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Analysis of Corrosion Potential Changes and Tensile Strength of Stainless Steel 304 After Thermal Loading

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Abstract

This study investigates the effects of thermal loading at 650°C and subsequent heat treatment at 450°C on the corrosion potential, tensile strength, and microstructure of Stainless Steel 304. Thermal loading increased the corrosion potential from 387 V to 569 V and reduced tensile strength from 3596.06 MPa to 3151.39 MPa, indicating heightened vulnerability to corrosion and mechanical degradation. Heat treatment for durations of 2, 4, and 6 hours gradually restored the material's properties, with corrosion potential decreasing to 391 V and tensile strength improving to 3729.62 MPa after 6 hours. Microstructural analysis revealed a reduction in dislocation density and restoration of grain boundary integrity post-treatment. Elemental analysis confirmed the redistribution of chromium and iron as a key factor in enhancing the material's performance. These findings highlight the importance of post-thermal heat treatment in restoring the functional performance of Stainless Steel 304 for industrial applications.

1. Introduction

Stainless Steel 304 is widely used in chemical, food, and nuclear industries due to its excellent corrosion resistance and mechanical properties. Previous studies have examined the effects of thermal loading on Stainless Steel 304, such as [1-3], which investigated high-temperature corrosion behavior and microstructural changes. However, these studies have been limited in simultaneously evaluating changes in corrosion potential and tensile strength following thermal loading and subsequent heat treatment with varying durations. Furthermore, quantitative analysis of elemental redistribution particularly chromium and iron and its role in restoring material properties remains underexplored. Unlike previous studies, which primarily focused on individual mechanical or corrosion aspects, this study simultaneously examines both parameters under controlled thermal loading and post-heat treatment conditions. This research aims to fill this gap by providing a comprehensive assessment of how thermal loading and controlled heat treatment influence the corrosion potential, tensile strength, and microstructure of Stainless Steel 304. The findings are expected to enhance industrial practices in maintaining material performance under thermal stress.

TABLE 1. Chemical composition of stainless steel 304 [4-6]

Element	Composition (%)
Chromium (Cr)	18.0–20.0
Nickel (Ni)	8.0–10.5
Carbon (C)	≤ 0.08
Manganese (Mn)	≤ 2.00
Silicon (Si)	≤ 1.00
Phosphorus (P)	≤ 0.045
Sulfur (S)	≤ 0.030
Iron (Fe)	Balance

Stainless Steel 304, a widely utilized material in the chemical, food, and nuclear industries, stands out for its excellent corrosion resistance and mechanical properties. Its unique composition, containing at least 18% chromium and 8% nickel, provides a protective oxide layer that enhances its durability [7-9]. Despite its robustness, Stainless Steel 304 is not immune to the effects of high temperatures and harsh environments, which can compromise its structural integrity[10-13]. Thermal loading, a common industrial scenario, can weaken this protective layer, rendering the material vulnerable to corrosion and mechanical failure. This necessitates a deeper understanding of how thermal loading affects its performance, particularly in applications requiring prolonged exposure to extreme conditions.

Heat treatment emerges as a potential solution to mitigate the adverse effects of thermal loading. By altering the microstructure of Stainless Steel 304, heat treatment can restore its mechanical and corrosion-resistant properties. However, the effectiveness of this approach depends on various factors, including temperature, duration, and the specific environmental conditions to which the material is exposed. Investigating these parameters can provide valuable insights into optimizing the material's performance and ensuring its reliability in demanding applications.

This study addresses a critical gap in understanding how thermal loading and subsequent heat treatment affect the mechanical and corrosion-resistant properties of Stainless Steel 304. Given the widespread use of this material in key industries such as transportation, energy, and manufacturing, optimizing heat treatment parameters is essential for enhancing material durability, reducing maintenance costs, and improving operational safety. Furthermore, by advancing knowledge of material behavior under thermal stress, this research supports global sustainability efforts through more efficient resource use and waste minimization, ultimately contributing to longer-lasting and more reliable industrial components.

This study focuses on investigating the effects of thermal loading at 650°C followed by heat treatment at 450°C on Stainless Steel 304. By analyzing changes in corrosion potential, tensile strength, and microstructure, this research provides a comprehensive understanding of how to maintain and improve the material's properties under thermal and environmental stresses. The findings aim to guide industries in adopting effective post-thermal treatment practices, ensuring the material's resilience and adaptability in various applications.

2. Research Methodology

This study aims to evaluate the changes in corrosion potential and tensile strength of Stainless Steel 304 after thermal loading. To achieve this objective, a systematic research methodology was developed, including specimen preparation, heat treatment, corrosion testing, tensile testing, stress measurement, and microstructural analysis. These steps were designed to ensure reliable results that accurately represent the behavior of Stainless Steel 304 in industrial environments.

2.1 Location and Duration of Study

The research was conducted at the Physical Metallurgy Laboratory, Department of Mechanical Engineering, Hasanuddin University, Gowa, from July 2024 until the study was completed. This laboratory was chosen for its advanced facilities suitable for thermal and microstructural testing.

2.2 Equipment and Materials

The primary equipment used in this study included:

1 Furnace: To apply thermal treatments at up to 650°C.
2 Tensile Testing Machine: For measuring the tensile strength of the specimens.
3 Voltmeter: Used for measuring galvanic potential.
4 Optical Metallurgical Microscope: For examining and capturing microstructural images.

The main material was Stainless Steel 304. Additional materials included $FeCl_3$ solution as a corrosive medium and NaCl solution as the electrolyte for galvanic tests. Stainless Steel 304 was chosen due to its widespread industrial applications and excellent corrosion resistance properties.

2.3 Specimen Preparation

The specimens were prepared in the form of rectangular blocks measuring 90 mm × 4 mm × 0.8 mm and 60 mm × 5 mm × 2 mm and designed using the Autodesk Fusion 360 application. After cutting, the specimens were polished using fine sandpaper (#80 to #2000) to ensure a clean surface, free from any contaminants that could affect the test results.

2.4 Heat Treatment

Thermal loading was applied to simulate the high-temperature conditions commonly encountered by Stainless Steel 304 in industrial environments. Specimens were heated at 650°C for 1 hour and allowed to air-cool. Subsequently, heat treatment was performed at 450°C for durations of 2, 4, and 6 hours to analyze the effect of holding time on material properties.

This step is important because it simulates the thermal degradation that materials may experience in real-world applications, such as chemical plants or power stations. By varying the holding time, the study provides insights into the material's response to thermal stress.

2.5 Corrosion Testing

The corrosion test was conducted using $FeCl_3$ solution, following the ASTM G48 standard. Specimens were immersed in the solution for 1 hour, and the weight loss method was used to calculate the corrosion rate.

2.6 Tensile Testing

Tensile tests were conducted to evaluate the mechanical properties of the specimens after thermal loading and exposure to corrosive environments. Specimens were placed in a tensile testing machine, and data were collected to generate stress-strain curves, which include tensile strength and Young's modulus.

This step is important because tensile testing evaluates the material’s ability to withstand mechanical loads after degradation, ensuring its reliability in structural applications where mechanical integrity is critical.

2.7 Microstructural Analysis

Microstructural analysis was performed using an optical metallurgical microscope. Specimens were etched with a 10% oxalic acid solution to reveal grain boundaries and structural details. The observations helped identify changes in the microstructure due to thermal loading and corrosion.

This systematic methodology was designed to ensure that the study provides a comprehensive evaluation of the physical and mechanical changes in Stainless Steel 304 due to thermal and environmental stresses. The findings will offer valuable insights for industries relying on this material, particularly in optimizing its performance under challenging conditions.

3. Results and Discussion

This section explores the effects of thermal loading and heat treatment on the corrosion potential, tensile strength, and microstructure of Stainless Steel 304. The findings provide valuable insights into the material's behavior under industrial conditions and the critical role of heat treatment in restoring its properties[14, 15].

3.1 Corrosion Potential: Impact of Thermal Loading and Heat Treatment

Thermal loading at 650°C for 1 hour resulted in a significant increase in corrosion potential from 387 V (raw material) to 569 V [16], as shown in Figure 1. This indicates heightened vulnerability to corrosion due to the destabilization of the passive oxide layer. However, post-thermal heat treatment at 450°C for 2, 4, and 6 hours gradually reduced the corrosion potential to 439 V, 425 V, and 391 V, respectively, approaching the original value. This demonstrates the effectiveness of heat treatment in restoring the material's corrosion resistance.

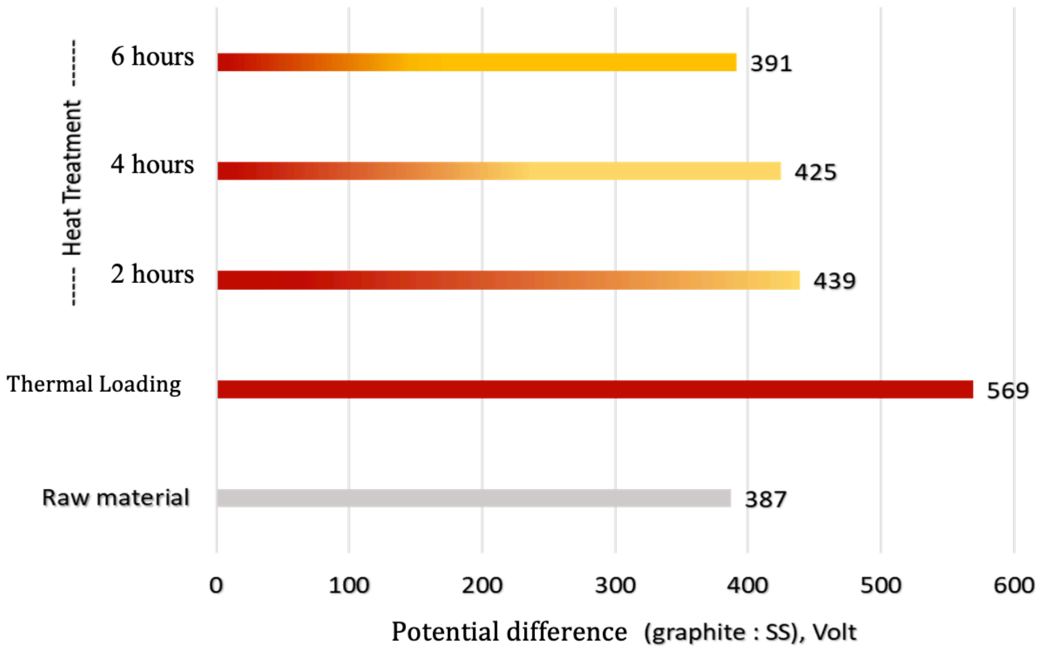

FIGURE 1. Corrosion potential testing of stainless steel 304

3.2 Visual Evaluation of Corrosion: $FeCl_3$ Immersion

The immersion of specimens in $FeCl_3$ solution further highlighted the effects of thermal loading and heat treatment. As illustrated in Figure 2, the thermally loaded specimens exhibited severe pitting corrosion, while the heat-treated specimens showed significantly less surface degradation. These findings align with the corrosion potential results, confirming the role of heat treatment in mitigating thermal-induced corrosion susceptibility.

FIGURE 2 Immersion of specimens in $FeCl_3$ solution.

3.3 Tensile Strength: Recovery Through Heat Treatment

The tensile strength of Stainless Steel 304 decreased significantly after thermal loading, dropping from 3,596.06 MPa (raw material) to 3,151.39 MPa. This reduction reflects the weakening of grain boundaries and increased dislocations caused by thermal stress. Heat treatment improved tensile strength to 3,729.62 MPa, 3,510.01 MPa, and 3472.87 MPa for 2, 4, and 6-hour treatments, respectively (Figure 3). These results demonstrate that heat treatment can partially restore the mechanical properties degraded by thermal loading.

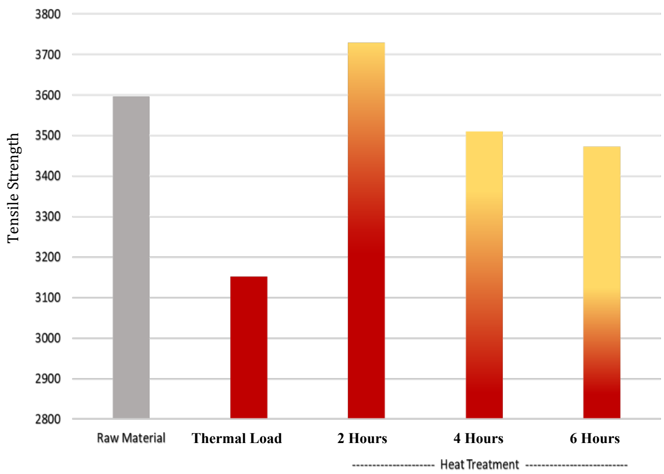

Figure 3 Tensile strength of corroded stainless steel 304

3.4 Microstructural Analysis: Grain Boundary and Dislocation Behavior

Microstructural observations revealed critical changes in grain boundary integrity and dislocation density. Figure 4 illustrates that thermally loaded specimens exhibited prominent dislocation lines and grain boundary weakening. Post-heat treatment, the microstructure showed significant recovery, with reduced dislocation density and improved grain boundary stability. These findings correlate strongly with the recovery of tensile strength and corrosion resistance.

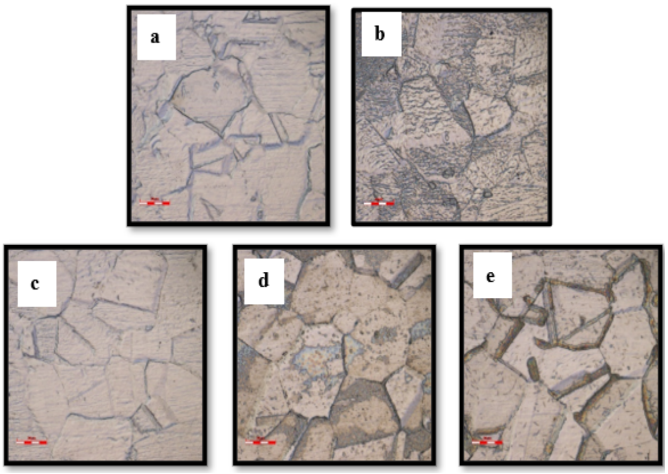

FIGURE 4 Microstructure of Stainless Steel 304 after $FeCl_3$ immersion (a) raw material, (b) thermal load 650°C for 1 hour, (c) heat treatment 450°C for 2 hours, (d) heat treatment 450°C for 4 hours, (e) heat treatment 450°C for 6 hours.

3.5 Elemental Distribution: A Key to Restoration

The distribution of key elements such as chromium and iron play a pivotal role in corrosion resistance and mechanical properties. After thermal loading, Figure 5 highlights uneven elemental distribution, which correlates with increased corrosion susceptibility and reduced tensile strength. Conversely, heat treatment restores uniformity, as seen in Figure 6, contributing to improved material performance.

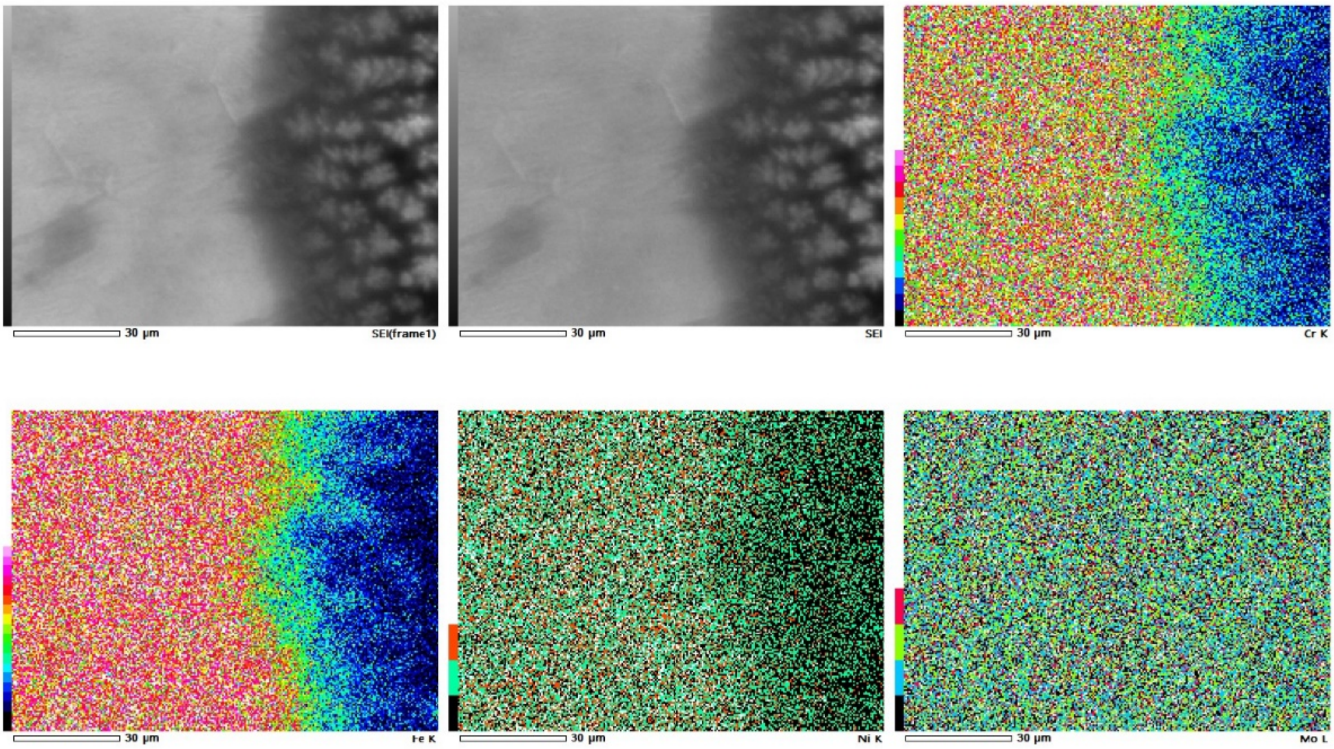

FIGURE 5 Element distribution after thermal loading

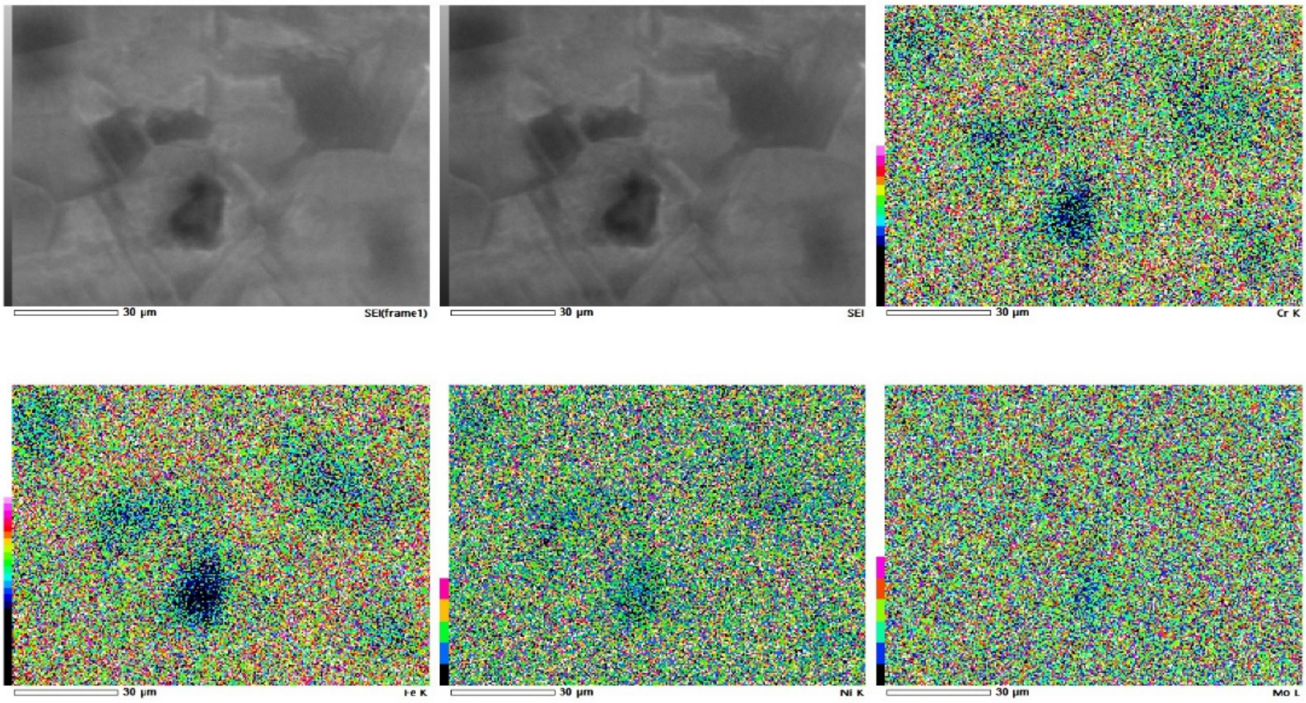

FIGURE 6 Element distribution after 6-hour heat treatment

The results clearly demonstrate that thermal loading compromises both corrosion resistance and tensile strength by destabilizing structural and elemental integrity. Heat treatment at 450°C, especially when applied for 6 hours, effectively restores these properties by enhancing mechanical strength and corrosion resistance. Furthermore, microstructural and elemental analyses emphasize that achieving uniformity and stability is crucial in mitigating the detrimental effects of thermal loading.

This study underscores the critical role of heat treatment as a post-thermal recovery strategy for Stainless Steel 304, with significant implications for industries such as transportation, energy, and manufacturing. By restoring the material's mechanical and corrosion-resistant properties, heat treatment can reduce maintenance frequency, extend component lifespan, and improve operational safety, thereby generating considerable economic benefits. However, practical implementation may be constrained by factors such as the cost of heat treatment equipment, energy consumption, process duration, and the need to integrate these processes within existing production systems. Addressing these challenges will be essential to maximize the industrial applicability of the proposed treatment.

4. Conclusion

To conclude, this study has clearly demonstrated the significant effects of thermal loading and the subsequent success of a specific heat treatment regimen on the critical properties of Stainless Steel 304. Thermal loading at 650^{o} C for one hour significantly degraded the material, increasing its corrosion potential from 387 V to 569 V and notably reducing its tensile strength from 3,596.06 MPa to 3,151.39 MPa; these adverse changes were primarily attributed to elemental segregation and structural degradation. Crucially, the subsequent heat treatment at 450^{o} C for durations of 2, 4, and 6 hours proved highly effective in mitigating this damage. This treatment successfully restored corrosion resistance, with the corrosion potential returning close to the raw material's value, reaching 391 V after the 6-hour treatment. While tensile strength showed partial recovery—reaching 3,729.62 MPa, 3,510.01 MPa, and 3,472.87 MPa for the respective 2, 4, and 6-hour treatments—microstructural and elemental analyses provided a clear mechanism for these property improvements. Specifically, the heat treatment was shown to reduce dislocation density and restore grain boundary integrity, while the uniform redistribution of chromium and iron was confirmed to be pivotal in enhancing both corrosion resistance and tensile strength. Collectively, these findings underscore the critical role of heat treatment in reliably restoring the functional properties of Stainless Steel 304, thereby ensuring its sustained performance in demanding industrial applications.

Recommendations

Based on the results of this study, the following recommendations are proposed:

1 Post-Thermal Treatment Protocol

Industries utilizing Stainless Steel 304 under high-temperature conditions should adopt heat treatment at 450°C for a minimum of 6 hours to restore corrosion resistance and mechanical strength.

2 Material Performance Monitoring

Regular microstructural and elemental analyses are recommended to monitor material degradation and assess the effectiveness of applied treatments.

3 Optimized Operational Conditions

Avoid prolonged exposure to temperatures in the sensitization range (600–900°C) to minimize material vulnerability to corrosion and mechanical failure.

4 Further Research

Future studies should explore the effects of varying heat treatment durations and cooling rates on the long-term performance of Stainless Steel 304 in different corrosive environments.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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