OPTIMIZING MECHANICAL AND CORROSION PROPERTIES OF UNS S41003 STAINLESS STEEL THROUGH AUSTENITIZING, QUENCHING, AND TEMPERING

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ABSTRACT

UNS S41003 (410D), ferritic stainless steel, demonstrates exceptional resistance to corrosive and abrasive environments, in addition to high mechanical strength and good weldability, making it an appealing option for structural applications. Heat treatments, which include austenitizing, quenching, and tempering, play a crucial role in enhancing its mechanical and chemical properties. These treatments influence the microstructure and impact hardness and corrosion resistance. However, a knowledge gap exists in the literature regarding the specific behaviour of UNS S41003 subjected to these treatments. This study aims to address this gap by investigating the impact of austenitizing, quenching, and tempering at various temperature ranges. Hardness measurements were taken at each stage of treatment, and electrochemical tests were conducted. Energy-dispersive spectroscopy (EDS) analysis was performed to assess chromium distribution. The results revealed an optimal condition: austenitizing at 1050°C for 30 minutes, followed by quenching, which exhibited superior hardness and corrosion resistance. Notably, the chromium distribution in this sample showed more uniformity within the matrix compared to others. By filling this research gap, this study contributes to a better understanding of the mechanical and corrosion properties of UNS S41003 steel under different heat treatment conditions, offering valuable insights for engineering applications.

KEYWORDS: *UNS S41003 (410D) ferritic stainless steel, heat treatment, corrosion, Cr distribution.*

I. INTRODUCTION

UNS S41003 (410D), ferritic stainless steel, is composed of a low-carbon alloy with additions of chromium and nickel. It offers outstanding resistance to corrosive and abrasive environments, coupled with high mechanical strength and good weldability. These attributes, combined with its cost-effectiveness within the realm of specialty steels, make 410D stainless steel a compelling choice for replacing materials typically used in structural applications, such as carbon, galvanized, or aluminized steels. 410D features a ferritic structure, allowing for easy manipulation, cutting, forming, and welding using conventional stainless steel methods [1].

The application of heat treatments is necessary to enhance the mechanical and chemical properties of the metal. The most common treatments, which will be discussed in this work, are austenitizing, quenching, and tempering. Austenitizing involves heating the metal to the austenitic range, where it is held at a specific temperature for a defined period, and then quenching is performed. Quenching is characterized by rapid cooling, imparting high hardness and elevated corrosion resistance to the metal. Following quenching, steels with martensitic phase can undergo tempering, which alters the microstructure and relieves the stresses induced by quenching. The main goal of tempering is to restore toughness by alleviating internal stresses and reducing hardness [2].

As noted by Alves and coauthors [3], the UNS S41003 (410D), is typically acquired in an annealed state, in this condition, its microstructure consists of a ferritic matrix with dispersed metallic carbides. The austenitizing treatment dissolves these carbides, which can occur partially or completely, depending on the austenitizing temperature, the soaking time, and even the heating rate.

As reported by Scheuer and coauthors [4], hardness increases with the increase in austenitizing temperature, which can be attributed to the higher levels of carbon and chromium in the martensite due to the dissolution of chromium carbides, thereby increasing carbon supersaturation in the martensite. Studies conducted with heat treatments at temperatures above 1100 °C, followed by quenching, have shown that the material's hardness tends to decrease. This decrease is due to the retained austenite fraction formed from these elevated temperatures. Retained austenite is a high-temperature phase that isn't entirely transformed into martensite during the quenching process. The presence of retained austenite at such high temperatures can lead to a reduction in material hardness. This occurs because austenite is a less hard phase when compared to martensite. Therefore, the greater the amount of retained austenite, the lower the material's hardness after quenching.

According to De-ning Zou and coauthors [5], the effect of austenitizing temperature after quenching on mechanical properties and microstructure can be divided into three temperature ranges: 940°C to 1000°C: Within this temperature range, there is a significant reduction in hardness and tensile strength; 1000°C to 1100°C: as the temperature increases within this range, the yield strength, hardness, and tensile strength increase due to the formation of a fine martensitic microstructure with very little retained austenite. Above 1100°C: beyond this temperature, there is the growth of the austenitic grain, resulting in a reduction in yield strength, tensile strength, and hardness.

In a recent study, Faria and coauthors [6], investigated the impact of martensite volume fraction on the mechanical behavior of a UNS S41003 dual-phase stainless steel. The study aims to develop hardening mechanisms without significant loss of ductility. The researchers performed various quenching heat treatments with different austenitizing temperatures and times to obtain dual-phase (ferrite-martensite) microstructures with varying martensite volume fractions. The results showed that higher austenitizing temperatures and times increased the martensite volume fraction, leading to greater hardness and mechanical strength but with a loss of ductility and fracture toughness.

Isfahany and coauthors [7] explore the effects of heat treatment on the mechanical properties and corrosion behavior of AISI420 martensitic stainless steel. The study found that the austenitizing temperature significantly influenced the mechanical properties, while the increase in tempering temperature led to precipitation of M7C3 carbides and secondary hardening. The microstructure analysis showed a mixed fracture mechanism at certain temperatures. The article also discusses the impact of heat treatment parameters on electrochemical behavior, specifically corrosion resistance.

The influence of the austenitizing process on the corrosion resistance of materials has generated conflicting findings in the existing literature [8]–[11]. Certain studies have suggested that austenitizing treatments when followed by quenching, have the potential to enhance the corrosion resistance of stainless steels. This effect is attributed to the ability of the austenitizing process to dissolve carbides and other inclusions, leading to a more uniform microstructure, and ultimately improving corrosion resistance [9], [10]. Conversely, other investigations have indicated that austenitizing treatments may diminish the corrosion resistance of stainless steel[8], [11]. In a broader context, austenitizing may foster the development of secondary phases, such as chromium carbides, which can serve as initiation sites for corrosion. Additionally, the austenitizing process can result in an uneven microstructure, potentially exacerbating the impacts of corrosion.

In many cases, tempering is commonly performed on stainless steels to enhance toughness [7], [12]–[14]. This post-austenitizing process serves to alleviate point defects, yielding tempered martensite, which relieves internal stresses and reduces hardness. However, it is important to note that carbide precipitation can occur during tempering, extracting chromium from the matrix and causing chromium depletion, potentially leading to reduced corrosion resistance.

However, a literature gap exists in understanding the effects of austenitizing, quenching, and tempering treatments on the mechanical properties and corrosion resistance of UNS S41003 (410D)

steel. The purpose of this study is to perform austenitizing, quenching, and tempering at different temperature ranges to analyze how the steel behaves under these treatments. Hardness was measured at each stage of the treatments, and electrochemical tests were conducted. EDS analysis was carried out to examine the distribution of chromium in the selected samples.

In the subsequent sections of this article, we delve into a comprehensive exploration of the mechanical and corrosion properties of UNS S41003 stainless steel under various heat treatment conditions. Section II provides a detailed overview of the materials and methods employed in this study, elucidating the experimental procedures and parameters used in the austenitizing, quenching, and tempering processes. Moving forward, Section III unveils the results and discussions, presenting microstructural analyses, hardness measurements, and electrochemical tests conducted on the treated samples. The section meticulously dissects the influence of different austenitizing temperatures and durations on the mechanical and corrosion characteristics of the steel. Furthermore, Section III sheds light on the impact of tempering on hardness and corrosion resistance. The culmination of our findings and insights is encapsulated in Section IV, where conclusive remarks and the significance of our study are succinctly summarized. This organizational structure aims to provide a systematic and in-depth exploration of the effects of heat treatments on UNS S41003 stainless steel, offering valuable insights for engineers and researchers alike.

II. MATERIAL AND METHODS

The focus of the present study is on the UNS S41003 (410D) ferritic stainless steel. The material was supplied in sheets with a thickness of 6 mm and was produced and donated for the study by Aperam Inox América do Sul S/A. The chemical composition of this material, provided by the company, is presented in Table 1.

Table 1. Chemical composition of UNS S41003 (410D) ferritic stainless steel.

Element	Wt(%)
C	0.014
Mn	0.561
Si	0.506
P	0.034
S	0.0001
Cr	11.072
Ni	0.327
Mo	0.029
Al	0.0014
Cu	0.029
Co	0.019
V	0.030
Nb	0.02
Ti	0.002
Sn	0.004
W	0.005
Fe	bal

The specimens were sectioned and subjected to an austenitizing treatment, followed by rapid water quenching. The austenitizing treatment was carried out at three different temperatures (980°C, 1015°C, and 1050°C), with each set of samples held in the furnace at its respective temperature for 30, 60, and 120 minutes. After the austenitizing process, the samples were promptly quenched in water. Following quenching, the specimens underwent tempering at 200°C and 400°C, each for 60 minutes, with forced air cooling. The selection of treatment temperatures and durations was based on prior references [7], [13].

After heat treatment, the specimens were ground with emery paper down to 4000 mesh. Initially, for the samples that underwent the austenitizing and quenching, the initial polishing was performed using

0.25 µm diamond paste. The final polishing was carried out using colloidal silica. The samples that underwent tempering treatment, were polished with 1 µm alumina, and the final polishing step utilized colloidal silica.

For the specimens subjected to austenitizing and quenching, an electrolytic etching was performed in an aqueous solution of nitric acid (40 vol% HNO3 and 60 vol% H2O), with a potential of 2.2 V applied for approximately 1 minute.

The samples were analyzed using an Olympus BX51M Optical Microscope (OM) equipped with an Olympus SC30 digital camera, as well as a Zeiss scanning electron microscope (SEM), model EVO MA10, which utilizes lanthanum hexaboride (LaB6) filaments. To determine the hardness of the samples, we used a Shimadzu HMV Vickers Hardness Tester with a load of 0,5 Kgf (4,903 N) for 15 seconds.

Polarization tests were conducted on samples using an Emstat3+-PalmSens potentiostat with PSTrace software. The specimens were immersed in a 1 M NaCl solution and deionized water at 25°C. A reference electrode (Ag|AgCl|KClsat.) and a platinum (Pt) counter electrode were employed. The specimens were exposed to the solution at the open circuit potential (OCP) at room temperature for up to 1800 seconds. The PC began at the OCP and had a scan rate of 1.00 mV/s towards more positive potentials, up to 250 mV vs OCP. After electrochemical tests, we examined the microstructure of unetched samples using SEM and conducted EDS analysis to determine the chromium (Cr) content.

III. RESULTS AND DISCUSSION

Figure 1 shows the as-received (AR) UNS S41003 (410D) steel micrograph. In it, a microstructure composed of carbides dispersed throughout the ferritic matrix is observed. The micrograph follows what is presented in the literature [6].

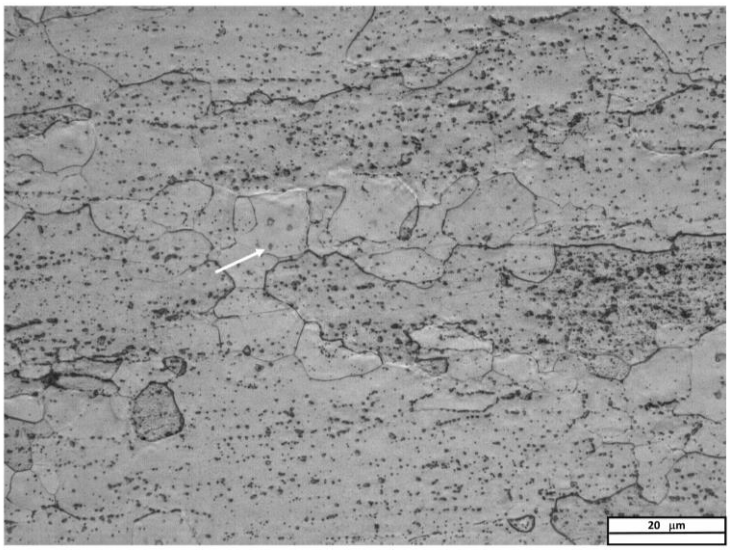


Figure 1. The as-received (AR) micrograph of UNS S41003 (410D) steel. The white arrow indicates the carbide.

The as-received 410D steel exhibits a hardness of 158 ± 2.31 HV, a lower value when compared to the literature values for other steels, such as 420A [15]. This difference is attributed to the varying carbon content in these steels, with 410D having a lower percentage and 420A having a higher percentage.

After being austenitized at three different temperatures and subjected to the water quenching process, the samples displayed the following Vickers hardness results, as shown in Figure 2

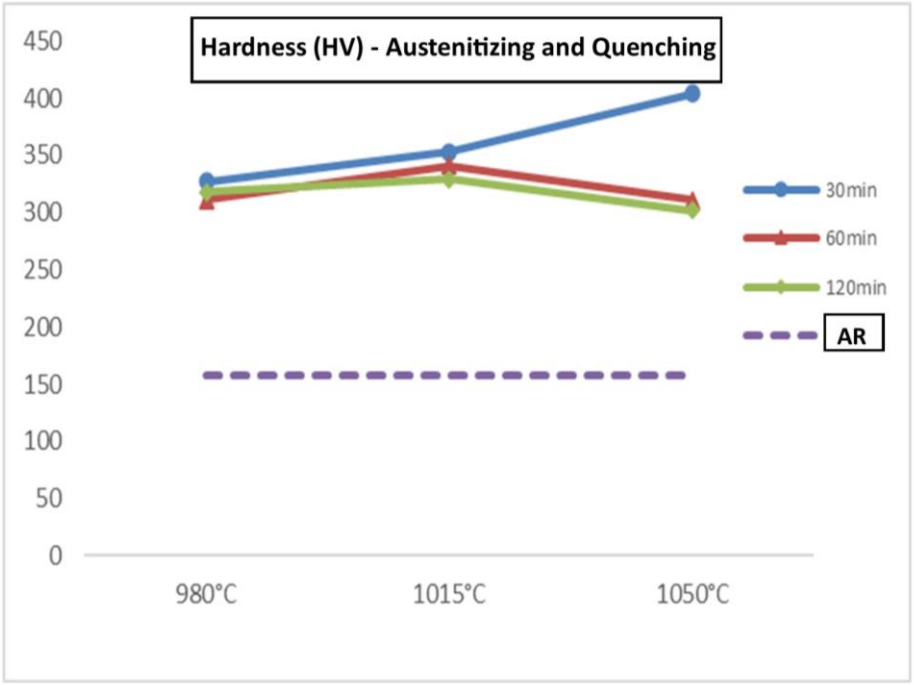


Figure 2. Comparison of Hardness Values (HV) at Different Times and Temperatures. AR – As-received sample.

After austenitizing and quenching, a significant increase in hardness occurs compared to the initial hardness (158 HV), as shown in Figure 2. Studies by Krauss [16] revealed that hardness is directly linked to the carbon percentage, with higher percentages resulting in greater hardness. Due to its lower carbon content, 410D steel does not naturally exhibit high hardness values compared to other steels in the 400 family. This is because a greater amount of available carbon allows for more distortion of the martensitic lattice, contributing to higher hardness.

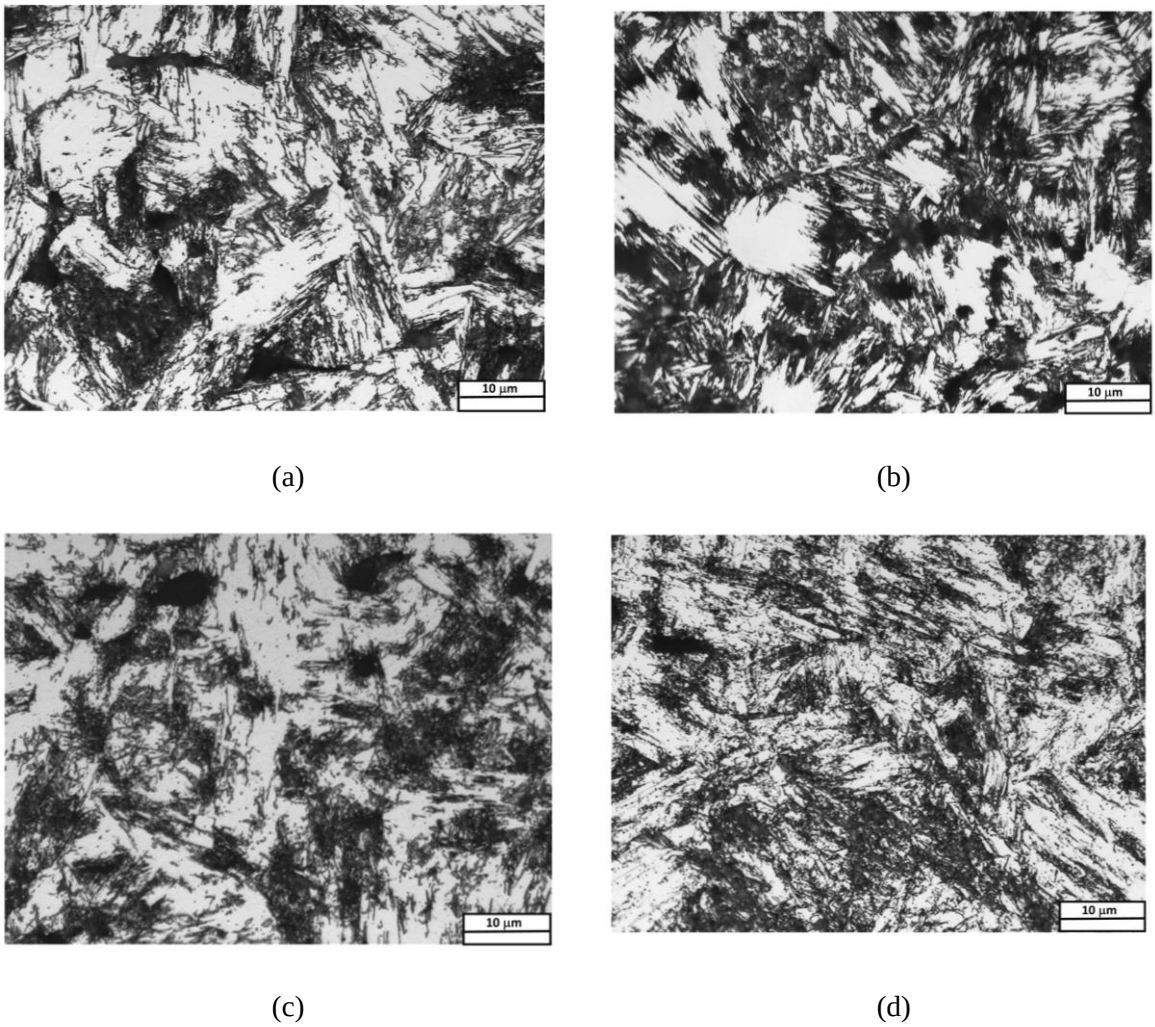
According to [17], the hardness average used in the industry for 410D steel can vary depending on the specific application and project requirements. However, it is common to find hardness ranges above 35 HRC for 410 steel. This hardness range provides a good combination of mechanical strength and toughness for many industrial applications. According to Figure 2, at a temperature of 1050°C for 30 minutes followed by quenching, the material has a hardness of 404 HV (41 HRC), followed by a hardness of 353 HV (36 HRC) at a temperature of 1015°C for 30 minutes followed by quenching, confirming that these treatments would meet the range mentioned earlier.

From Figure 2, it can be observed that hardness exhibits a similar behavior across different temperatures and treatment times. There is a slight increase in hardness from 30 minutes to 60 minutes, which can be explained by the increased dissolution of carbides from 30 minutes to 60 minutes [12]. Subsequently, there is a decrease in hardness for the 120-minute treatment, which can be attributed to the potential increase in austenitic grain size with longer soaking times [12]. The only point that deviates from this trend is the treatment at 1050°C for 30 minutes followed by quenching, which exhibits the highest hardness. Likely, the 30-minute time was insufficient to increase the size of the austenitic grain, and at 1050°C, there was the most significant carbide dissolution, resulting in martensite with greater lattice distortion and the highest hardness value.

We selected samples for microstructural and corrosion analysis with similar hardness results. These samples were austenitized at 980°C, 1015°C, and 1050°C for 120 minutes and then quenched. Additionally, we examined the sample that was austenitized at 1050°C for 30 minutes and then quenched. Figures 3a-d display micrographs under these conditions. In these figures, martensite is represented in black, appearing as laths or in the form of a percolation cluster[18], [19], while the

austenite matrix is shown in white. The martensite volume fraction in these samples, as measured by the occupied area fraction, is approximately 55%.

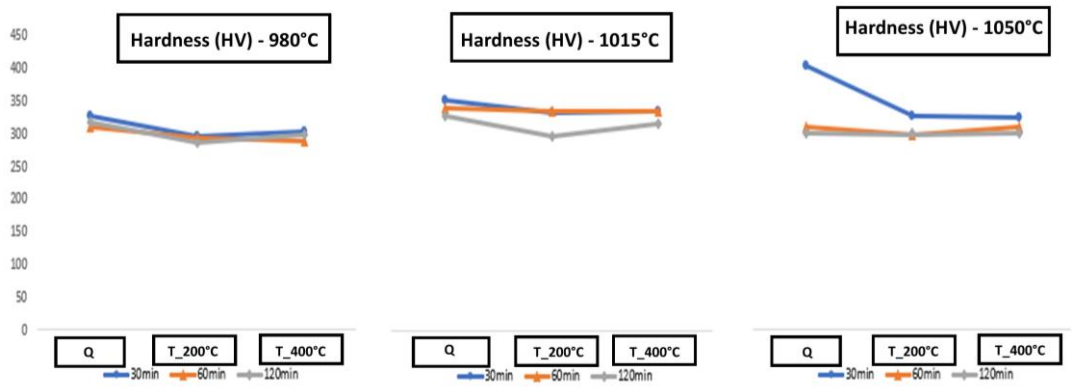
After austenitizing and quenching, the samples were tempered at 200°C and 400°C for 60 minutes and cooled with forced air. Figure 4 compares the hardness values of these treatments. From Figure 4a, it is observed that the hardness values are nearly identical for the temperature of 980°C in all performed treatments. In Figure 4b, the hardness remains relatively constant for the 1015°C temperature, with no significant change. In the tempering at 200°C, as shown in Figure 4b, a slight decrease in hardness is noted for 1015°C for 60 minutes. As seen in Figure 4c, tempering at 200°C and 400°C results in nearly equal hardness values, but they are lower than those of samples solely quenched. The behavior observed in Figure 4c is in line with expectations, as the creation of tempered martensite entails modifications in the crystal lattice, resulting in a reduction in hardness [7].



(a) (b)

(c) (d)

Figure 3. Micrographs (OM) of the samples austenitizing a) at 980°C for 120 minutes; b) at 1015°C for 120 minutes; c) at 1050°C for 30 minutes, and d) at 1050°C for 120 minutes. All of them were quenched in water after austenitizing.



(a) (b) (c)

Figure 4 – Comparison of the hardness values (HV) of the samples austenitized at a) 980°C, b) 1015°C, and c) 1050°C: quenched (Q); quenched (Q) and tempered (T) at 200°C and 400°C.

Analyzing the hardness results presented in Figures 2 and 4, and after electrochemical tests with a 1 mol/L solution, we selected samples for microstructural analysis via SEM. In addition to the as-received (AR) sample, we chose samples austenitized at 1050°C for 30 min and 120 min and then quenched. To examine the effect of tempering, we selected samples treated at 1050°C for 30 min and 120 min, quenched, and then tempered at 400°C for 60 min.

Figures 5-6 show the micrographs of the samples after the electrochemical tests. Figure 5 displays the micrograph of the as-received sample. In Figure 5, large pits caused by the electrochemical test are visible.

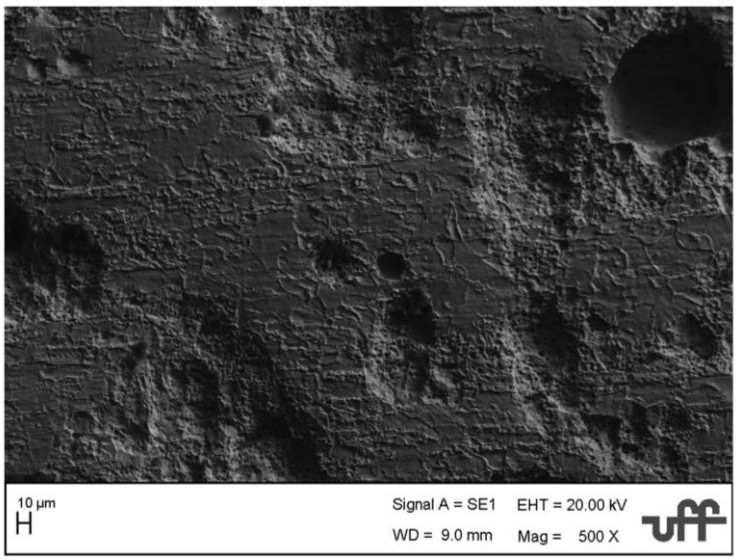


Figure 5. The as-received (AR) micrograph of UNS S41003 (410D) steel after electrochemical test.

Figure 6 a-d displays the micrographs of the samples austenitized at 1050°C for 30 min and 120 min, quenched, and the samples austenitized at 1050°C for 30 min and 120 min, quenched, and then tempered at 400°C, respectively.

Figures 6a-b display the photomicrographs of the samples austenitized at 1050°C for 30 min and 120 min, and then quenched, respectively. When analyzing Figures 6a-b, one can observe only martensite

needles with an absence of pits. The white arrows indicate the carbides that were not dissolved during the austenitizing process.

Figures 6c-d display the photomicrographs of the samples austenitized at 1050°C for 30 min and 120 min, quenched, and then tempered at 400°C. Tempering can lead to the precipitation of chromium carbides, which are phases rich in carbon and chromium. These carbides can reduce the amount of available chromium in the steel matrix, thus diminishing its ability to form a protective passive layer of chromium oxide [13]. A preferential site for carbide precipitation is at the grain boundaries. Figures 6c-d show intergranular corrosion. According to Peissl and coauthors [20], at tempering temperatures equal to or above 400°C, a reduction in corrosion resistance is common due to the possible pronounced precipitation of fine chromium-rich carbides, which reduces corrosion resistance.

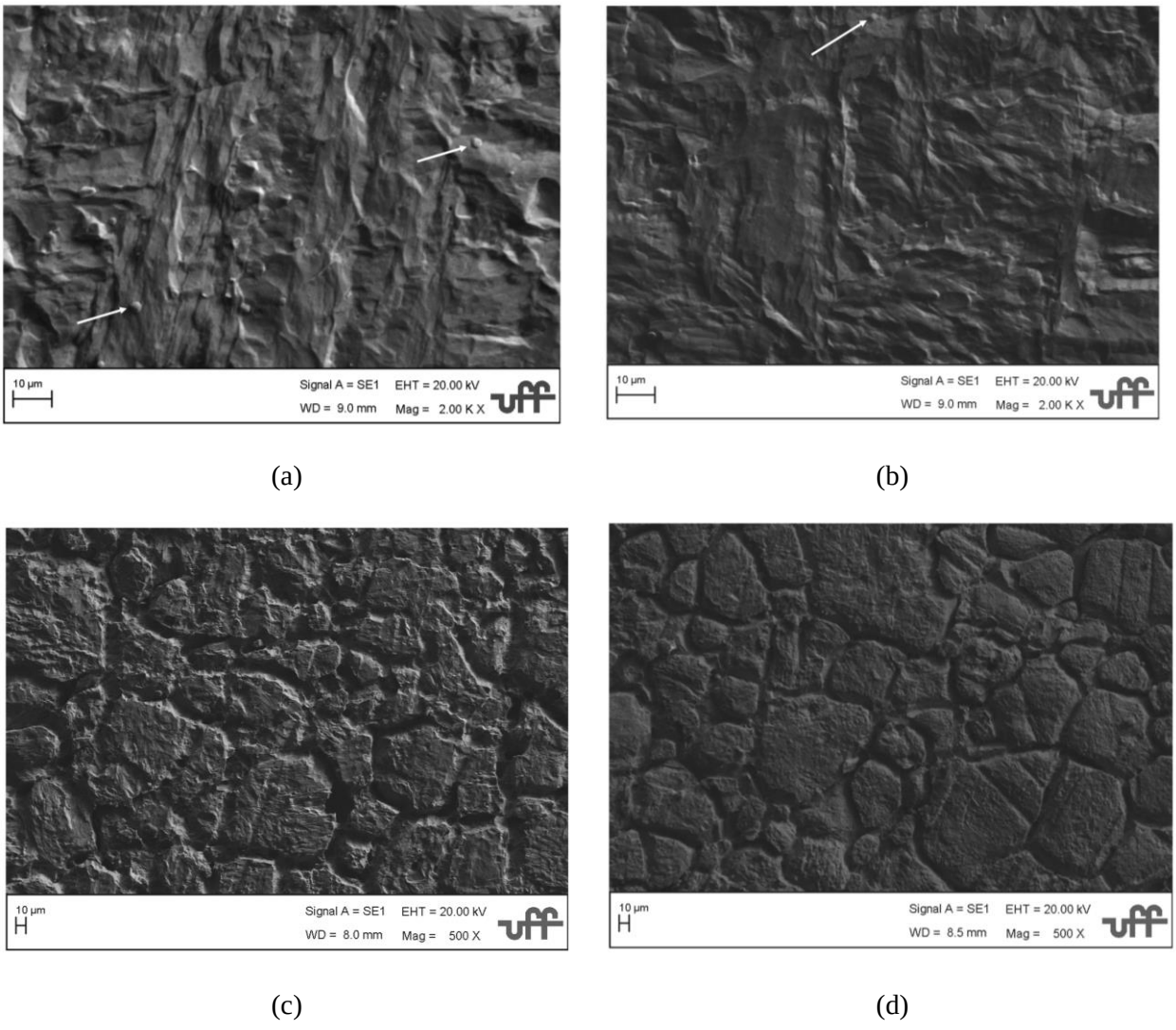


Figure 6. Micrographs (SEM) of the samples austenitizing at: a) 1050°C for 30 minutes; b) 1050°C for 120 minutes.; c) 1050ºC for 30min and tempered at 400ºC; d) 1050ºC for 120 min and tempered at 400ºC. All of them were quenched in water after austenitizing.

After the microstructural analysis presented in Figure 6, it was decided to compare the distribution of Cr in the 4 samples, which are: samples austenitized at 1050°C for 30 min and 120 min, and then quenched; and samples austenitized at 1050°C for 30 min and 120 min, quenched, and tempered at 400°C. Figure 7 presents the distribution of Cr in these 4 samples.

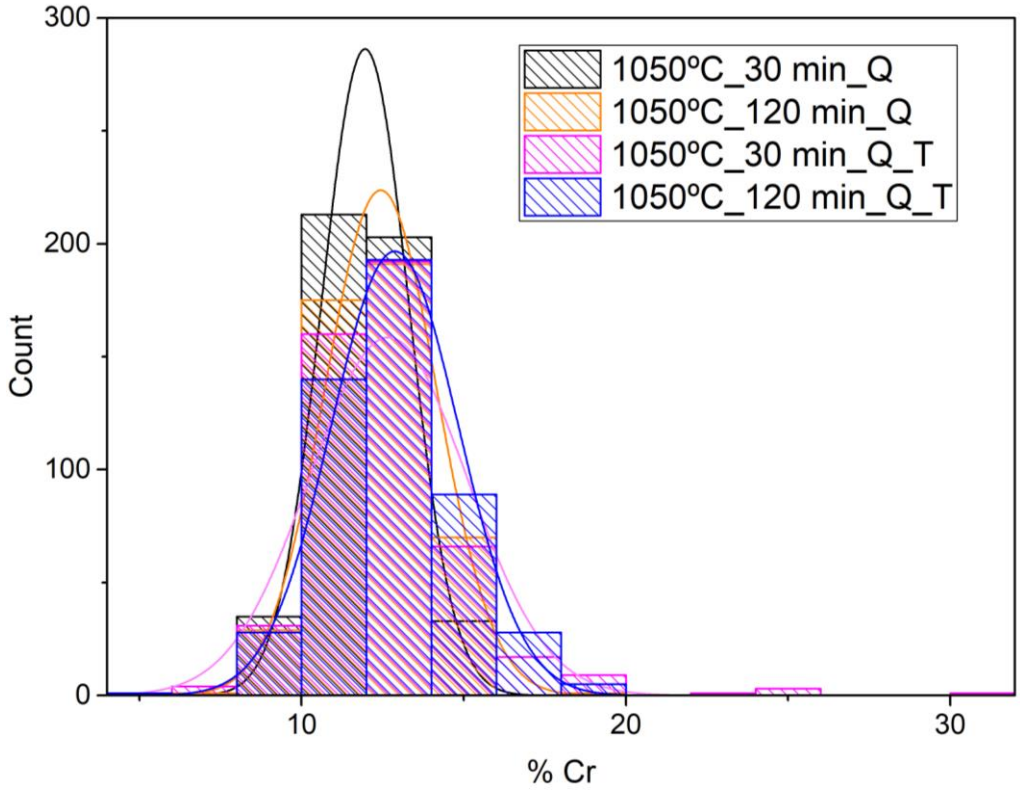


Figure 7 – Cr distribution in the samples, Q – Quenching, T – Tempering at 400ºC for 60 min.

Figure 7 presents the EDS analysis of the Cr distribution in the samples: austenitized at 1050°C for 30 min (black curve), austenitized at 1050°C for 120 min (orange curve), austenitized at 1050°C for 30 min, and then tempered at 400°C (pink curve), and austenitized at 1050°C for 120 min, and then tempered at 400°C (blue curve). In Figure 7, it can be observed that the pink and blue distribution curves exhibit greater dispersion, indicating a higher variation in Cr content in these samples. This variation is likely due to the migration of carbides to the grain boundaries, causing depletion of Cr in the matrix. In these cases, the carbides have a higher Cr content, leading to intergranular corrosion, as observed in Figure 6 c-d.

The orange curve begins to display a more uniform distribution, but it's in the black curve that the distribution becomes more homogeneous, with an average of approximately 11% Cr. In these two conditions, samples that were only quenched did not experience intergranular corrosion, Figure 6a-b. The analysis of Cr distribution, Figure 7, in conjunction with the micrographs presented in Figure 6, confirms that the sample austenitized at 1050°C for 30 min exhibits the best corrosion resistance. This condition is also the most interesting due to its higher hardness, as shown in Figures 2 and 4.

IV. CONCLUSIONS

In the present study, microstructural, mechanical, and electrochemical changes in 410D ferritic stainless steel were analyzed. Austenitizing, quenching, and tempering heat treatments were performed, and the main conclusions obtained are as follows:

- In summary, the austenitizing and quenching treatments effectively transformed the microstructure of 410D steel, leading to the formation of martensite and a substantial increase in hardness. The peak hardness of 404 HV (41 HRC) was achieved in the sample austenitized at 1050°C for 30 minutes followed by quenching. Subsequent tempering resulted in slightly lower but uniform hardness values, consistent with the expected reduction in hardness associated with tempered martensite.

- The optimal condition, identified as the sample austenitized at 1050°C for 30 minutes and quenched, exhibited superior hardness and corrosion resistance properties. The uniform distribution of chromium in the matrix in this condition further supports its favorable mechanical and corrosion performance. These findings highlight the crucial role of specific heat treatment parameters in tailoring the properties of 410D ferritic stainless steel for optimal engineering applications.

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