

ELECTROCHEMICAL CORROSION BEHAVIOUR OF BORONIZED CARBON STEEL 1020 AND STAINLESS STEEL 304

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Abstract

This study investigated how boronizing affects the electrochemical corrosion behaviour of boronized carbon steel 1020 (0.049 wt.% C and 12.700 wt.% B) and stainless steel 304 (0.003 wt.% C and 8.940 wt.% B). Both materials were boronized using Borax powder at 900°C for eight hours, forming boride layers on their surfaces. The light optical microscope revealed distinct differences between the two steels with carbon steel 1020 developing a thick sawtooth-shaped boride layer while stainless steel 304 formed a thin more compact layer. XRD (X-ray diffraction) analysis confirmed the presence of the FeB phase in both samples. Case boronizing significantly increased the surface hardness of both steels with carbon steel 1020 showing a greater hardness than stainless steel 304 as confirmed by hardness profiling. Corrosion resistance improved in both materials after boronizing, though the effect was more pronounced in carbon steel 1020 which saw a nearly fivefold increase in corrosion resistance compared to its untreated reference sample. Despite that stainless steel 304 remained the most corrosion-resistant overall even after the slight improvement from boronizing. In conclusion, boronized carbon steel 1020 exhibited the greatest overall improvement in mechanical properties particularly in terms of hardness and corrosion resistance making it an excellent candidate for applications requiring enhanced durability and long service life.

Keywords: Boride layers, Corrosion- resistance, Hardness, Carbon steel 1020, Stainless steel 304

1. INTRODUCTION

Corrosion is an issue that plague the metallurgical industry, and companies are constantly trying to solve them. If resolved the companies will be able to save money because the metal products will have a longer life cycle hence, they will not have to be replaced regularly. Corrosion occurs when a metal chemically interacts with its environment, leading to its gradual degradation. Carbon steel 1020 is used in the making of shafts, axles, gears, crankshafts, couplings, and forgings. stainless steel 304 is used to manufacture transmission parts in the automotive industry like gears, shafts, and bearings amongst other things. These two types of metals are expected to have high resistance to corrosion in most of these applications given the environments they are consistently exposed to during service. In order to improve their corrosion resistance properties, boronizing was applied as an effective surface hardening solution. Boronizing is a thermochemical surface-hardening procedure in which boron atoms are dispersed through the surface of a workpiece to create complex borides with the base metal, such as FeB/Fe₂B. The most commonly known factor that is influenced by boronizing is the hardness of the metals that successfully undergo the process. When the treatment is performed at the optimum conditions the hardness can increase by 5 times the original value at the outer casing of the material.

This research seeks to characterize the corrosion of boronized carbon steel 1020 and stainless steel 304, to identify the improvements or general changes of both metals based on applicability. The boronized and

reference samples of the metals of interest were then characterized through microstructural analysis, hardness profiling and XRD analysis.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

Samples were prepared through metallographic preparation where same later on went through the boronizing procedure. After the boronizing and preparation of the samples optical microscopy was used to analyze surface modifications while a micro-Vickers hardness tester (HV_{0.3} load) measured the hardness variations. XRD identified phase compositions and surface characteristics of the boronized and untreated samples. For corrosion testing samples were ground, cold mounted and connected with copper wires before emission in a 3.5% NaCl solution at 25°C using a three-electrode system. Open Circuit Potential (OCP) was recorded over 24 hours, followed by Tafel plot analysis using a potentiostat to determine corrosion rates.

3. RESULTS AND DISCUSSION

3.1. Microstructural Changes

3.1.1. Carbon Steel 1020

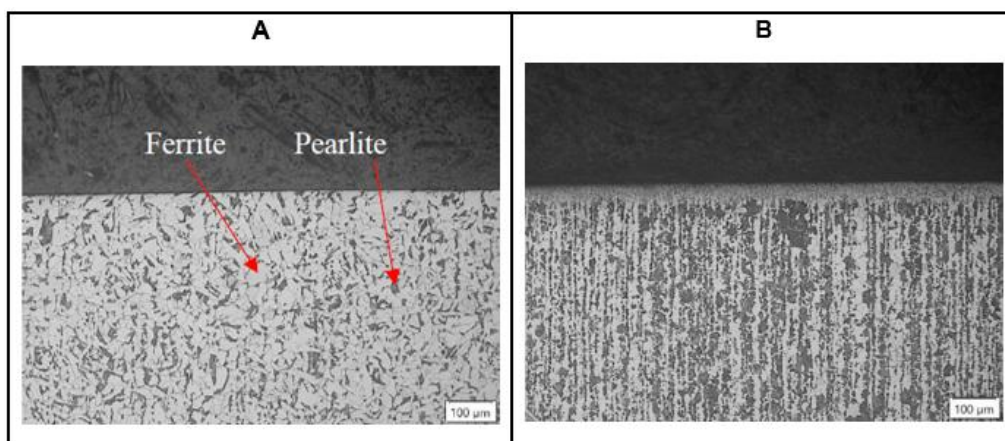


Figure 1 Optical micrograph of (A) Carbon steel 1020 reference sample (B) Boronized carbon steel 1020

Optical microscopy revealed that boronized carbon steel 1020 developed a thick, sawtooth-shaped boride layer, a common feature in low-alloy steels [1], [2], [3] as shown in (**Figure 1A**) and (**Figure 1B**). In contrast, the reference sample exhibited the typical microstructure of carbon steel 1020 with consistent grain size and phase distribution. The sawtooth morphology of the boride layer showed no contrasting colours, indicating that only one phase, FeB, was formed.

Table 1 Carbon steel 1020 case hardened at 900°C-boride layer thickness results.

Reference	Carbon steel 1020 Boride layer thickness
Sample Comment	boronized at 900°C for 8 hours
Min.	22.86 µm
Mean	41.38 µm
Max.	56.27 µm

The boride layer thickness was measured using Olympus software on an optical microscope, showing an average thickness of 41.38 μm (**Table 1**). Below the boride layer of (**Figure 1B**) was a pearlitic and ferritic microstructure relatively identical to the carbon steel 1020 reference sample in (**Figure 1A**) which remained unchanged. These results align with studies conducted on AISI 1020 boronized at 920°C [3], confirming that the boronizing process altered only the outer case while preserving the core properties of the material.

3.1.2.. Stainless Steel 304

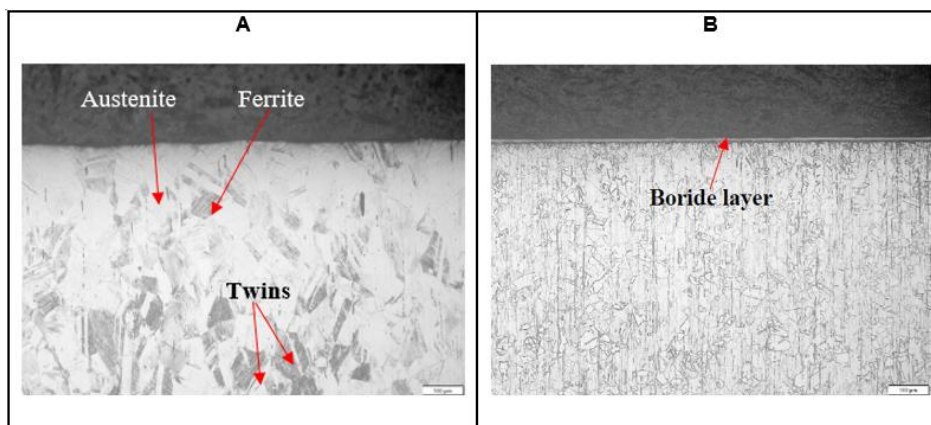


Figure 2 Optical micrograph of (A) Stainless steel 304 reference sample (B) Boronized stainless steel 304 sample

After boronizing, the stainless steel 304 sample was analyzed using optical microscopy, revealing the formation of a flat boride layer morphology, as illustrated in (**Figure 2A**) and (**Figure 2B**). Unlike carbon steel 1020, stainless steel 304 did not form a sawtooth structure but rather a smooth and compact layer, which is typical of austenitic stainless steels [4].

Table 2 Stainless steel 304 case hardened at 900°C-boride layer thickness results.

Reference	Stainless steel 304 Boride layer thickness
Sample Comment	boronized at 900°C for 8 hours
Min.	7.71 μm
Mean	8.96 μm
Max.	9.85 μm

The boride layer thickness, measured using Olympus software, was found to be 8.96 μm on average (**Table 2**). Below the boride layer, a porosity layer was observed, followed by the main matrix [5], [6]. This porosity likely resulted from rapid carbon diffusion and carbide precipitation at grain boundaries [6]. The boronized sample displayed a high boron concentration at the surface, while the underlying austenitic-ferritic microstructure remained unchanged, ensuring the core's original mechanical properties were retained.

3.1.3. Overall Microstructural Observations

Comparing the microstructural changes in boronized carbon steel 1020 and stainless steel 304, the results confirm that boronization was successful in both materials. However, the boride layer morphologies differed significantly: carbon steel 1020 developed a sawtooth-shaped FeB layer, whereas stainless steel 304 formed a thin, flat FeB layer due to alloying elements at the grain boundaries preventing deep boron diffusion.

Additionally, stainless steel 304 exhibited a porosity layer beneath the boride layer, a feature absent in carbon steel 1020 [6].

3.2. Microhardness Profiling

One of the primary goals of this boronizing experiment was to enhance the surface hardness of carbon steel 1020 and stainless steel 304 by diffusing boron at 900°C for eight hours, forming a hardened outer case. To evaluate the success of the process, Vickers microhardness testing ($HV_{0.3}$ load) was performed.

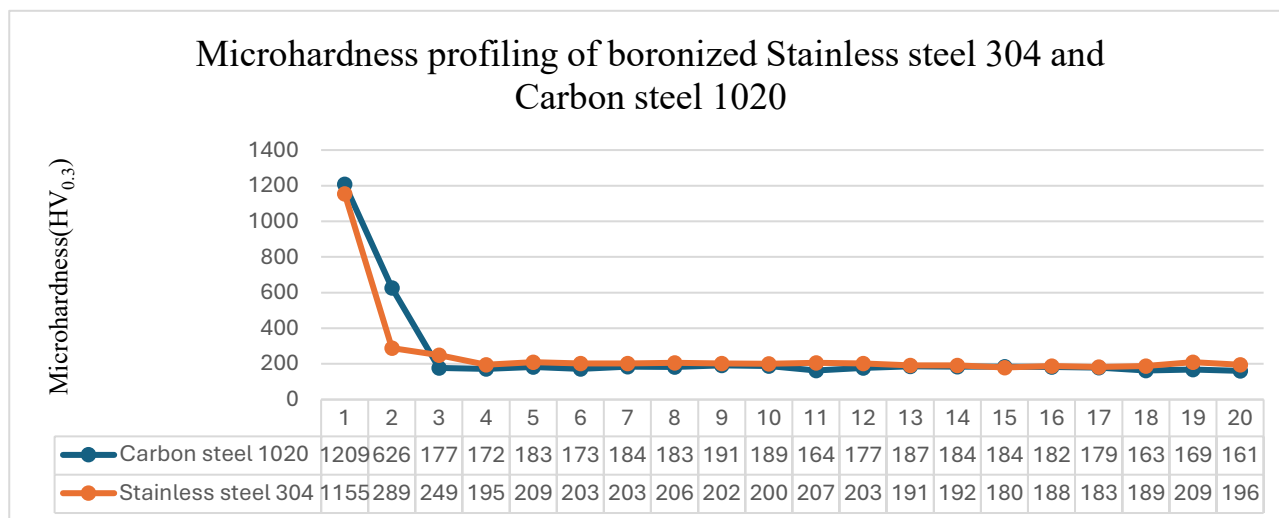


Figure 3 Comparison of microhardness profiling values of boronized carbon steel 1020 and stainless steel 304 samples

The reference carbon steel 1020 sample had an average hardness of 139.75 $HV_{0.3}$. After boronizing, microhardness profiling was conducted at 0.25 mm (250 μ m) intervals, showing that the boride outer layer reached 1209 $HV_{0.3}$, while hardness gradually decreased toward the core, settling at 161 $HV_{0.3}$ (**Figure 3**). The boride layer was 7.5 times harder than the matrix. The reference stainless steel 304 sample had an average hardness of 275.5 $HV_{0.3}$. After boronizing, microhardness profiling showed that the boride layer reached 1155 $HV_{0.3}$, but hardness significantly decreased toward the core, reaching 196 $HV_{0.3}$ (**Figure 3**).

Both boronized carbon steel 1020 and stainless steel 304 exhibited significant hardness improvements compared to their reference samples. However, boronized carbon steel 1020 had a slightly higher boride layer hardness than boronized stainless steel 304. Notably, stainless steel 304 experienced a drastic drop in hardness at the second measurement interval (289 $HV_{0.3}$), which was 3.99 times lower than its boride layer hardness, while carbon steel 1020 showed a smaller decrease (only 1.9 times lower at the second interval).

The difference in boride layer thickness and hardness retention was due to the slower boron diffusion rate in austenitic stainless steel, where carbon is pushed into the base metal but has 250–300 times lower diffusivity in austenite than in ferrite [6]. This limited diffusion resulted in a thinner boride layer in stainless steel 304 compared to carbon steel 1020.

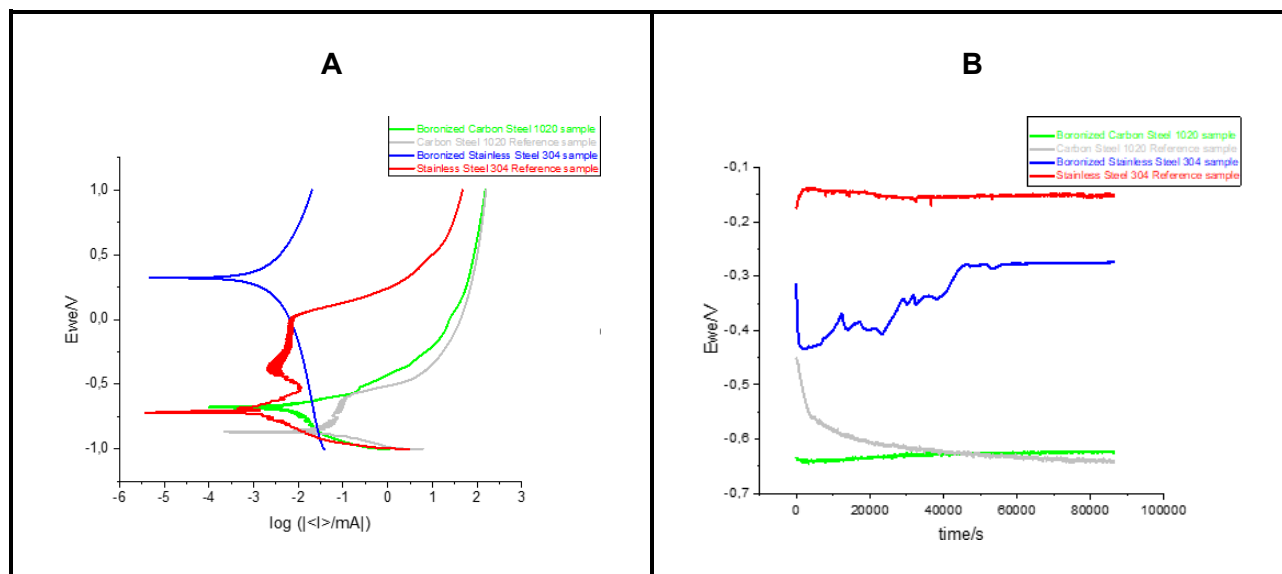


Figure 4 Open Circuit potential (OCP) results for boronized stainless steel 304 sample, boronized carbon steel 1020 sample, stainless steel 304 reference sample, and carbon steel 1020 reference sample

3.3. Electrochemical Corrosion

Corrosion is the deterioration of metals due to environmental interactions, often leading to material failure and significant economic losses. This study investigated the corrosion behavior of boronized and reference samples of stainless steel 304 and carbon steel 1020 using electrochemical corrosion testing in a 3.5% NaCl solution [7]. This environment was chosen because both metals are commonly used in marine and high-salinity environments. The electrochemical testing included Open Circuit Potential (OCP) measurements to assess sample stability and Tafel plot analysis to determine corrosion rates.

Table 3 Tafel data

Tafel data	Carbon steel 1020 Reference sample	Boronized carbon steel 1020 sample	Stainless steel 304 Reference sample	Boronized stainless steel 304 sample
E_{corr} (mV)	$-8,71 \times 10^2$	$-6,79 \times 10^2$	$-7,11 \times 10^2$	$3,22 \times 10^2$
β_a (mV)	$5,93 \times 10^2$	$0,86 \times 10^2$	$1,62 \times 10^2$	$2,49 \times 10^2$
β_c (mV)	$0,73 \times 10^2$	$2,64 \times 10^2$	$1,38 \times 10^2$	$3,13 \times 10^2$
i_{corr} (μA)	$412,0 \times 10^{-1}$	$58,3 \times 10^{-1}$	$9,81 \times 10^{-1}$	$6,50 \times 10^{-1}$
Corrosion rate (mmpy)	$25,50 \times 10^{-2}$	$5,11 \times 10^{-2}$	$1,78 \times 10^{-2}$	$1,25 \times 10^{-2}$

3.3.1.. Carbon steel 1020

OCP results (**Figure 4B**) showed that the reference carbon steel 1020 sample initially had a higher potential but gradually decreased and stabilized at a lower potential than the boronized sample. In contrast, the boronized carbon steel 1020 sample started at a highly negative potential, which gradually increased and stabilized at a higher potential than its reference counterpart [8]. This indicates that boronized carbon steel 1020 has a lower tendency to oxidize and greater corrosion resistance compared to its reference sample. Tafel plot results (**Figure 4A**) confirmed that no protective oxide film formed on either carbon steel sample, as their

anodic curves showed continuous metal dissolution without passivation, consistent with previous studies [9], [10]. Corrosion rate calculations (**Table 3**) revealed that the reference carbon steel 1020 sample had a corrosion rate of 25.50×10^{-2} mmpy, while the boronized carbon steel 1020 sample had a significantly lower rate of 5.11×10^{-2} mmpy. This indicates that boronizing improved the corrosion resistance of carbon steel 1020 by a factor of five.

3.3.2. Stainless steel 304

For stainless steel 304, the OCP results (**Figure 4B**) showed that the reference sample started at a low potential but rapidly increased due to the formation of a protective oxide film. This film stabilized over time, creating a more stable and corrosion-resistant surface. However, the boronized stainless steel 304 sample exhibited a different trend, initially dropping in potential before gradually increasing and stabilizing at a lower potential than the reference sample. This suggests that the boride layer formation inhibited oxide film formation, impacting its initial corrosion response. Tafel plot results (**Figure 4A**) showed that, unlike the OCP results, boronized stainless steel 304 had a higher corrosion potential than its reference sample, indicating greater corrosion resistance in the electrochemical environment. The anodic branch of the stainless steel 304 reference sample exhibited a plateau before showing continuous corrosion, indicating partial passivation. Corrosion rate calculations (**Table 3**) showed that the reference stainless steel 304 sample had a corrosion rate of 1.78×10^{-2} mmpy, while the boronized sample had a lower rate of 1.25×10^{-2} mmpy. Although the improvement was minor, it confirmed that boronized stainless steel 304 had slightly better corrosion resistance than its reference sample.

3.3.3. Overall Corrosion Observations

The OCP results (**Figure 4B**) ranked the samples from most stable to least stable in a 3.5% NaCl solution as follows: stainless steel 304 reference sample (highest stability), boronized stainless steel 304, boronized carbon steel 1020, and carbon steel 1020 reference sample (lowest stability). Tafel plot results (**Figure 4A**) ranked corrosion resistance in the following order: boronized stainless steel 304 (highest resistance), stainless steel 304 reference sample, boronized carbon steel 1020, and carbon steel 1020 reference sample (lowest resistance). While boronized stainless steel 304 exhibited the greatest corrosion resistance overall, boronized carbon steel 1020 showed the most significant improvement, with its corrosion rate five times lower than its reference sample but 2.8 times higher than the stainless steel 304 reference sample.

From an economic and performance perspective, boronizing carbon steel 1020 is more beneficial, as it results in a greater improvement in corrosion resistance at a similar cost compared to stainless steel 304, which showed only minor corrosion resistance gains after boronizing.

4. CONCLUSION

A comparison between boronized and reference samples of both steels revealed that the boronized samples exhibited higher hardness at the boride layer due to the increased boron content in the case-hardened outer layer. XRD analysis further confirmed the presence of the FeB phase in the boride layers. Additionally, microstructural analysis visually demonstrated the formation of these boride layers at the edges of the cross-sectional samples. Hardness profiling revealed that the boride layer in boronized carbon steel 1020 was harder than that in boronized stainless steel 304.

The boronized samples also demonstrated improved corrosion resistance, though the effect was more pronounced in carbon steel 1020, which exhibited a 4.99-fold increase in corrosion resistance compared to its reference sample.

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