

Article

Performance Analysis of Fe-Cr Alloys Inside a Corrosive Environment at High Temperatures 500 and 600 °C

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Abstract

The new requirements for materials with improved properties and resistance to hazardous aggressive environments is very important in industrial incinerators and stoves. Thus, the present manuscript is dedicated to the study of the chemical interaction between Fe-Cr alloys at high temperatures (500–600 °C). Four alloys with different Al, Si, and Mo chemical composition were tested to determine their resistance to active laboratory conditions. The conditions were established based in those inside waste disposal incinerators. Laboratory equipment was set up to reproduce an enclosed aggressive but controlled atmosphere. Cylinders filled with N₂ and O₂ generated an 8% vol, and other containers produced a 220 vppm of HCl, 360 Vppm of H₂O, and 200 vppm of SO₂. The exposition was not continuous because the goal was to analyze the material response along different exposition times. The corrosion products that resulted after chemical etching were characterized using Scanning Electron Microscopy (SEM), X-ray diffraction (XRD), and taking an average of various thermo-gravimetric measurements. The main products were Cr₂O₃, Fe₂O₃, Fe_{0.6}Cr_{0.4}, and Fe and Cr. The alloy with the best performance was found and theoretical principles of corrosion were analyzed to understand the corrosion mechanisms, which were driven by the formation of non-protective oxides.

Keywords: waste incinerator atmosphere; aggressive environments; Fe-Cr alloys; high temperature corrosion; materials characterization



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1. Introduction

Nowadays, recycling and re-using have become popular topics for returning our world to its natural balance. Pollution in the world has become a relevant topic for the future sustainability of human life [1–6]. Recycling has become a new branch of science and has gone through enormous development during the beginning of the 21 century [1–3,5–12]. The technology of processes and huge budgets has made possible many very expensive processes, which can be adopted as suitable for recycling almost any waste materials. However, there are some unclassified and hazardous materials which remain complicated

to recycle [10–15]. These materials are frequently those with a complex manufacturing process, and they are sent to waste disposals to be burned in furnaces or industrial boilers as unrecoverable or non-recycled materials [1–4,14–20]. Combustion is employed to eliminate them. However, high temperatures are absolutely necessary to burn some of the plastic and chemical residues which make up these materials; these are organic but have a complex return process for being recycled or re-used [6–9,20–25]. Consequently, temperatures between 500 and 600 °C or even higher must be used in furnaces. Some authors have reported results considering temperatures up to 1000 °C in Boliers and other chemical reactors [1–3,14–18]. Unfortunately, aggressive atmospheres with flowing hazardous gases are formed as a consequence of the formation of HCl and water vapor [6–11,17–24]. These gases make contact with the incinerator walls corroding them. Industrial stoves and furnace incinerators, including heat interchanges and boilers, are made with Fe-Cr or Fe-Cr-Ni ferritic and austenitic alloys because a hard resistance protective scale is formed, preventing the corrosion process from continuing [6–11,18–31]. The scale is a corundum type (Al_2O_3), but based on $(\text{Cr-Fe})_2\text{O}_3$. However, the formation of the protective scale over the sample surface depends on the chemical activity inside the furnace. Thus, it is so important to understand the corrosion mechanisms in every incinerator [6–11,20–25]. An aggressive environment is an active gaseous atmosphere containing reactive substances passing across the wall, as is the case in incinerators. This fluid flow touches the wall surfaces, accelerating the corrosive conditions.

An additional problem which complicates industrial operations and practices is the heterogeneity of the wastes burned. Thus, an alternative but appropriate solution is to have a good control of the waste compositions in order to take control over the chemical activity [6–11,25–28,32–39]. Unfortunately, this is a serious limitation because many of these wastes are received mixed and without previous selection. For this reason, some authors have dedicated their research to working with different chemical compositions and using different temperatures and different industrial practices to guarantee safe industrial operating conditions and extend as long as possible the lifetime of the walls of industrial incinerators and buildings [6–11,17–23,28–37]. Some authors have worked testing aluminum alloys due to their resistance to corrosion. Others have dedicated their work to validating steel's resistance to corrosion due to its better mechanical resistance. Still other authors have tested synthetic materials, plastics, or different alloys with a metal base [24–27,32–34,40–49].

Some authors have reproduced rare, aggressive environments, including mechanical works and efforts inside tanks, chemical reactors, boilers, and other devices to study the corrosion process. They have also studied corrosion in mechanical components in contact with humidity and other aggressive gases and liquids. Moreover, salts and little abrasive solids can adhere to the surfaces, also producing corrosion, or act as erosive gridding dusts, affecting the walls' lifetime [11–14,28–37]. Other authors have produced, tested, and characterized different metallic alloys, trying to extend the lifetimes of mechanical components in machines [21–27,35–42,50,51]. The different chemical compositions of wastes will create different kinds of gases, and the amounts of these generate increments of pressure and temperature conditions which can accelerate the corrosion process [16–21,27–30,32–34,40–43,46–49,51]. Some authors have done extensive work studying the structure of the scale formed, measuring its hardness and the measuring its thickness using different laboratory equipment such as Scanning Electron Microscopy or X-Ray Diffraction XRD techniques [1–6,11–15,24–51].

The understanding of the corrosion mechanisms allows a determination of whether a protective scale will be formed and whether it would vanish under certain chemical activity

or flow conditions. Thus, it is possible to evaluate the effectiveness of any alloy under any probable solution [21–27,40–47].

Sometimes the scale formed over the contact surfaces is weak and disappears, but forms again and again, making a continuous periodic mass loss and affecting the mechanical properties of the material. Therefore, the integrity of the component can be comprised [16–22,35–40,50,51]. Thus, the goal of this research is focused on the characterization of four different alloys based on Fe-Cr with varying amounts of Al, Si and Mo inside a furnace under two different temperatures, 500 and 600 °C.

Some authors have studied the problem of corrosion at high temperatures because it is a frequent problem in chemical reactors and other devices that use a combustion process to burn hazardous materials. Previous research has explored the possibility of employing different kinds of steel. Steel is a material frequently selected to build these reactors due to its high fusion temperature, which allows the incineration of almost every organic or hazardous material. Sometimes, stainless steel is selected to build the walls of these reactors [6–11,27–30,32–34,40–43,46–51]. Nevertheless, it is very expensive. Many authors have therefore studied the use of alternative low-cost alloys based on Fe-Cr. Others have tried developing coatings for covering and avoid the corrosion activity. Thus, the authors on the corrosion field have divided their research, taking into account the following factors [30,31,35–37,40–47].

- (a) The chemical composition of the metallic material being supported, including some protective elements.
- (b) Operational conditions inside the incinerator, such as the temperature and pressure of the components.
- (c) Fluid flow of the gases or humidity inside the chemical reactor.
- (d) Chemical reaction (Interaction) between the surface of the sample and the homogeneity of the scale formed.
- (e) The chemical composition of the wastes burned and the consequently aggressive environment formed.

2. Sample Preparation

During this research, four alloys based on Fe-Cr were made in a foundry and cast using dust metal with a controlled purity of 99.9%. The dust was treated inside a mill operating at a low rotating speed; this procedure was used to avoid pollution as much as possible. The metals were melted in an induction furnace. Then, the melting metal was cast in rustic but clean iron molds to form 150 × 150 mm ingots. These ingots were cut in the middle zone, and a thermo-mechanical process was applied to get a grain refinement. Then a heat treatment at 900 °C was applied for one hour. After this, the samples were cut to 10 × 10 × 2 mm. Finally, the samples were sanded using 180, 250, 400, and 600 SiC sandpaper, cleaned with acetone and ethanol in an ultrasonic bath, and weighed. The four alloys' chemical composition is shown in Table 1.

Table 1. Nomenclature and chemical composition of the alloys.

Alloy	Cr	Mo	Al	Si	Fe
Fe9Cr2.5 AlSi5Mo	9	5	2.5	2.5	Balance
Fe9Cr2.5 AlSi3Mo	9	10	2.5	2.5	Balance
Fe9Cr1.5 AlSi3Mo	9	10	1.5	1.5	Balance
Fe9Cr3AlSi3Mo	9	3	3.0	3.0	balance

3. Hardness Analysis

The hardness testing was applied to the samples in a calibrated hardness testing machine. Five measurements of every sample were taken. Hardness Vickers testing was applied to a set of prepared samples to determine their hardness after being cast and after the heat treatment. The results are shown in Tables 2 and 3. After checking that this analysis was possible, we confirmed that there is a noticeable difference in the hardness of the four alloys after casting. Nevertheless, this difference was noticeably reduced after heat treatment [22–27,35–39,42–47]. Then, we applied a treatment that homogenized the grains' structure, creating reliability for the next round of testing and its results. Alloy four demonstrated the highest hardness values. Hardness was not measured after the corrosion experimental exposures because it was assumed that the corrosion process did not affect the hardness of the original samples. Alloys Fe9Cr2.5AlSi5Mo and Fe9Cr1.5AlSi3Mo demonstrated major differences after casting. However after the heat treatment, the fluctuation mean was reduced to that of the other two alloys [8–12,29–31,35–37]. It is important to mention that these conditions allowed us to test different steels with different chemical compositions but also allowed us to test steel with the same chemical compositions but with or without a heat treatment, providing a variety of possibilities for future research and future suggestions for materials with applications in aggressive environments.

Table 2. Micro-hardness Vickers after casting.

Sample	Fe9Cr2.5AlSi5Mo	Fe9Cr2.5AlSi3Mo	Fe9Cr1.5AlSi3Mo	Fe9Cr3AlSi3Mo
1	266.0	235.6	188	231
2	271.1	219.7	217.4	240
3	262.0	228.3	178.8	272
4	262.0	242.5	198.6	280
5	284.0	233.1	206.5	300
6	310.2	218.2	194.2	310
7	311.4	239	198	277
8	284.0	229.9	213.8	299
9	292.0	230.7	213.3	305
10	292.0	234.8	249.7	303
average	283.47	231.18	205.83	281.7

Table 3. Micro-hardness Vickers after heat treatment.

Sample	Fe9Cr2.5AlSi5Mo	Fe9Cr2.5AlSi3Mo	Fe9Cr1.5AlSi3Mo	Fe9Cr3AlSi3Mo
1	247.0	203.2	210.1	272.2
2	218.9	209.6	200.2	268.0
3	232.3	213.5	198.2	272.2
4	225.1	202.3	188.2	280.7
5	229.9	213.5	195.4	267.0
6	234.8	198.3	187.7	268.0
7	225.9	217	199.1	280.7
8	225.9	219.9	189.3	268.0
9	233.1	212.2	195.5	265.0
10	222.0	214.2	184.3	274.3
average	229.49	210.7	194.8	271.61

After the samples' foundry and cast procedures were done, the differences between the hardness measurements were averaged. An analysis to determine the value variation is shown in Table 4. Here, it is evident that variations after heat treatment derived from a more homogeneous grain structure, and the hardness values variation was reduced for the four alloys. Additionally, the values of the standard deviation were calculated, evidencing a total correspondence of the dispersion of data; high values indicate a major dispersion.

Table 4. Maximum variation between averaged hardness measurements and standard deviation values.

Sample	Fe9Cr2.5AlSi5Mo	Fe9Cr2.5AlSi3Mo	Fe9Cr1.5AlSi3Mo	Fe9Cr3AlSi3Mo
casting	14.556	5.82	14.31	21.7
heat treatment	5.93	5.616	5.94	4.41
Standard deviation				
casting	91.8907	7.7176	19.650	27.6085
heat treatment	7.9525	6.9538	7.6639	5.5501

4. Experimental Testing Procedure (Chemical Etching)

Figure 1 shows the experimental setup arrangement for the simulation of the aggressive environment. Here, O₂ and SO₂ flow directly toward the furnace. The HCl and H₂O are introduced using N₂ as a gas propellant, which moves them toward the furnace. The N₂ is used as a propellant gas for moving H₂O and HCl. Thereafter, the aggressive atmosphere will contain a percentage of both gases plus certain amounts of O₂ and SO₂, controlled using the valves in the sketch [17–22,35–39,42–47]. Additionally, every gas mentioned is typical of gases or products obtained after combustion. Moreover, the mechanism for oxide formation is illustrated in Figure 1b. Here, we can appreciate the ions' evolution in the metal and the fluid environment and how they form Fe(OH)₂ in response to the activity of the oxygen with the Fe metal base. In addition, rust formation due to the interactivity between the incinerator walls and the trespassing non-protective scale is shown in Figure 1c. Here can also be appreciated a breaking crack in the formed scale, which obviously allows the interaction between the aggressive external environment and the metal base, promoting the continuation of the corrosion reaction [27,28,32–45].

The samples were exposed to the aggressive environment N₂-O₂ 8% vol with 220 vppm, HCl 360 vppm, H₂O 220, SO₂, inside the furnace with a 50 mm diameter quartz glass to 500 and 600 °C during 300 h. The gas proportion was controlled with an opening valve integrated to a fluid flow fluxometer. Then, mass loss was measured and the corrosion products were analyzed at 1, 3, 10, 30, 100, and 300 h [17–22,38,39,45–51]. During the test, 16 samples were placed inside and two of them were taken out to be weighed. This was the way we obtained measurements of the mass difference shown in the thermo-gravimetric curves. Corrosion products were eliminated using a chemical solution of KMnO₄ at 80 °C, then another ultrasonic bath with NaOH. The obtained corrosion products in the samples were characterized using a high resolution scanning electron microscope (HR-SEM Jeol 6701-F; JEOL Ltd., Akishima, Tokyo, Japan) and using an energy dispersing X-Ray spectrometer DRX. The voltage applied was 20kV and the diffractometer was a Bruker D8 focus (Bruker AXS GmbH, Karlsruhe, Germany) [11–15,24–27,32,33,40–45].

This study was focused on experimental studies and the characterization of corrosion products. Fluid flow and dynamic interaction was not studied.

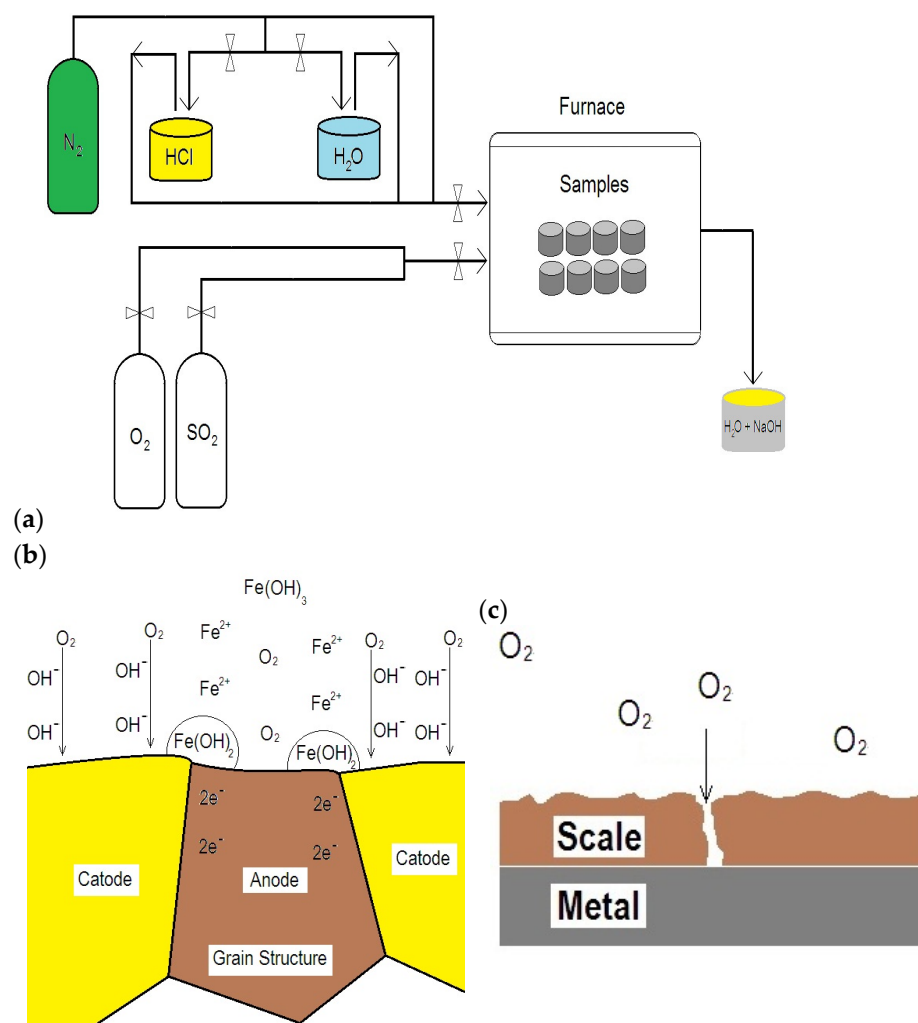


Figure 1. (a) Laboratory setup for testing the samples illustrating the glass furnace. (b) Corrosion mechanism in the metals surface. (c) Cracking over metal surface allowing O_2 to continue to react with the metal base.

5. Surface and Transversal Microscopy Analysis of the Sample

Figure 2a–d shows the morphologies at 500 °C for the four alloys, showing a size of 10 μm . These photographs were taken after 300 h. In Figure 2a,b, we can see the presence of whiskers and some isolated regions of oxides. In Figure 2b, a more homogeneous oxide scale can be seen. Consequently, the isolated regions are reduced. In Figure 2c, a homogeneous scale has formed, but there is also a certain quantity of oxide flakes of Fe. In Figure 2d, the oxide scale is homogeneous and totally formed; the presence of Si and O_2 was detected on the quasi-spherical Figure forms.

Figure 3a–d shows the samples after the etching at 600 °C after 300 h. In Figure 3a, an homogeneous scale of oxide can be observed; it is composed of Fe and Cr oxides identified after mapping the samples' surfaces. Scales present whiskers, which formed quickly in some alloys, an observation in agreement with other authors' reports [22–27,35–39,45–49]. In Figure 3a, we can appreciate a small isolated region with oxide over the scale. In Figure 3b, a thin scale can be seen over the oxide. In Figure 3c, the sand-lines can be appreciated; the oxide scale was so thin it allowed the detection of the metal base.

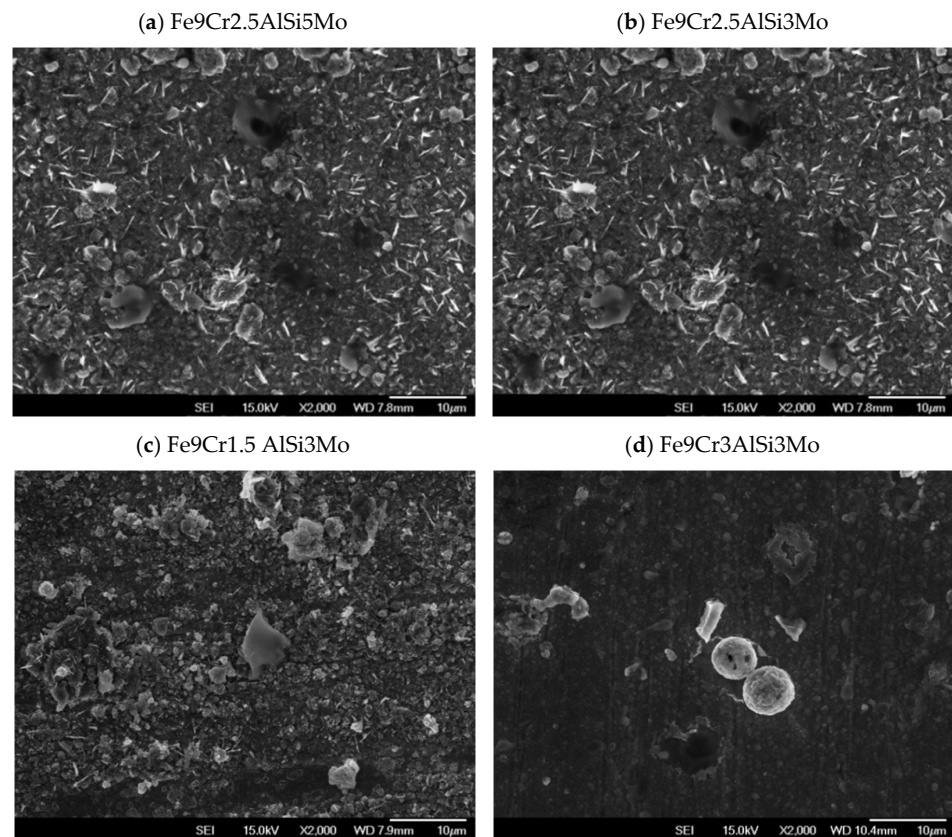


Figure 2. SEM photographs of the four alloys based on Fe-Cr after 300h at 500 °C of exposure to the aggressive atmosphere analyzed.

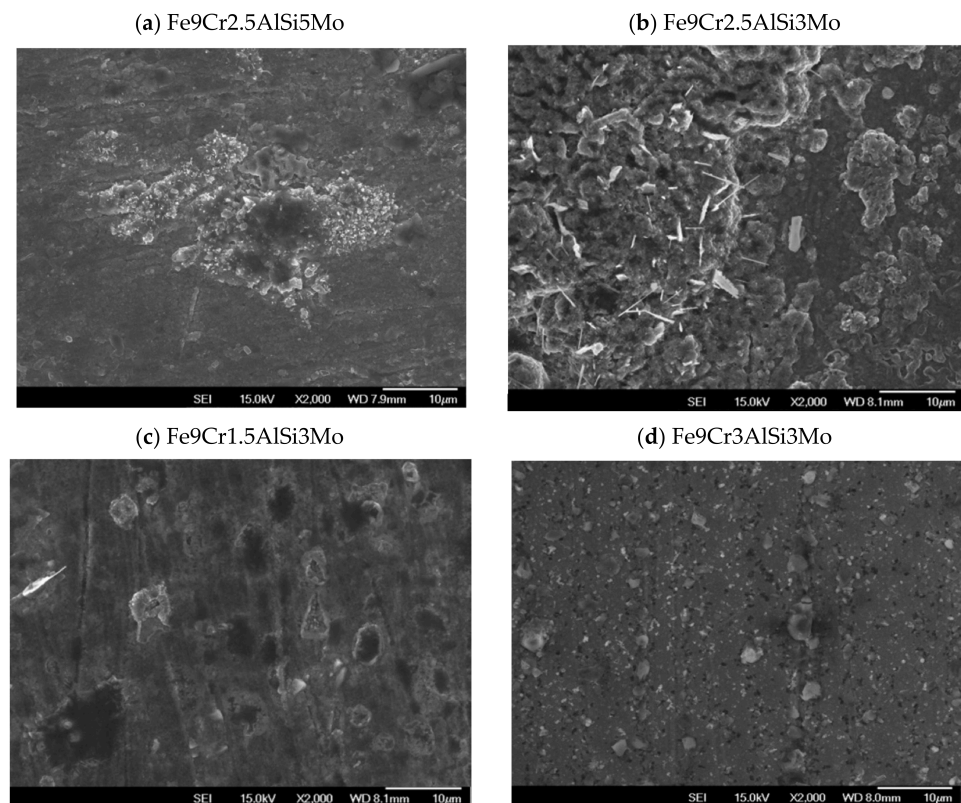


Figure 3. SEM photographs of the four alloys based on Fe-Cr after 300 h at 600 °C of exposure to the aggressive atmosphere analyzed.

The characterization of the oxide metallic scale between the interphase and the metal base is necessary to know whether the scale formed was protective. Moreover, it is evidence that it formed due to chemical reactions between the surface and the aggressive atmosphere. When applied to the environment $\text{N}_2\text{-O}_2$ 8% vol. 220 vppm, HCl 360, vppm H_2O vppm SO_2 during 300 h at 500 °C, the mapping and Energy Dispersive Spectroscopy (EDS) analysis provided evidence of the presence of high intensity peaks of Fe and Cr oxides on the scale with a thickness from 1 to 4 μm . The scales can be appreciated if these have a good adhesion to the surface. In Figure 4b, for the $\text{Fe}_9\text{Cr}_{2.5}\text{AlSi}_3\text{Mo}$, it is possible to see that scale has not formed over all of the surface. Moreover, the thickness of the scale is not well identified; only in the center of the micrograph is it possible to appreciate a 2 μm thickness. In Figure 4c, using the alloy $\text{Fe}_9\text{Cr}_{1.5}\text{AlSi}_3\text{Mo}$, an oxide scale was formed with a thickness of 1 μm or thinner, validating the thermo-gravimetric analysis done previously. Figure 4d shows that in the case of the alloy $\text{Fe}_9\text{Cr}_3\text{AlSi}_3\text{Mo}$, the thickness of the scale is around four μm , which also corresponds to a major mass loss.

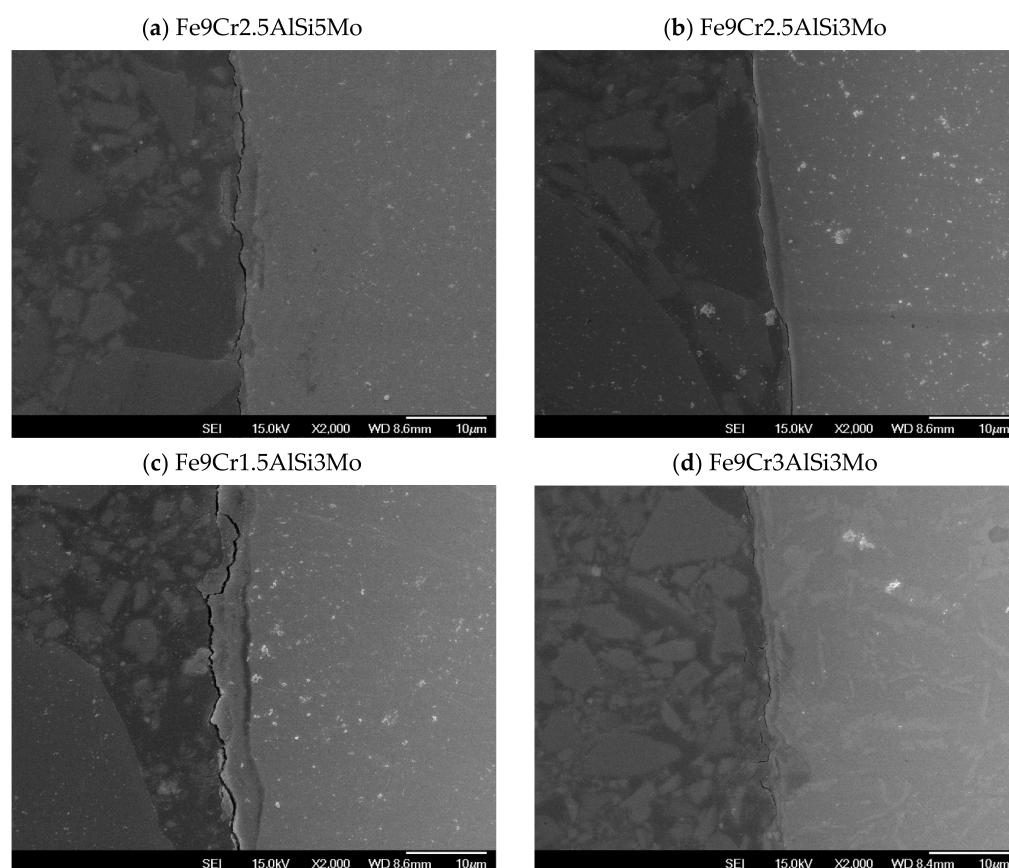


Figure 4. SEM transversal photographs of the four alloys based on Fe-Cr after 300 h at 500 °C of exposure to the aggressive atmosphere analyzed.

In the samples exposed to the same aggressive atmosphere at a temperature of 600 °C, we can observe that the increment of temperature has a strong influence over the scale thickness. In Figure 5a, the scale formation is nearly absent, but in Figure 5b,d, a scale measuring from 4 to 10 μm can be appreciated. There is a light breaking of the scale. However, in Figure 5c there is no apparent scale appearing.

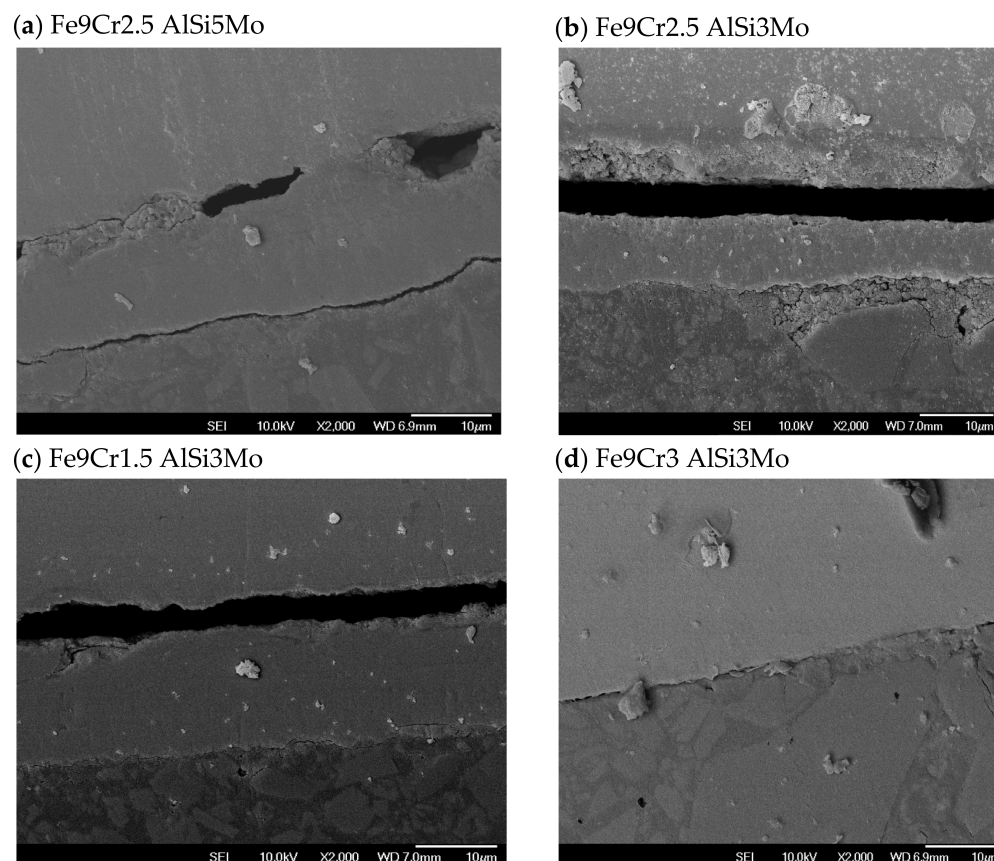


Figure 5. SEM transversal photographs of the four alloys based on Fe-Cr after 300 h at 600 °C of exposure to the aggressive atmosphere analyzed.

Mapping was applied to the samples in order to determine the elements in the scale and the presence of Fe and Cr oxides Fe_2O_3 and Cr_2O_3 . The XRD analysis confirmed the presence of several scales, and some of them were completely separated, providing evidence that the scale was not well adhered and the protective effects were not good.

It is important to mention that the absence of scale formation does not always indicate that corrosion is not happening. It is possible that the corrosion scale can be forming but also quickly vanishing. Thus, the most appropriate method is to weigh the sample to determine whether the mass loss is considerable.

6. Thermo-Gravimetric Analysis

The alloy $\text{Fe}_9\text{Cr}_{2.5}\text{AlSi}_5\text{Mo}$ showed the same behavior at both temperatures, with an irregular period of initiation but a long stable period. The alloys $\text{Fe}_9\text{Cr}_{2.5}\text{AlSi}_3\text{Mo}$ and $\text{Fe}_9\text{Cr}_3\text{AlSi}_3\text{Mo}$, after the initial corrosion accelerated, also showed reduced corrosion later. In contrast, the alloy $\text{Fe}_9\text{Cr}_{1.5}\text{AlSi}_3\text{Mo}$ was the alloy with the best performance, because it has a low corrosion rate. The thermo-gravimetric analysis of the analyzed alloys under the aggressive atmosphere is shown in Figure 6. According to these, the alloy $\text{Fe}_9\text{Cr}_3\text{AlSi}_3\text{Mo}$ was quickly corroded. The influence of a major temperature exposition at 600 °C was notable.

Curves with the highest mass loss are in coincidence with thin scales and with quasi to no existence of them. Because the scale formed was not protective, it vanishes continuously and forms again and again, promoting the continuations of corrosion processes. According to Figure 6, the highest mass loss can be identified as the highest slope (a vertical curve). The initiation of corrosion process appears during the initial 10 and continues until 50 h.

After that, the scale formed can protect the alloy surfaces with a passive period where chemical activity between the sample's surface and the aggressive environment is avoided.

Thermo-gravimetric measurements were taken, weighing the samples directly at every indicated time from the furnace. In contrast, mass loss was counted by removing the corrosion products.

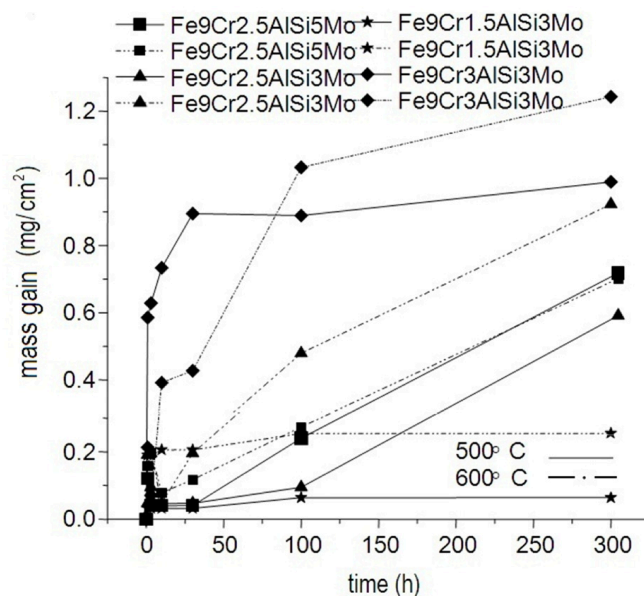


Figure 6. Thermo-gravimetric analyzed applied after 300 h of exposition to the aggressive environment.

7. Mass Loss

After removing the corrosion products according to the procedures described, these products were weighed. The analysis to calculate the mass loss of the four alloys under the atmosphere analyzed demonstrated that the alloy Fe9Cr3AlSi3Mo experienced major mass loss, as is shown in Figure 7. In contrast, the alloy Fe9Cr1.5AlSi3Mo showed minor mass loss. These two were the alloys with the worst and the best performance.

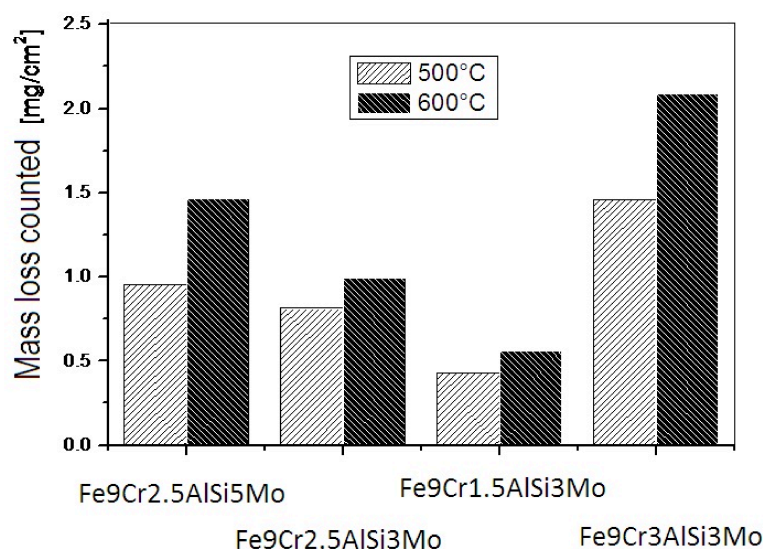


Figure 7. Mass loss analysis for the four alloys tested.

8. X Ray Diffraction Analysis

For the four alloys under the atmosphere analyzed, the XRD analysis results are in Figures 8 and 9. Here, there is a presence of Fe_2O_3 , Cr_2O_3 , $(\text{Fe}_{0.6}\text{Cr}_{0.4})_2\text{O}_3$, FeSiO_4 , and $(\text{Cr, Fe})_2\text{O}_3$ as the most common corrosion products in large quantities, due to the scale produced after the initiation of the corrosion process was not protective enough. Thicknesses were not so thick. Consequently, the X-Rays pass across the scale, providing information about the Fe-Cr alloy.

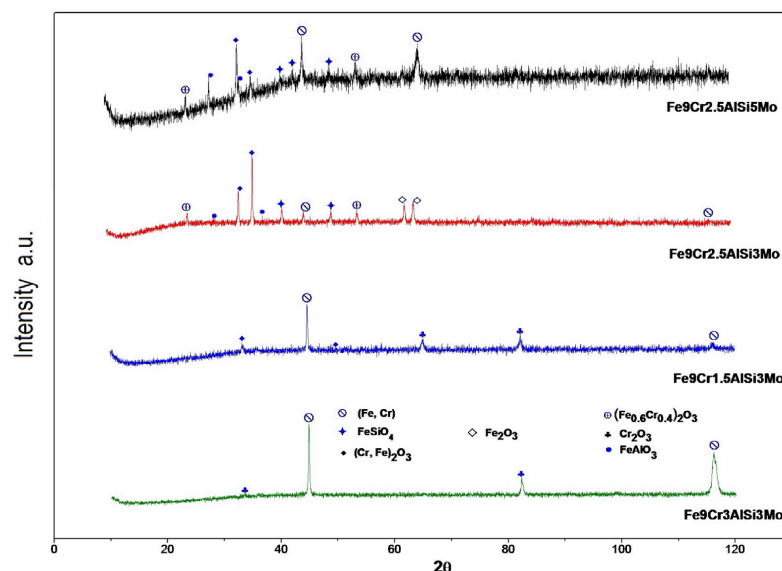


Figure 8. Diffractogram for the four alloys tested at 500 °C.

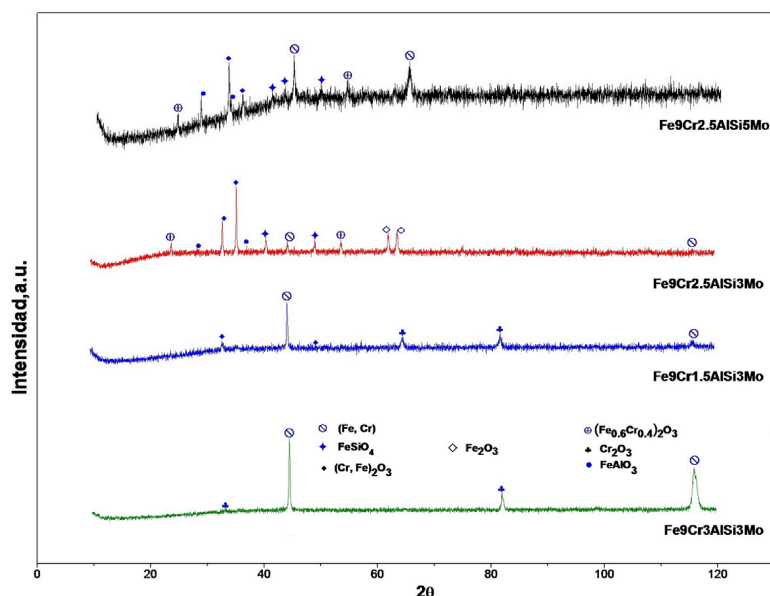


Figure 9. Diffractogram for the four alloys tested at 600 °C.

The presence of many elements and compounds is validated also with the graphics of EDS shown in Figures 10–16. Furthermore, in Figures 8 and 9, the similarity between the products found is evident, and it again confirmed the presence of Fe and Cr oxides.

9. Mapping over the Samples Surface

Additionally, the presence of oxygen over the scales formed validates the statement that there are oxides of Fe and Cr and the presence of the other elements in a minor

quantity. Figures 10–13 correspond to the four alloys at 500 °C. Figures 14–16 are for the four alloys at 600 °C. Unfortunately, it was impossible to make an EDS analysis of the alloy Fe9Cr3AlSi3Mo at 600 °C, because the scale formed was minimal, as can be appreciated in Figure 5d. Thus; it was concluded in concordance with the mass loss measured that the scale was not hard and not protective. It was disappeared from the sample surface, and the corrosion process continues in it. Additionally, the elements found in the scale samples are shown on these EDS graphics. The colors show the places where every element was found. Some samples do not show all of the colors because we found only a few of the total in the alloy. Intensity also evidences the quantity of the elements. There are dark zones on all of the graphics, evidencing zones with an absence of the element in the regions snapped.

For the four alloys with samples etched at 500 °C, the common elements found were C, Al, Cr, Mo, O, Si, Fe and S. In the samples of Fe9Cr5.5AlSi3Mo and Fe9Cr3AlSi3Mo, there was no S, and in the last alloy a certain percentage of Cl was found.

For the tested alloys, the same elements were found in the samples. The only strange element found was Ca, assumed to be present due to the small quantities of slag during the casting of the ingots. Scales in the initial figures shown that were taken at 2 µm.

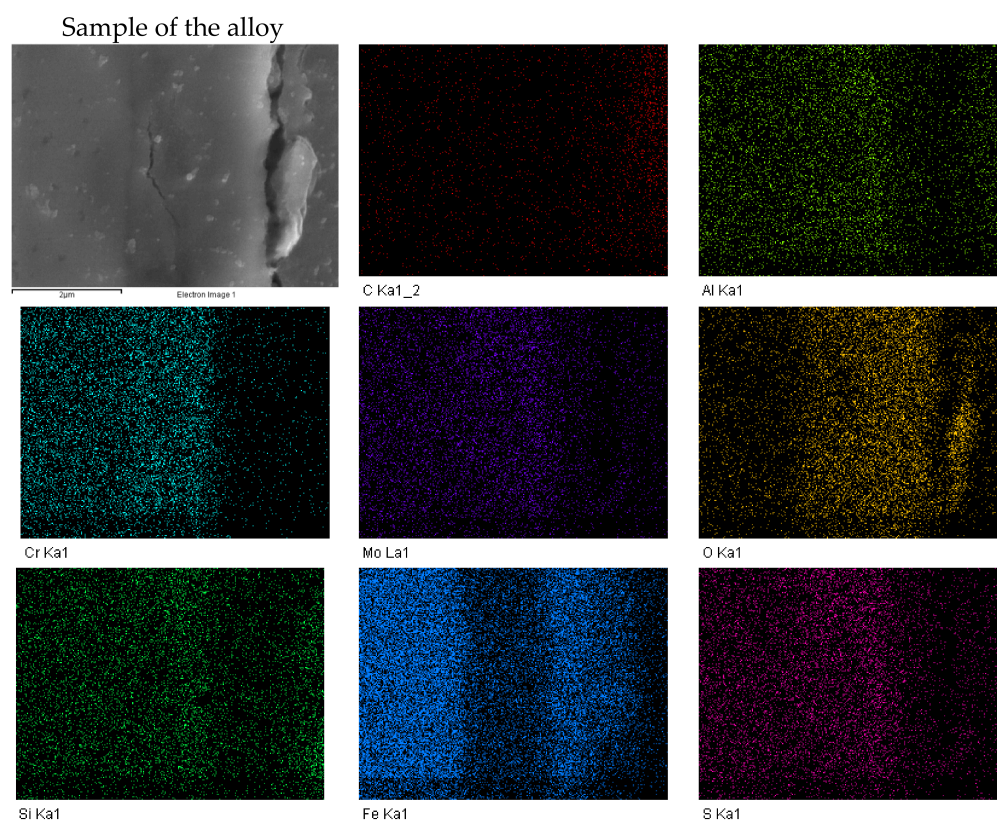


Figure 10. Mapping of transversal zone for the alloy Fe9Cr2.5AlSi5Mo under the aggressive atmosphere simulated after 300 h at 500 °C. Sample of the alloy, rest of figures elements characterized.

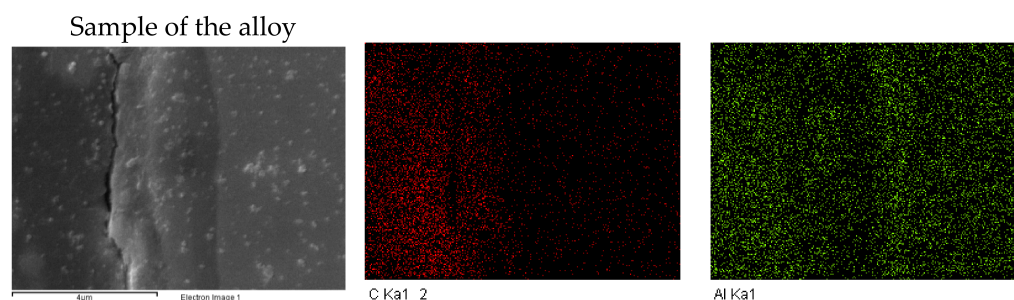


Figure 11. Cont.

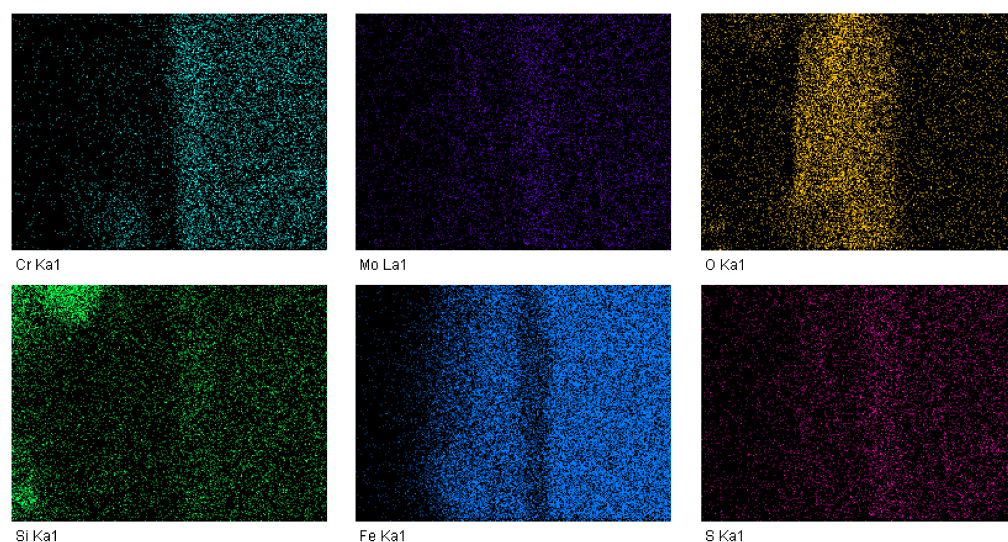


Figure 11. Mapping of transversal zone for the alloy Fe9Cr2.5AlSi3Mo under the aggressive atmosphere simulated after 300 h at 500 °C. Sample of the alloy, rest of figures elements characterized.

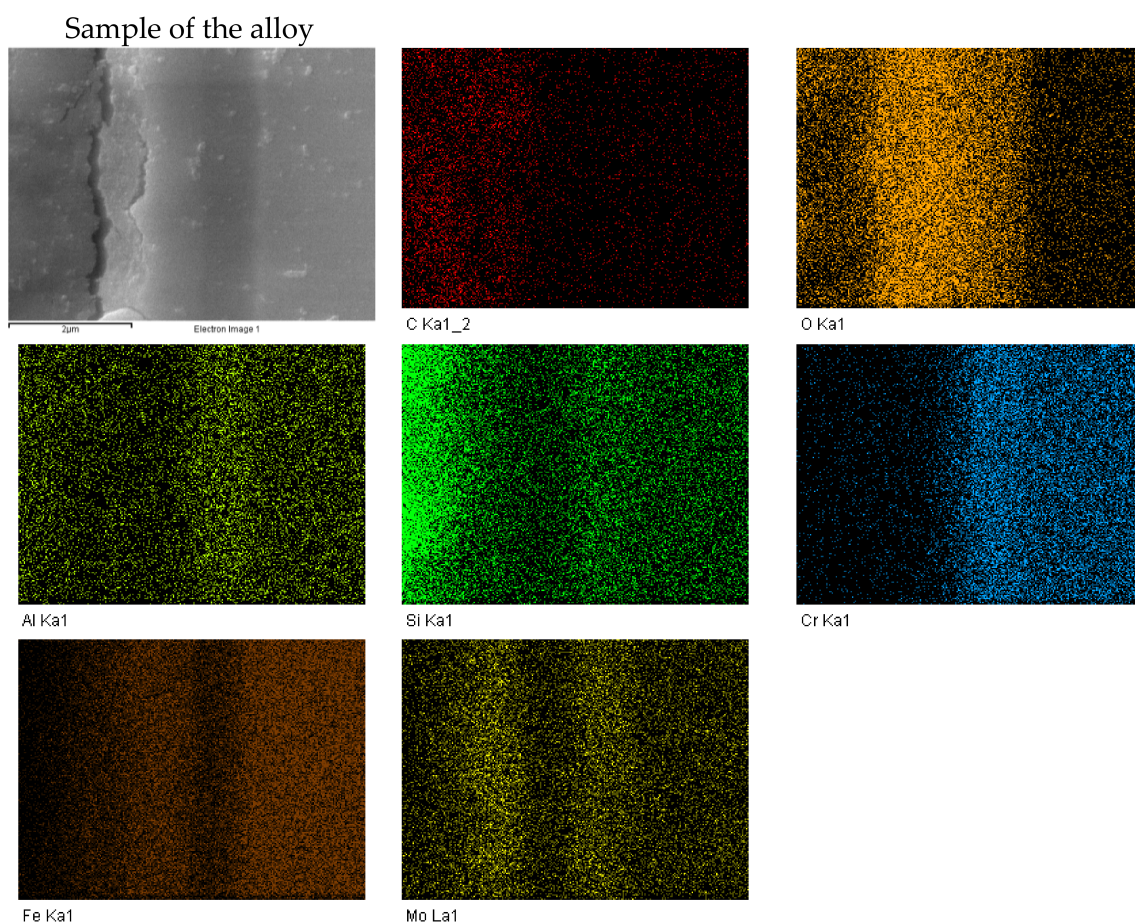


Figure 12. Mapping of transversal zone for the alloy Fe9Cr1.5AlSi3Mo under the aggressive atmosphere simulated after 300 h at 500 °C. Sample of the alloy, rest of figures elements characterized.

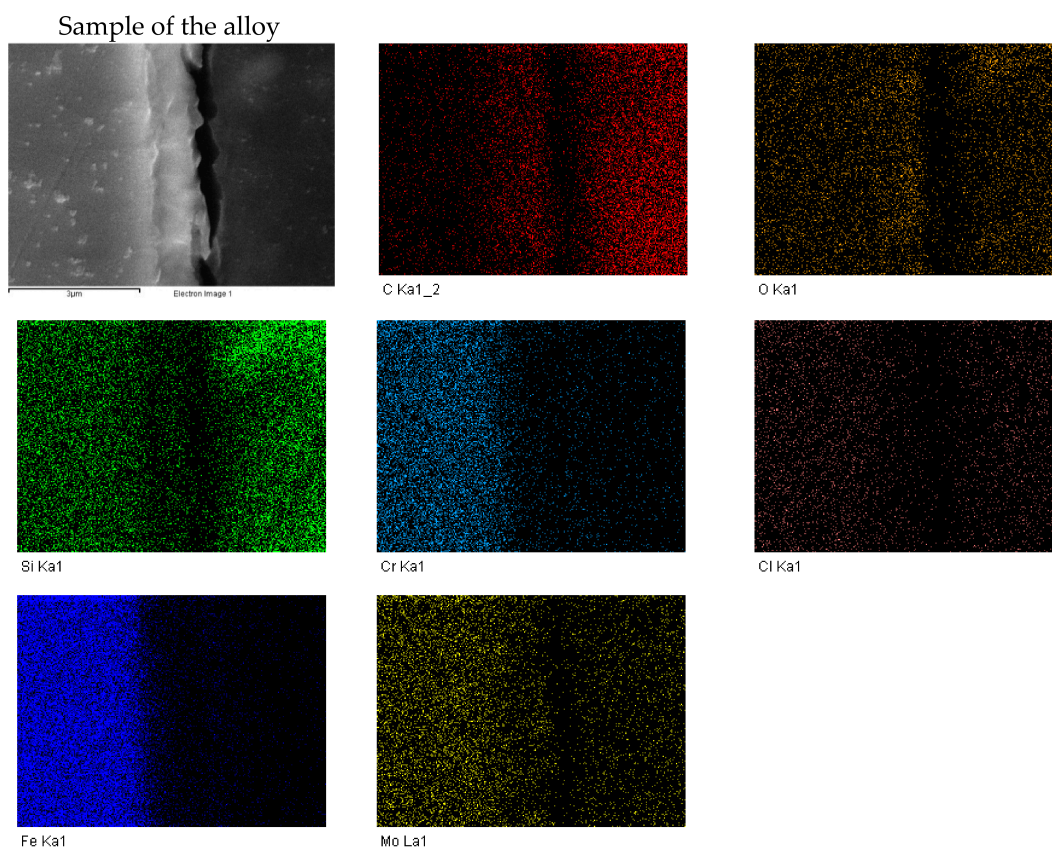


Figure 13. Mapping of transversal zone for the alloy Fe9Cr3AlSi3Mo under the aggressive atmosphere simulated after 300 h at 500 °C. Sample of the alloy, rest of figures elements characterized.

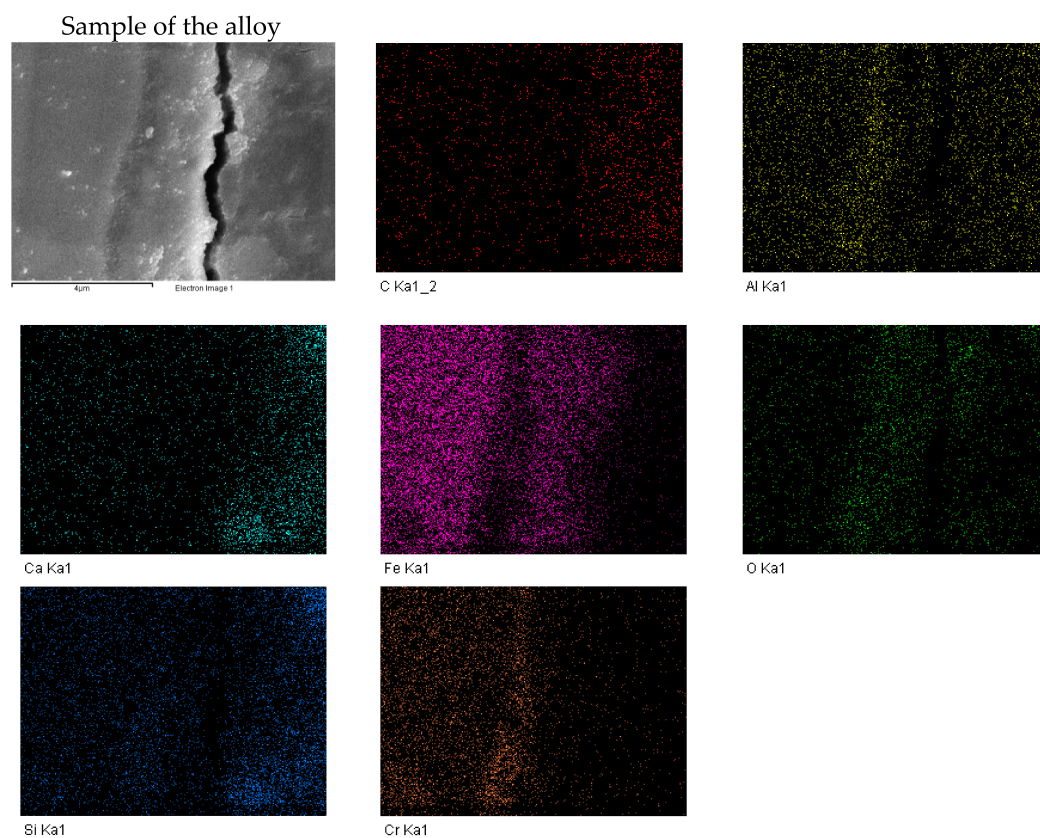


Figure 14. Mapping of transversal zone for the alloy Fe9Cr2.5AlSi5Mo under the aggressive atmosphere simulated after 300 h at 600 °C. Sample of the alloy, rest of figures elements characterized.

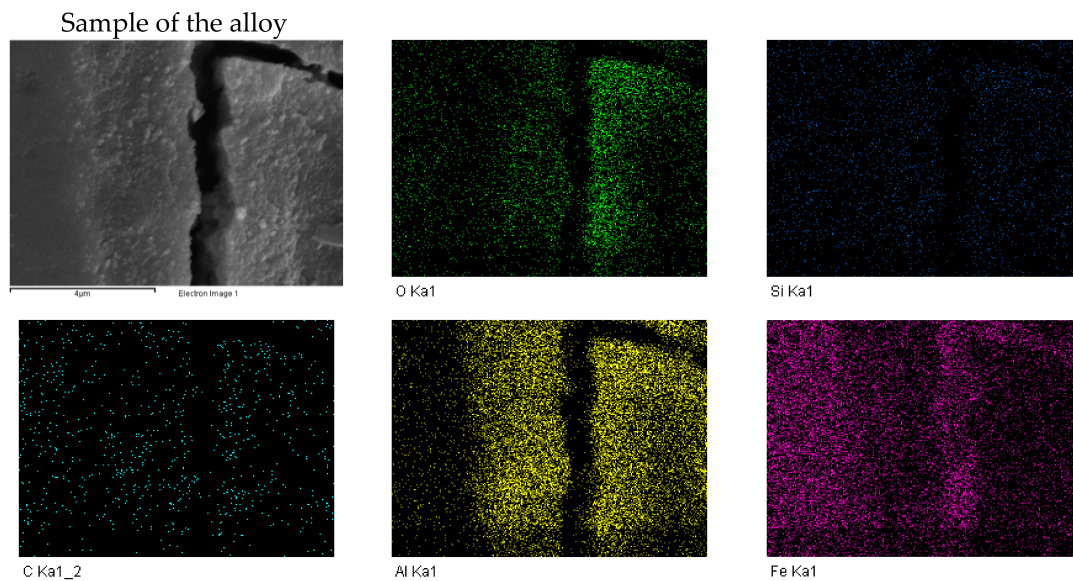


Figure 15. Mapping of transversal zone for the alloy Fe₉Cr_{2.5}AlSi₃Mo under the aggressive atmosphere simulated after 300 h at 600 °C Sample of the alloy, rest of figures elements characterized.

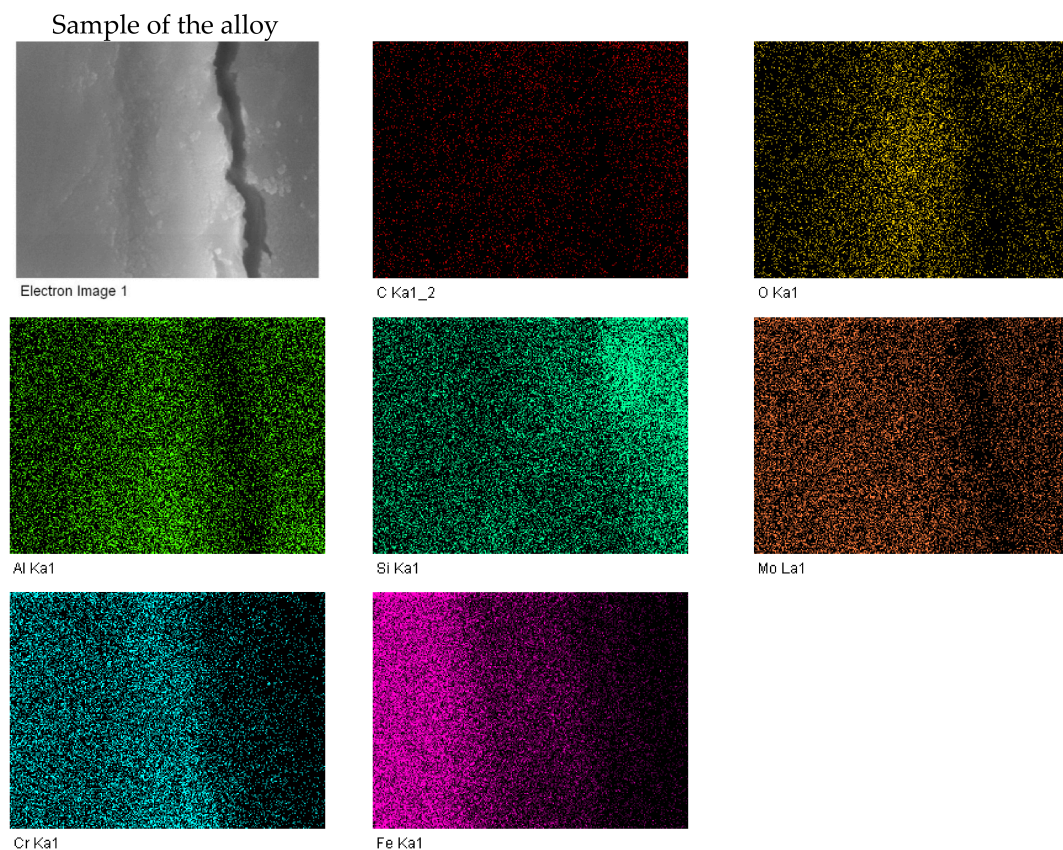


Figure 16. Mapping of transversal zone for the alloy Fe₉Cr_{1.5}AlSi₃Mo under the aggressive atmosphere simulated after 300 h at 600 °C. Sample of the alloy, rest of figures elements characterized.

10. Conclusions

After the characterization of the corrosion products, the samples in the aggressive atmospheres reacted, and the main oxides found were Fe₂O₃ and Cr₂O₃, which were identified after mapping by XRD and EDS. Moreover, there were also found (Fe_{0.6}Cr_{0.4})₂O₃ FeSiO₄ and (Fe, Cr)O₃. In addition, the elements of the alloy Fe and Cr and others were

appreciated, evidencing that scales were not strong or thick enough to protect the entire surface of samples.

After thermo-gravimetric and mass loss analysis, at 500 °C the scales' reported thickness was between 1 to 2 µm, and for 600 °C the oxide scale thickness was between 5 to 10 µm. The influence of the increment of temperature was notable in a more aggressive environment. The alloy with the best performance was Fe₉Cr_{1.5}AlSi₃Mo due to its minor mass loss and minor values on the thermo-gravimetric analysis. The evidence was the minor mass loss and the formation of a protective scale. There were samples with a minor weight derived from chemical reactions, but the corrosion process was unstopped; consequently the mass loss continued.

The corrosion mechanism was controlled by oxides. In contrast to our expectations, which were that HCl would be the most aggressive gas, forming chlorines, these were not found during characterization. The evidence of the mass mapping and XRD diffraction show that the corrosion mechanism is related to oxide formation. The most probable reason is that O₂ was used as a propellant and it is predominant in the aggressive environment.

The influence of the base alloy elements on increasing the resistance to corrosion is evident, even in small quantities. Nevertheless, more analyses are required to explore more possibilities for application. We suggest to exploring the addition of Al, Si, and Mo in major quantities and characterizing the corrosion products.

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