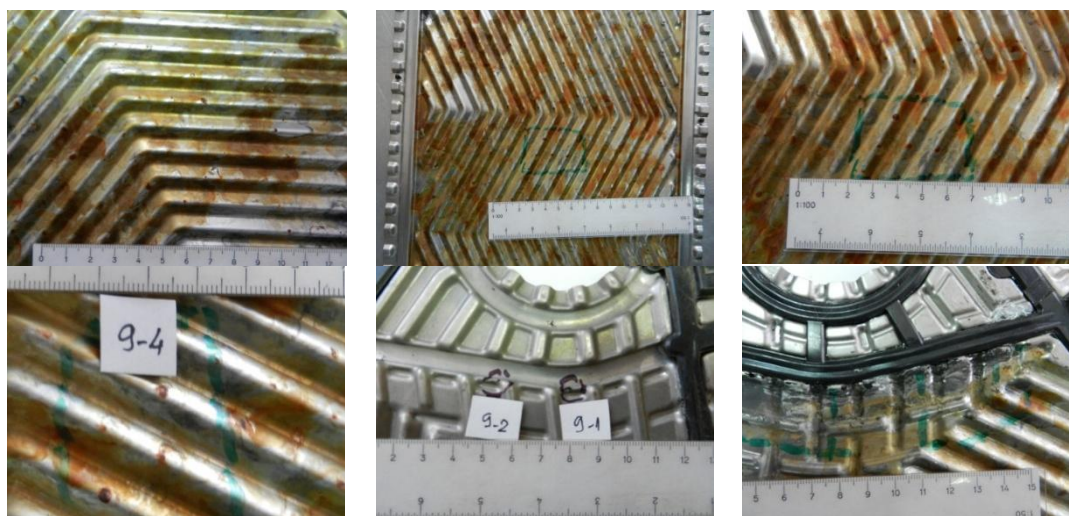


Figure 5. Macroscopic appearance of the mark 2 sample

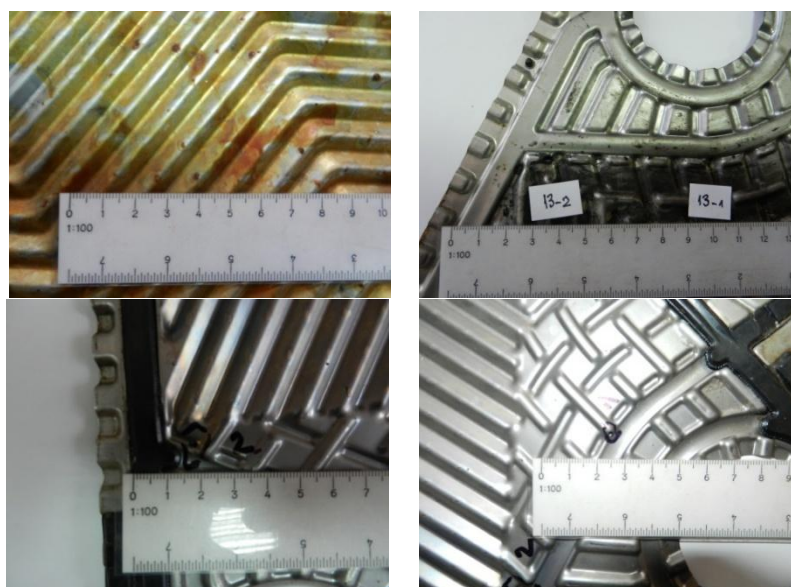


Figure 6. Macroscopic appearance of the mark 3 sample

The following can be observed:

a) the two faces of each plate differ significantly in appearance; one of them is clean and with a metallic sheen, while the other shows an uneven appearance, with stains and deposits of a yellowish-brown color; thus, in the case of plates marked 1 and 4, the affected faces are those on which the contour gasket is fixed, while in the case of plates marked 2 and 3, the affected faces are the opposite faces to the face with the contour gasket; [8,9]



Figure 7. Macroscopic aspect of the mark 4 sample

b) the faces with yellowish-brown deposits show numerous points, randomly positioned on the face of the plate, in which local deterioration processes occur on the surface of the plate; in the vast majority of cases, these points are positioned on the tips of the protrusions that shape the plate;

c) the most affected areas, in which the deterioration process has caused the perforation of the material and the development of holes up to 5 mm in size, are located near the circular cutouts; in these areas, the material shows a strong local profiling; the thickness of the material decreases in these areas up to approx. 0,38 mm, compared to ca. 0.50 mm in the undeformed areas at the periphery of the plates.

2.1.2 Optical microscopy analysis

One of the perforations in the plate marked 4 is shown in Figure 8. It was located in the ambushed area at the contour of the circular cutout illustrated in Figure 7.



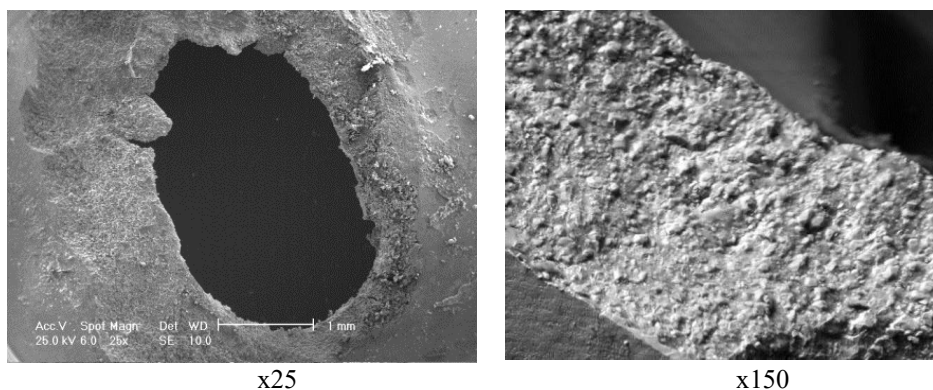
Figure 8. Corrosion in the crevice in the area of the circular cutout in the plate mark 4

The detail images showing the two faces of the material show that the tear-out was caused by localized corrosion. The edges are corroded, with undercuts towards the face with the gasket. We assess that this type of highly localized corrosion is “crevice” corrosion. Both faces of the analyzed area are in the proper face environment with yellow reddish deposits.

2.1.3 Electron microscopy analysis

The surface morphology of the exchanger plates in the areas affected by corrosion was also analyzed under the FEI QUANTA 450 FEG electron microscope.

In the case of the plate mark 4 the top of a strongly deformed area was examined in which the plate presented a corrosion spot with wall perforation. The images included in Figure 9 illustrate the outline of the plate wall puncture point and the appearance of the corrosion surface at the edge of the hole.



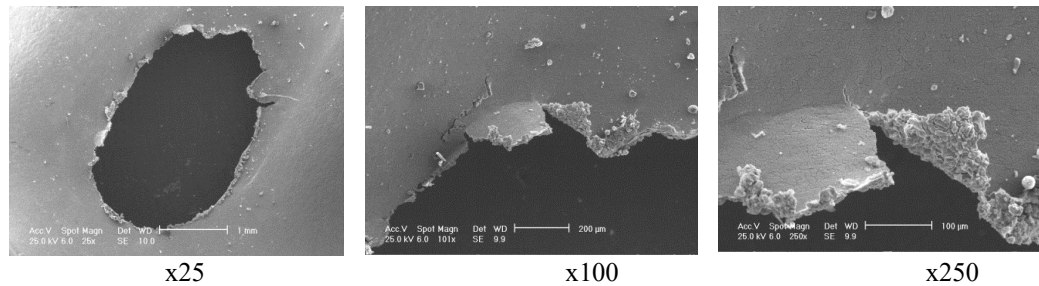


Figure 9. Appearance of a pitting corrosion spot, present in the plate mark 4 a) face of the plate without gasket (with yellowish-brown spots) b) face of the plate with gasket (with clean surfaces, with metallic sheen)

It is evident that the corrosion process has penetrated the passivated layer on the surface of the material and has progressively expanded by increasing both the contour and the depth of the affected area. The corrosion initiating surface is the one corresponding to the face of the plate without gasket (yellowish-brown color).

A separate analysis aimed to highlight the particularities of the yellowish-brown colored plate face in an uncorroded area, on which there is an adherent deposit. The appearance of such an area is shown in Figure 10. It shows the presence of a relatively uniform deposit, which after drying shows extensive cracking after drying, as well as an area with prominent formations in relation to the face of the plate, consisting of adherent deposits.

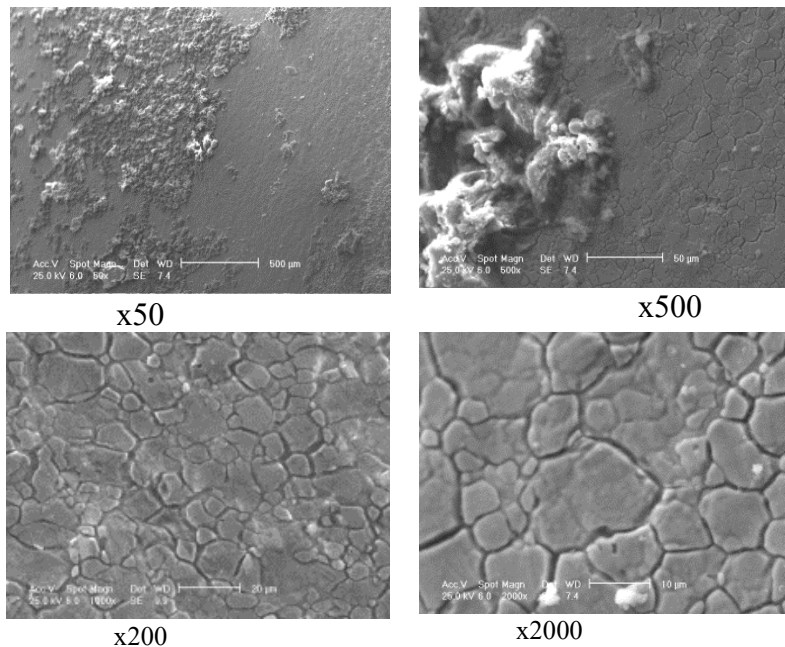


Figure 10. Deposits on the face of the plate marker 4 ; Qualitatively, the nature of the deposits is evidenced by the X-EDS emission spectra (Figure 11a). Quantitative data obtained after fluorescence correction are shown in Figure 11b

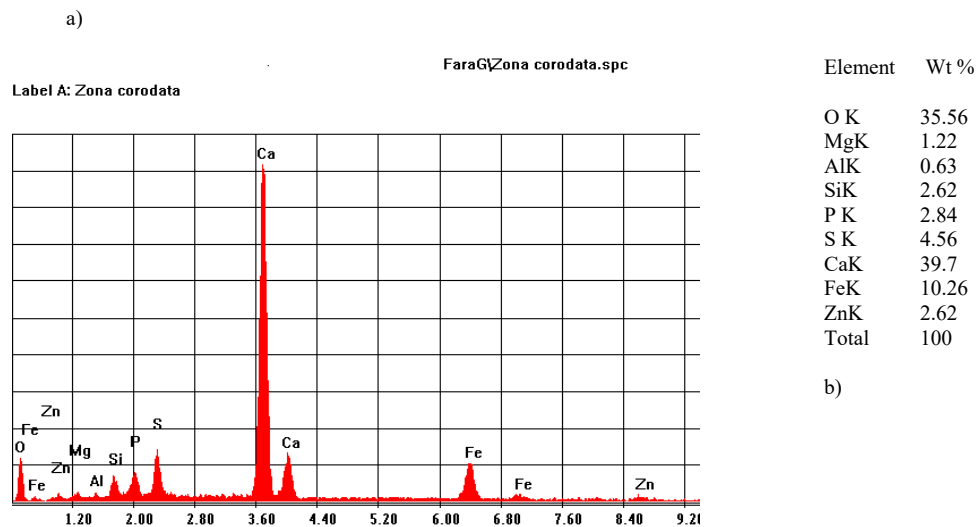


Figure 11. Analysis of the nature of the deposits on the yellowish-brown colored surface of the plate mark 4

The presented data reflect the nature and proportion of the products in the medium in contact with the respective face of the heat exchanger plate.

3. Interpretation of the results

The results of the investigations carried out on the heat exchanger plates indicate that the premature failure of the heat exchanger plates occurred as a result of spot or crevice corrosion processes affecting the faces of the plates in contact with the cooling water. In relation to these processes, the following clarifications are made. [10]

a) Corrosion resistance is the main criterion for the use of stainless steels in applications of the analyzed category. This is not a material property itself but results from the interaction between the material and the environment in contact with its surface. In the case of the analyzed material, in addition to the aspects related to the steel grade, i.e. its chemical composition, an important aspect is the structural state determined by the profiling process of the heat exchanger plates;

b) The resistance of stainless steel to localized corrosion attack by pitting or crevice corrosion increases with the Cr, Mo and N content. To order the steels according to their sensitivity to localized pitting (CPT) or crevice corrosion (CCT), laboratory tests are performed with highly corrosive solutions whose aggressiveness is stimulated by increasing temperature. Critical temperature is the temperature at which a steel shows corrosion initiation. Figure 10 shows the critical temperatures for crevice or pitting corrosion determined for a number of stainless steels in a ferric chloride solution.[11] It should be noted that these temperatures

cannot be interpreted as indicating in detail the behavior of a given steel in a given environment, but steels with higher CCT or CPT critical temperatures generally have superior corrosion resistance in a wide range of real environments.

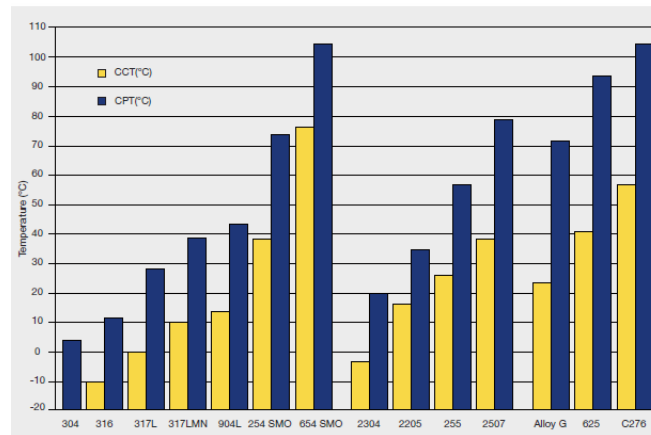


Figure 12. Spot (CPT) or crevice corrosion resistance (CCT) of different stainless steel grades [4]

It can be observed that the steel of the grade 1. 4404 according to EN 10028 used in the execution of the analyzed exchanger plates can be appreciated as showing satisfactory resistance to spot or crevice corrosion in cooling water environment with temperatures up to 40 ÷ 50 0C and controlled acid number [5,6].

The steel grades mentioned in Table 3 shows superior resistance to spot or crevice corrosion.

Table 3. Steel grades with high pitting or crevice corrosion resistance [7]

Symbol acc. to EN 10088		Content in %				
		Cr	Ni	Mo	C _{max}	Altele
X2CrNiMo18-14-3	1.4435	17÷19	12,5÷15	2,5÷3,0	0,03	≤ 0,11 N
X2CrNiMoN22-5-3	1.4462	21÷23	4,5÷6,5	2,5÷3,5	0,03	0,1÷0,2 N
X2CrNiMoN17-13-5	1.4439	16,5÷18,5	12,5÷14,5	4÷5	0,03	0,1÷0,2 N
X1CrNiMoCuN20-18-7	1.4547	19,5÷20,5	17,5÷18,5	6÷7	0,02	0,18÷0,25 N 0,5÷1,0 Cu
X1CrNiMoCuN25-20-7	1.4529	19÷21	24÷26	6÷7	0,02	0,15÷0,25 N 0,5÷1,5 Cu

c) The plates of the heat exchanger show areas with significant plastic deformation of the material, i.e. with thickness reductions reaching values of approx. 20 ÷ 25 %. As it can be seen in the diagram in Figure 13, the plastic deformation generates a strain hardening process identified in the case of E-01 heat exchanger plates by local hardness increases of approx. 100 % compared to the average values identified in the undeformed areas on the contour of the plates.

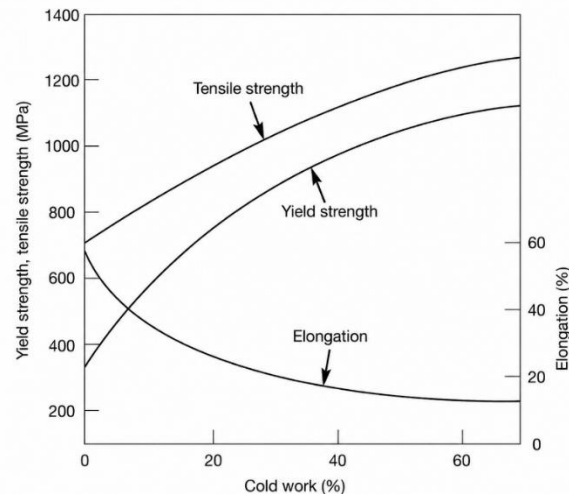


Figure 13. Effect of cold deformation on the mechanical properties of an austenitic steel with 0.2% nitrogen [4]

Scaling is a factor that sensitizes the material to spot or crevice corrosion. In the case of the material of the exchanger plates, this aspect is evidenced by the intensity of the corrosion process revealed by microscopic examination. The initiation of the corrosion process was favored by the presence of adherent deposits of products carried by the cooling water, as well as by the constructional particularities of the plates, such as the proximity of circular perforations. [12,13]

d) Conditions in the cooling water that favor spot or crevice corrosion include halide ion contents and the presence of oxidizing agents. Data on the composition of the deposits present on the faces of cooling plates affected by spot or crevice corrosion can be useful in analyzing the presence of factors in the cooling water that can stimulate corrosion processes.

4. Conclusions

The analysis of the four plates from the heat exchanger revealed the following aspects.

- The material of the plates is an austenitic stainless steel with low carbon content and molybdenum addition. Its chemical composition falls within the provisions of the EN10028 standard corresponding to the W1. 4404; in the areas profiled by embossing, the microstructure of the material shows an accentuated, textured distribution, inducing a specific cold deformation hardening; the hardness of the material shows important variations from values of 145.... 150 HV_{0,2} in the contour areas, apparently undeformed, up to 270 HV_{0,2} in the strongly profiled areas, for example near the circular perforations

- In each of the examined plates, one of the faces has a clean surface and maintains its metallic luster, while the other face shows stains and signs of deposits of a yellowish-reddish color; in the case of plates marked 1 and 4, the affected faces are the ones on which the contour gasket is fixed, while in the case of plates marked 2 and 3, the affected faces are the ones opposite to the face with the contour gasket;

- The four plates examined show numerous signs of local corrosion attack, developed in some cases up to the penetration of the metal wall and the formation of holes up to 5 mm in size; in all cases, the corrosion initiation sites are located in areas of protrusions of the plate profile that correspond to important plastic deformations of the material, as is the case of the areas near the circular perforations;

- The macroscopic and microscopic examination of the damaged surfaces revealed pitting or crevice corrosion processes initiated from the surface with yellowish-reddish spots and deposits. At each point of attack, the corrosion penetrated the passivated surface layer of the material and progressively extended by increasing both the contour and the depth of the affected area. The intensity of the corrosion process is evidenced by the appearance of the corrosion surface, which shows the deep penetration into the plate thickness (see Fig. 9).

- The corrosion process that generated the premature failure of the heat exchanger was determined by the incompatibility between the constructive particularities of the heat exchanger plates and the working environment, which caused the change in appearance and the formation of deposits on one of the faces of each plate of the heat exchanger. In the case analyzed, it is to be assumed that the most probable corrosive medium is cooling water.

From the constructive point of view, the geometrical features of the plate profile of the exchanger plates are noted, which caused the sensitization of the material by erosion and increased the speed of development of corrosion processes in the 1.4404 steel. In connection with these aspects, it would be necessary to analyze the technological solutions practiced when forming the exchanger plates or promoting a stainless steel grade with superior resistance to spot or crevice corrosion.

Author Contributions

Conceptualization, C.P.; methodology, A.B.; S.C.; validation, C.P.; S.C. and G.C.; formal analysis, A.B. and S.C.; investigation, A.B. and E.M., G.C., M.S. and A.P.; writing—original draft preparation, C.I.T. and A.G.; writing—review and editing, K.S.S. and M.R.D.; supervision, S.C. and A.P. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

Artificial Intelligence Disclosure

No artificial intelligence-based or generative tools were used in the preparation of this manuscript.

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