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The Influence of Heat Treatment on the Corrosion Resistance of Weld Deposits on Steel X8CrNi25-21

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Abstract

This work focuses on a comprehensive study of the influence of weld overlays on X8CrNi25-21 austenitic stainless steel, a material known for its excellent heat and corrosion resistance. The main objective is to investigate the mechanisms of sensitization induction in the material due to the thermal cycles associated with the overlay process. Subsequently, the study analyzes the possibility of reversing this undesirable condition through controlled heat treatment. The experimental part includes a detailed characterization of the material before and after welding, as well as after the application of reverse heat treatment. Key parameters evaluated include material hardness and microstructural changes. It is hypothesized that applying a specifically designed heat treatment regimen will allow for the dissolution of precipitated chromium carbides (primarily Cr23C6) at grain boundaries, thereby restoring the local chromium concentration and improving corrosion resistance. The service life of a material plays a very important role in practice, mainly from an economic and, in this case, safety perspective. The aim of this work was to analyze the effect of 70% atmospheric humidity on X8CrNi25-21 steel welds, which are used in roof constructions. The aim of the work was to analyze the effect of heat treatment on intergranular corrosion in steel welds X8CrNi25-21, which is used as a roof structure.

Keywords: Heat treatment, Atmosphere, Intergranular corrosion, Anti-corrosive steels, Welding

1. Introduction

Corrosion-resistant steels are a critical class of materials with irreplaceable mechanical and corrosion properties. These properties are key to various industrial sectors, such as energy and chemical processing, and are also commonly used in the construction industry. Their exceptional resistance is primarily due to the formation of a stable passivation layer on their surface [1-3]. This layer protects the material from aggressive environments and enables its long-term use. Among these steels are austenitic steels with a high content of chromium and nickel. Despite their designation, they cannot be considered completely "stainless" because they can be subject to various forms of corrosive attack under certain conditions. One of the most serious problems encountered with austenitic steels is sensitization, which leads to a weakening of their corrosion resistance. This phenomenon is caused by technological processing, such as welding, or by long-term operation at critical temperatures (500-900 °C). Under these conditions, chromium carbides precipitate at the grain boundaries, which results in the depletion of chromium in the surrounding areas [3,4]. This disrupts the material's ability to passivate and makes the steel susceptible to intergranular corrosion, which can even lead to the failure of the entire component. For this reason, research and practice focus on methods to prevent sensitization. One proven approach is to control the steel's chemical composition. By

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reducing the carbon content to below 0.02%, the formation of chromium carbides is significantly reduced. Another increasingly popular alternative is alloying with nitrogen [3-5]. Nitrogen acts as a strong austenite stabilizer while also reducing the diffusivity of carbon and chromium, thereby slowing down the sensitization process. In addition, nitrogen also increases the steel's strength and hardness, making this approach particularly attractive. However, if sensitization has already occurred, it can be reversed by a suitable heat treatment. A process known as solution annealing can dissolve the formed carbides and restore a homogeneous chromium distribution within the structure, thus returning the material to its original corrosion resistance [5,6].

This article contributes to a deeper understanding of the formation and reversibility of sensitization in complex alloys like X8CrNi25-21 steel, especially in the context of stress from welding processes. It provides valuable insights into the correlation between microstructural changes, mechanical properties (hardness and tensile strength), and corrosion resistance. By identifying the optimal heat treatment parameters for reversing sensitization, the scientific basis for designing material strategies in critical applications is expanded. From a practical perspective, this work has significant importance for the construction industry, where X8CrNi25-21 austenitic steel is commonly used for roof structures [6-8]. Despite its high corrosion resistance, a key risk is material sensitization after welding. This process leads to a breakdown of corrosion resistance, causing intergranular corrosion even in common operating environments with elevated humidity. Such conditions occur, for example, in the interiors of swimming pools, industrial heat treatment plants, or other facilities where humidity exceeds 60%.

Weld overlay techniques are often necessary for the repair, regeneration, or modification of these components. Sensitization caused by overlays can lead to a reduced service life and premature failure. The results of this study will provide specific recommendations for post-weld heat treatment that can effectively restore the material's corrosion resistance and mechanical properties [7,8]. This will directly contribute to increased reliability, safety, and the extended service life of critical industrial equipment, thereby reducing operational costs and the risk of accidents.

2. Materials and Methods

The experimental material used is X8CrNi25-21 steel (AISI 310S). This is a high-alloy austenitic heat-resistant steel with very good oxidation resistance up to 1100 °C. It has a lower carbon content, which makes it less susceptible to sensitization. However, sensitization can still occur in welding/weld overlay zones, which makes it important to evaluate its behavior before and after heat treatment [8,9].

Under certain conditions, X8CrNi25-21 steel is prone to sensitization, which primarily occurs with prolonged exposure to temperatures in the range of 500–800 °C. In this interval, chromium carbides can precipitate at the grain boundaries, leading to a localized depletion of chromium and, subsequently, a reduced resistance to intergranular corrosion. This phenomenon is especially significant during welding or weld overlay processes, where the material enters this critical temperature range [10].

Despite this, X8CrNi25-21 steel has good weldability, and preheating is not required for standard applications. When selecting filler materials, it is recommended to choose low-carbon or stabilized types to minimize the risk of carbide formation and, thus, sensitization. A key factor is the proper management of the thermal cycle and subsequent treatment, which can partially eliminate the resulting degradation of corrosion resistance.

Table 1 presents the chemical composition of the tested material, as measured by a Q2 ION spectrometer.

Table 1.
Chemical composition

Ch. element	Chemical composition [%]		
	Sample	X8CrNi25-21	
		min.	max.
C	0.082	-	0.1
Si	0.65	-	1.5
Mn	1.59	-	2.00
S	< 0,010	-	0.015
P	0.02	-	0.045
Cr	25.02	24.00	26.00
Ni	21.03	19.00	22.00

Thanks to its properties, X8CrNi25-21 steel finds wide application in high-temperature environments. It is typically used in the structural parts of furnaces, in heat treatment baskets, in combustion chambers, and in the chemical or energy industries, where resistance to oxidation up to 1100 °C is required. Its high chromium and nickel content ensures a stable austenitic structure and a good combination of mechanical and corrosion properties, even under prolonged stress [11,12]. The thermal process for X8CrNi25-21 steel was experimentally designed as a combination of solution annealing followed by heating to temperatures near the critical point, where the steel tends to sensitize. The temperature regimen for solution annealing was determined based on theoretical knowledge of the material and by considering the size and thickness of the sample to be annealed. A crucial part of this was the correct selection of the cooling medium to achieve a sufficiently rapid cooling rate. This rapid cooling prevents the re-precipitation of chromium carbides ($Cr_{23}C_6$) along the austenitic grain boundaries [13-15].

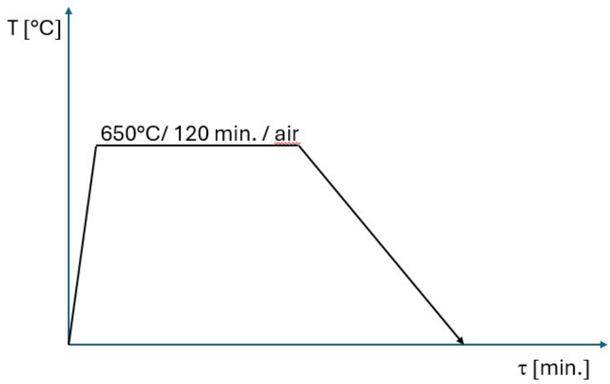

Fig. 1. Heat Treatment regime for One Set of Samples

Three sets of samples (5 pieces per set) were tested experimentally. The first set served as the initial state after welding. The welding was performed using the GTAW method (80 A and 60 V), which ensures that the material reaches sensitization temperatures (in the range of 450–850 °C). Heat treatment was then carried out on the other two sets of samples. This treatment compared different approaches aimed at reversing the sensitization that had occurred. Corrosion is only observed in the TOO, as it did not occur in the weld.

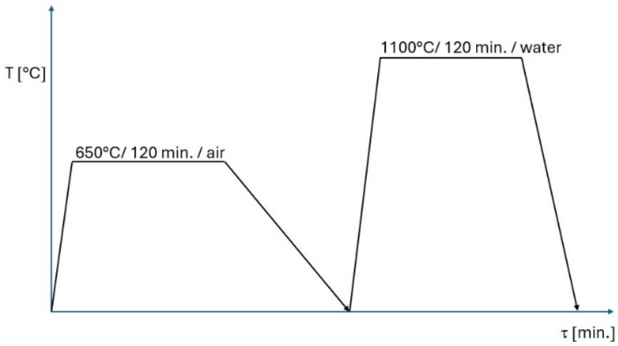

Fig. 2. Temperature regime for the second series of samples

Verification of sensitization of austenitic stainless steels by ASTM A262 method - method A.

The evaluation of the degree of sensitization in samples according to ASTM A262 – Practice A is based on classifying grain boundary attack. This method distinguishes three types of etched structures: step, dual, and ditch. If no ditches are observed at the grain boundaries and only steps are present between grains (formed due to different dissolution rates of various grain orientations), the structure is classified as stepped [16,17]. This indicates that the material shows no signs of sensitization and has high resistance to intergranular corrosion. The presence of ditches at the grain boundaries indicates the dissolution of carbides during the etching test. The test is used for a rapid verification of sensitization and the susceptibility of stainless steel to intergranular corrosion. If the result is negative, it can be stated with certainty that the material is not sensitized and has high resistance to intergranular corrosion in solutions of inorganic acids. Method A is based on the electrochemical etching of the material in an oxalic acid solution at a temperature of 20 ± 3 °C with a hold time of 90 seconds. The current density of 1.0 A/cm² is determined by the sample's surface area. If no grain is completely surrounded by carbide ditches, it is a dual structure. If at least one grain in the structure is completely encircled by ditches, the structure is classified as ditched, which is a clear sign of material sensitization.

3. Results

Chromium carbide of the type $M_{23}C_6$ locally precipitates along the austenitic grain boundaries (Fig. 3). In stainless steels, this occurs at high temperatures and leads to chromium depletion in the areas adjacent to the grain boundaries. The precipitation takes place precisely at the points where individual austenitic crystalline grains meet. When chromium is consumed for carbide formation at the grain boundaries, the nearby areas become depleted of chromium, which is crucial for corrosion resistance. These depleted areas then become anodic relative to the rest of the material and are susceptible to corrosion. Intergranular corrosion spreads along the grain boundaries, which is visible in the image as green, branched lines [18,19]. This undesirable phenomenon is most widespread in the heat-affected zone around the weld. The heat generated during welding is responsible for this phenomenon.

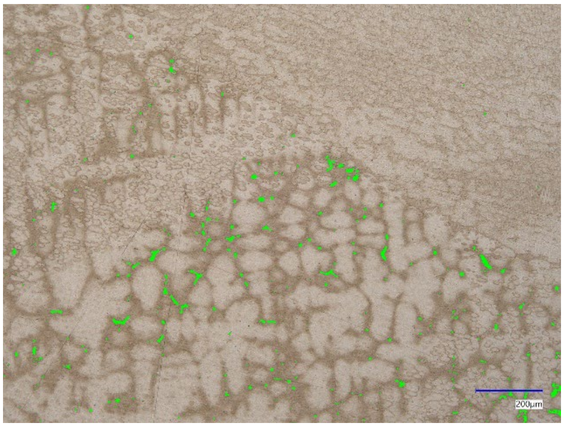

Fig. 3. Microstructure X8CrNi25-21, local precipitation of $M_{23}C_6$ along the austenitic grain boundaries with the presence of intergranular corrosion

In Fig. 4, the microstructure of X8CrNi25-21 is shown, where intergranular corrosion is visible along the material's grain boundaries. We can observe the local precipitation of $M_{23}C_6$ carbides along the austenitic grain boundaries.

To evaluate the degree of intergranular corrosion in the welded joints, a quantitative approach based on the analysis of microstructural images was applied [20,21]. The percentage of the area affected by corrosion was determined using VHC7000 software, where the value represents the proportion of the damaged area relative to the total analyzed area of the image. Measurements were performed in square micrometers (µm²).

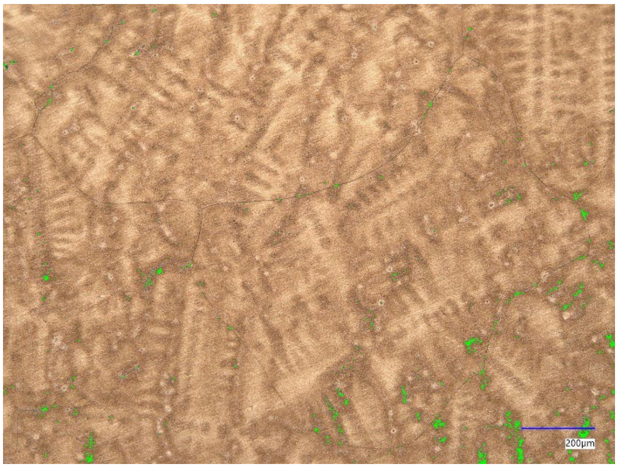

Fig. 4. Microstructure of X8CrNi25-21 after heat treatment 650°C/120min./air

Fig. 5 presents the microstructure of X8CrNi25-21 after solution annealing. Signs of intergranular corrosion are very localized and minimal. This experiment confirms the suitability of this solution for microstructure material repair after welding.

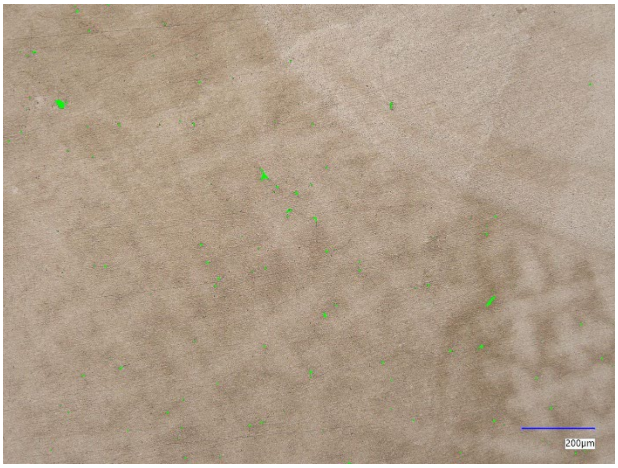

Fig. 5. Microstructure of X8CrNi25-21 after solution annealing

The results of the analysis are as follows:

Series after welding (without additional heat treatment): For samples directly after welding, it was found that the volume area fraction affected by intergranular corrosion reaches 0.79%. This value indicates sensitization of the material due to the welding process.

Series after heat treatment (650 °C / 120 min / air): Samples that underwent an additional heat treatment at 650 °C for 120 minutes and subsequent cooling in air showed a significant reduction in the extent of intergranular corrosion. The volume area fraction affected by corrosion was measured at 0.49%. This heat treatment contributed to the reduction of corrosion.

Series after solution annealing: The most significant improvement was observed in the samples that underwent solution annealing. In this case, the volume of intergranular corrosion area was only 0.14%. These results confirm the high effectiveness of solution annealing in eliminating sensitization and restoring the material's resistance to intergranular corrosion.

Tensile strength UTS [MPa] and hardness

The ultimate tensile strength was evaluated by comparing the results of tensile tests. All samples were tested, divided into three sets of 5 pieces each. Simultaneously, the Vickers hardness was measured on each sample using an INNOVATEST hardness tester. The determination of the samples' mechanical properties was carried out through a static tensile test. This method falls under the category of short-term destructive tests and was performed in accordance with the EN ISO 6892-1 standard [22,23]. A universal testing machine, model Inspekt desk 50 kN, was used for the tests. This device has a nominal load capacity of 50 kN and allows for a testing rate ranging from 0.0005 to 250 mm/min.

Table 2.
Mechanical properties

Mode	UTS [MPA] ± 10	Hardness HV± 5	Corrosion area [%] ± 5 %
the Weld	140	164	0.79
650 °C / 2hr/ air	121	141	0.49
solution annealing	94	175	0.14

Table 2 shows only the average values from these measurements. The graphical and visual documentation indicates that the average mechanical property values are strongly dependent on temperature. The analysis confirms differences in tensile strength, as the samples demonstrate an increase in both strength and hardness with changes in the heat treatment of the welds.

4. Discussion

This article presents a simulation of sensitization in X8CrNi25-21 steel through the creation of weld overlays. This process has a negative effect on the properties of stainless steels, such as an increased susceptibility to intergranular corrosion. Subsequently, the induced sensitization was corrected using two different heat treatment methods, both of which showed an improved state and a reduction in intergranular corrosion. Fig. 6 graphically presents the difference in tensile strength, average hardness values, and the percentage of intergranular corrosion per unit area. These findings provide a better understanding of the influence of sensitization on the properties of stainless steels and highlight the importance of proper heat treatment in minimizing this phenomenon.

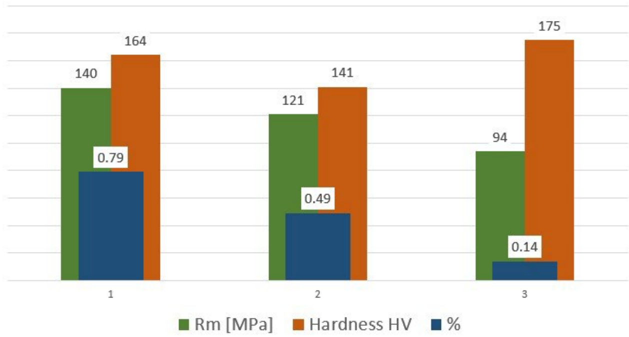

Fig. 6. Comparison of mechanical properties

Surface damage is a phenomenon that affects a component's durability. While temperature is one of the main factors influencing a material in service, this article confirms that the characteristics of the environment are also a significant factor [24]. The X8CrNi25-21 steel exhibits intergranular corrosion after weld overlaying. The real danger, however, lies in failing to perform a post-weld heat treatment, as high atmospheric humidity can lead to a catastrophic failure in a relatively short time. Corrosion-resistant steels are crucial in industry because they can withstand aggressive environments and maintain their mechanical properties even with long-term exposure to moisture and chemical substances. It is therefore appropriate to emphasize the importance of proper heat treatment, even at the cost of increased production expenses.

5. Conclusions

- According to metallographic evaluation, the % content for individual samples is: sensitized 0.79%; mode 650°C/2hr/air 0.49%; solution annealing 0.14%.
- Hardness HV is for: sensitized 164 HV; mode 650°C/2hr/air 141 HV; solution annealing 175HV.
- Tensile strength is for: sensitized 140 MPa; mode 650°C/2hr/air 121 MPa; solution annealing 94MPa.

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