coatings

Article

Characterization and Optimization of Boride Coatings on AISI 1137 Steel: Enhancing Surface Properties and Wear Resistance

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Abstract: This study investigates the optimization of boron coating parameters for medium-carbon steels, specifically AISI 1137, and their subsequent effects on mechanical properties, which are crucial for industrial applications. Despite extensive research on boronizing processes, an understanding of the optimal conditions that enhance wear resistance and hardness while maintaining structural integrity is still lacking. To address this gap, we systematically examined the impact of boronizing temperatures (850 °C and 950 °C) and durations (2, 4, and 8 h) on the structural and mechanical properties of AISI 1137 steel. Our findings indicate the need for improved surface properties in medium-carbon steels used in demanding environments, such as automotive and machinery components. The boronizing process was carried out using Ekabor 1 powder, with characterization performed through optical microscopy, pin-on-disk wear tests, and Vickers hardness analysis. Results showed that the thickness of the boronized layer ranged from 50.6 µm to 64.8 µm, with wear resistance increasing by 1.8 to 3.9 times at 950 °C compared to at 850 °C. The measured hardness of the boronized surface layers varied between 1963.7 HV and 219.3 HV, decreasing from the boronized layer toward the base material. The optimal parameters for wear resistance and hardness were found to be a temperature of 950 °C and a duration of 8 h, facilitating the formation of FeB and Fe_2B phases, which significantly enhanced the steel's mechanical properties. This research provides valuable insights into the boronizing process and establishes a foundation for the optimizing of surface treatments to extend the lifespan and performance of medium-carbon steels in industrial use.

Keywords: AISI 1137; thermo-diffusion coating; boron oxide; abrasive wear; thermal analysis; optical image analysis; Taguchi analysis and ANOVA

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1. Introduction

Coating thickness is crucial for the longevity and effectiveness of surface treatments. An optimal coating thickness is essential; lower thicknesses fail to provide adequate protection, while higher thicknesses can lead to adhesion problems and reduced coating life. Therefore, determining the optimum coating thickness is vital for enhancing the durability of coated materials [1,2]. In the machinery manufacturing sector, fatigue and wear are common damage mechanisms. These issues typically initiate on the surface, making surface coating or hardening processes necessary. Boronizing, a process involving the alloying of boron atoms to a metal surface via thermo-diffusion, forms a thin, hard layer of metal borides (FeB and Fe_2B) on the surface, significantly enhancing hardness and wear resistance [3,4]. This process can be carried out using solid, liquid, and gas methods [5].

Boronizing is widely applied to various iron alloys, including steel, to preserve the material's toughness while extending the time until damage in machine elements [6]. The surface hardness of boronized parts can vary between 2000 and 2500 HV (Vickers), depending on the steel's chemical composition and the boronizing technique used. Compared to other surface treatments, boronizing offers high surface hardness, a reduced friction coefficient, and increased corrosion resistance [7,8].

Several studies have explored the effects of boronizing on different materials. For instance, in a study where AISI 1050 steel was boronized for 3 h at 950 °C, the hardness values of the main layer were found to be 496–1290 HV in the boride layer, 300–334 HV in the transition zone, and 260–266 HV in the main structure [9]. However, it was determined that the effect of boride decreased due to the reduction in the amount of diffusion from the surface into the material. As the processing time increases, the differences between the thicknesses of the boride layers also increase [10].

In this surface hardening technique, the formation of a single-phase Fe_2B layer is preferred over a dual-phase Fe_2B + FeB layer. The FeB phase creates tensile stress, while the Fe_2B phase creates compressive stress. These opposing stresses can lead to cracks between the two phases [11]. Due to their different thermal coefficients, cracks can occur at the interface of the FeB/Fe_2B dual-phase layer. In another study, SAE 4140 steel samples were boronized for 120, 240, and 480 min. The thickest boron layer was obtained at a temperature of 1050 °C for 6 h. It was emphasized that the abrasion resistance of boronized samples increased by 3–4 times, with the best abrasion resistance observed in samples boronized at 900 °C for 6 h. External factors such as dynamic variable mechanical stresses and sudden thermal changes can cause these phase structures to separate and rupture from the surface, a phenomenon described as dehulling of the hardened layer [12,13]. Zhang [14] explored how the boronizing process affects the microstructure and mechanical properties of 20CrMnTi steel. Boronizing is a surface treatment process where boron atoms are diffused into the surface of a metal, typically to improve its hardness, wear resistance, and corrosion resistance.

The focus of this study is to determine the effect of the thermo-diffusion boriding process on the thickness, hardness, and wear resistance of the borided layer. Improving the surface properties of AISI 1137 medium-carbon steel is preferable over using higher-cost alloy steels in the production industry.

2. Experimental Details

In this study, thermo-diffusion boronizing was applied to AISI 1137 steel, which is frequently preferred in spline shafts, studs, bolts, nuts with machined threads, and similar parts. Thus, this process aimed to harden the surface of the steel and determine the mechanical properties and morphology of the formed boride layers. The test samples were prepared in a 20 × 20 × 20 mm^3 on a milling machine and were readied for boronizing. The chemical composition of the AISI 1137 steel used in the experiments is given in Table 1.

Table 1. Chemical composition of AISI 1137 steel.

C %	0.32–0.39
Fe %	97.79–98.25
Mn %	1.35–1.65
P %	$\leq$0.040
S %	0.080–0.13

The boronizing process was conducted using a Protherm PLF 120/10 electric resistance furnace, ensuring precise temperature control with an accuracy of ±5 °C. For microstructural characterization, we utilized a Nikon Eclipse MA200 optical microscope, offering a resolution of 0.1 μm and equipped with a state-of-the-art digital imaging system. Hardness measurements were performed using a Future-Tech FM-700 Vickers microhardness tester, capable of applying loads ranging from 10 g to 1 kg. Wear tests were executed on a Tribotester T10/20 pin-on-disk tribometer, providing high precision with a sensitivity of ±0.1 mg. The boronizing powder used in this study was Ekabor 1. This powder featured a particle size distribution of 50–100 μm and comprised 90% B_4C as the primary source, 5% KBF_4 as an activator, and 5% SiC as a filler, with a purity exceeding 98%.

In the process of diffusion in boronization, the material to be boronized is placed in the middle of powdered boron and is usually held at 850–1000 °C for 2–10 h.

The rationale for using Ekabor 1 in this study includes the following:

- Optimal Layer Thickness: Ekabor 1 is known to produce consistent and optimal boride layer thickness, which is crucial for achieving the desired surface properties.
- Surface Quality: The use of Ekabor 1 results in high-quality surface roughness, which is beneficial for applications requiring smooth and wear-resistant surfaces.
- General Purpose: Ekabor 1 is suitable for use with general-purpose iron and steel materials, making it a versatile choice for various industrial applications.

A total of 12 samples were boronized at 850 °C and 950 °C for 2, 4 and 8 h, with 2 pieces boronized using the same parameters. Boronized samples were first subjected to abrasion tests. Abrasion tests were performed using the disk-pin test assembly. Using abrasives of 800 and 1200 mesh Al_2O_3, for a total length of 150 m with 25 m intervals, abrasive wear tests were performed using a pin-on-disc type tribometer under dry sliding conditions. The tests were conducted at room temperature with an applied load of 5 N, a sliding speed of 0.1 m/s, and a sliding distance of 1000 m. The wear track diameter was set to 6 mm, and Al_2O_3 balls with a 6 mm diameter were used as the counter body. The samples were wiped and cleaned with alcohol before the test and were weighed before and after the wear test by 0.1 mg precision scales. New abrasive sandpaper was used for each test.

Then, samples were polished with a metallographic polishing technique, and images were taken under an optical microscope. In this way, the depth of the boronized layer was measured. After this examination, the surfaces of the samples were polished again and microhardness measurements were made in order to remove the chemical effect of acid etching. Hardness measurements were performed using a Future-Tech FM-700 Vickers microhardness tester under a load of 100 gf with a dwell time of 15 s, following ASTM E384 standards [9,10]. Measurements were taken at intervals of 10 μm from the surface to a depth of 160 μm to evaluate the hardness gradient. For each depth, five measurements were taken, and the average values were calculated, along with their standard deviations.

The hardness of the boronized layer was assessed using Vickers microhardness testing. Measurements were taken at various depths from the surface to evaluate the hardness gradient. The highest hardness value recorded was 1963.7 HV, at a depth of 10 μm from the surface, while the lowest value was 219.3 HV, at a depth of 160 μm, near the base metal. The results demonstrated that both the boronizing temperature and time contribute to the hardness of the boride layer. Higher temperatures and longer durations facilitate greater boron diffusion, resulting in a thicker and harder surface layer. This increased hardness is crucial for enhancing the wear resistance of the steel.

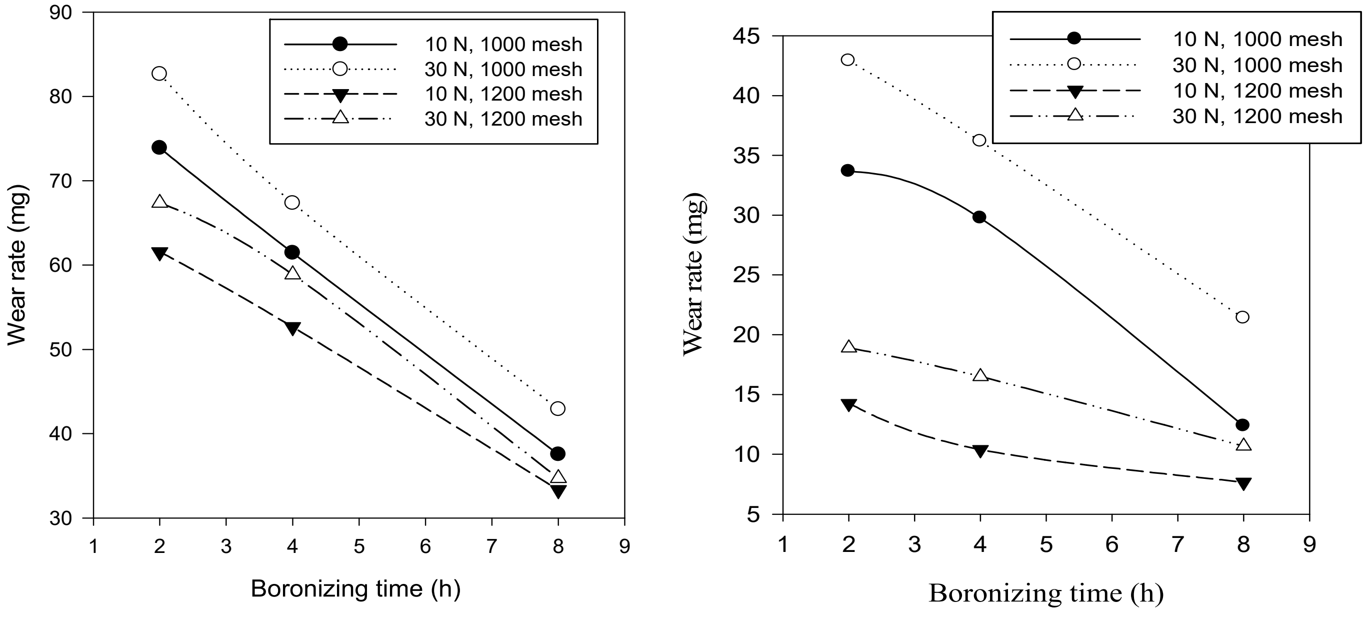
3. Results and Discussion

3.1. Wear Resistance Tests

The wear behavior analysis revealed that increasing the abrasive grain size to 1000 mesh resulted in higher wear loss in boron-coated samples. This increased wear loss can be attributed to several factors:

1. Mechanical Interaction:
    - Larger abrasive particles creating deeper scratches and more material removal;
    - Higher contact stresses at individual particle–surface interfaces;
    - More aggressive material displacement during sliding contact.
2. Surface Layer Properties:
    - The interaction between larger abrasive particles and the boride layer structure;
    - Potential microcracking in the coating due to higher localized stresses;
    - The role of the FeB and Fe_2B phases in resisting abrasive wear.
3. Load Distribution:
    - Changes in load distribution patterns with larger particles;
    - Increased effective contact pressure per particle;
    - Modified wear mechanism due to particle size effects.

Wear behavior tests of boron-coated samples showed that wear loss increased when abrasive grain size (1000 mesh) increased. Also, when evaluating wear loss according to applied loads, it increased with increments of load, too. It was also found that with increasing boronization time, the thickness of the boron layer increased, and consequently, wear loss decreased. The lowest wear rate was determined to be in materials boronized at 950 °C for 8 h. This is due to the formation of FeB on the surface of the material depending on the boronization time [15]. The FeB phase increases the hardness and abrasion resistance of the material [16,17]. The highest wear loss was found on samples boronized at 850 °C for 2 h (Figure 1).



(**a**) (**b**)

Figure 1. Wear rates of boronized AISI 1137 steels: (**a**) 850 °C; (**b**) 950 °C.

Upon examining Figure 1a,b, it was observed that when the compressive force applied during abrasion tests was increased for samples boronized at 850 °C, the resulting change in the amount of abrasion was less significant compared to in the boronized samples processed at 950 °C. The wear resistance of the boronized AISI 1137 steel samples was evaluated through a series of abrasion tests. These tests were conducted using a disk-pin test assembly with abrasives of 800 and 1200 mesh Al_2O_3.

The results indicated a significant improvement in wear resistance with increasing boronizing temperature and time. Specifically, samples boronized at 950 °C exhibited superior wear resistance compared to those treated at 850 °C. This enhancement is attributed to the formation of a thicker and harder boride layer at higher temperatures, which effectively protects the underlying steel from abrasive wear. However, it was observed that the bonding between the base material and the boronized layer could be compromised at higher temperatures, leading to partial wear in the base material under increased load conditions. This phenomenon, described as crusting in the brittle layer, is thought to occur due to the effect of the increased load and partial wear in the base material.

3.2. Optical Image Analysis and Thickness Measurement

The microstructural analysis of the boronized samples was performed using optical microscopy. The samples were prepared through metallographic polishing and acid etching to reveal the boride layer. The thickness of the boronized layer was measured from the optical images, showing a clear correlation between the boronizing parameters and the layer thickness.

The analysis revealed that both the boronizing temperature and time significantly influence the thickness of the boride layer. Samples treated at 950 °C for 8 h exhibited the maximum layer thickness, at 127.45 µm. This increase in thickness with higher temperature and longer duration is due to the enhanced diffusion of boron atoms into the steel substrate, forming a more substantial boride layer.

When the optical images were examined, it was found that the boron layer obtained an inhomogeneous appearance as the processing time increased. Although the thickness of the boron layer increased from the surface inward, a thermally affected layer formed toward the base material (Figure 2d–f). The details are given in Table 2.

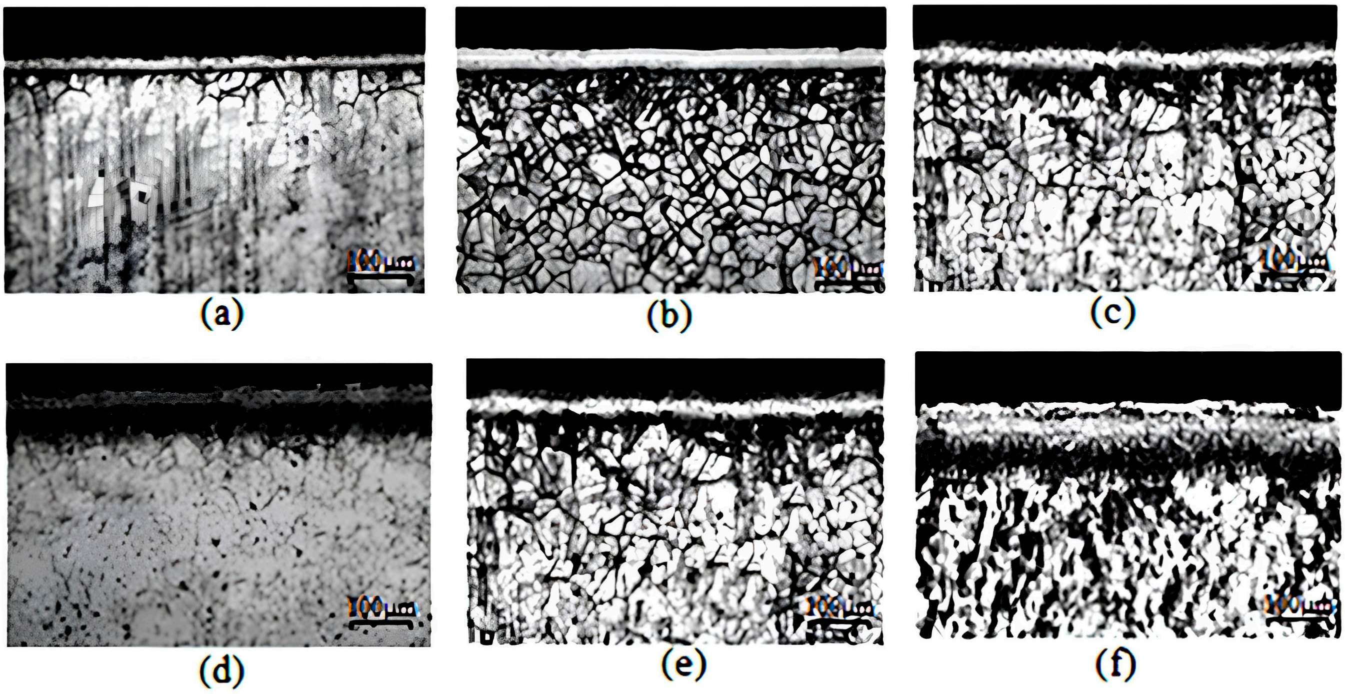


Figure 2. Optical images of boronized layers: (**a**) 2 h—850 °C; (**b**) 4 h—850 °C; (**c**) 8 h—850 °C; (**d**) 2 h—950 °C; (**e**) 4 h—950 °C; (**f**) 8 h—950 °C.

Table 2. Boronized layer thicknesses.

Boronizing Temperature (°C)	Boronizing Time (h)	Boronized Layer Thickness (μm)
850	2	64.8
	4	78.36
	8	102.65
950	2	73.45
	4	94.78
	8	127.45

3.3. Hardness Measurement

The metallographic examination of the surfaces of the specimens polished by fine sandpaper and the hardness measurements were performed at the diffusion and transition layers. The hardness of the boronized layer increased with increasing processing temperature and time. The commercially available non-boronized sample's hardness 207 HV. Microhardness values increased by 1.14–9.48 times when compared to the untreated sample (Figure 3). The highest value measured was 1963.7 HV, in the sample boronized at 950 °C for 8 h. As the thickness of the hard and brittle layer decreased moving inward to the base material, the hardness value decreased as well. When the hardness values were measured near the top of the surface for all samples and then compared, it was observed that hardness increased with an increasing thickness of the layer. This is due to the more effective diffusion of boron on the outermost surface of the sample at a high temperature. For special applications, it is suggested that the temperature scale and thermal holding time should be evaluated separately. In studies involving heat transfer and energy transfer, it is essential to investigate the effect of the temperature difference which the surface layer generated by the boronizing process on steel is exposed to on wear resistance. This aspect stands out as a prominent issue in research assessing the impact of varying temperature and pressure conditions on material properties. It is crucial to determine the temperature effect in studies examining how different flow conditions influence heat transfer performance, or in studies investigating the impact of parameters such as jet flow density and velocity on heat transfer on a flat surface. This is emphasized as an important aspect for understanding and improving the performance of different heat transfer systems in academic research [18,19].

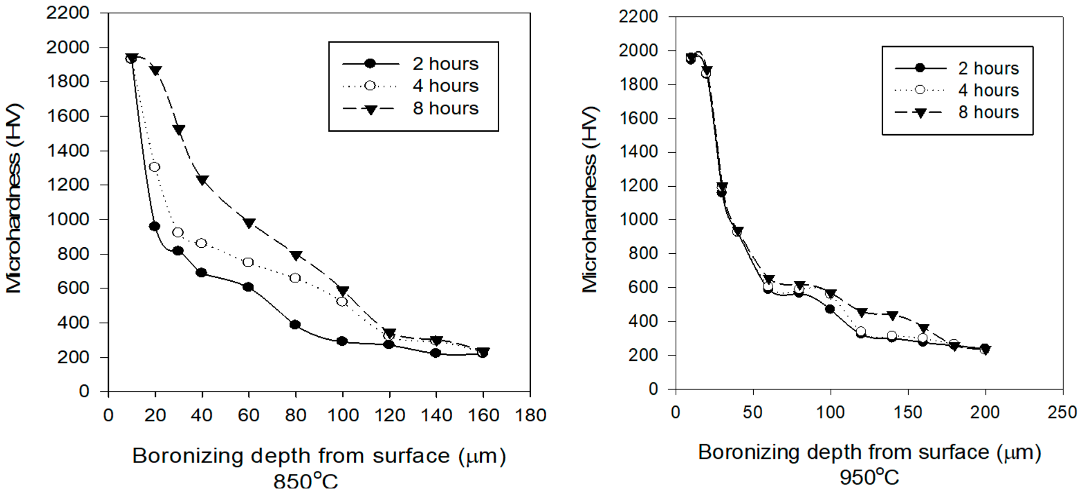


Figure 3. Variation in surface hardness of boronized layers at different temperatures and times.

Ultimately, both graphs unequivocally depict the influence of boronizing temperature and duration on the microhardness profile. It is evident that boronizing carried out at 950 °C typically yields higher microhardness values than the process conducted at 850 °C, and longer durations tend to promote the formation of harder surface layers. This comparative analysis offers valuable insights for the optimization of the boronizing process.

3.4. Discussion of Results

The experimental results indicate that the thickness of the boronized layer, the hardness, and the wear resistance of AISI 1137 steel are significantly influenced by the boronizing temperature and time. The increase in layer thickness with higher temperatures and longer durations can be attributed to the enhanced diffusion of boron atoms into the steel matrix. At elevated temperatures, the atomic bonds within the base metal weaken, facilitating a deeper penetration of boron atoms and resulting in a thicker boronized layer.

The observed increase in hardness is primarily due to the formation of hard boride phases such as FeB and Fe_2B. These phases are known to enhance the surface hardness and wear resistance of the material. The highest hardness values were recorded at the surface and decreased with depth, indicating a gradient in boron concentration.

The wear resistance tests revealed that samples boronized at 950 °C exhibited significantly lower wear rates compared to those boronized at 850 °C. This can be explained by the formation of a more robust and wear-resistant boride layer at higher temperatures. The FeB phase, in particular, is known for its superior hardness and abrasion resistance, which likely contributed to the improved wear performance.

These findings are consistent with the existing literature, which also reports increased hardness and wear resistance with higher boronizing temperatures and longer durations [8–10,15–17]. However, this study provides a more detailed optimization analysis using Taguchi and ANOVA methods, offering valuable insights for industrial applications.

In summary, the underlying phenomena driving the observed improvements in mechanical properties are primarily related to the diffusion kinetics of boron atoms and the formation of hard boride phases.

3.5. Wear Mechanisms and Practical Implications

The wear tests conducted at different loads (10 N and 30 N) showed quantitative differences in wear rates between samples boronized at different temperatures and times. Specifically, samples treated at 950 °C exhibited lower wear rates compared to those treated at 850 °C. The wear resistance results are presented in terms of weight loss measurements, providing quantitative data on the performance of the boronized layers under different treatment conditions. The results showed improved wear resistance in samples treated at higher temperatures, as evidenced by the reduced weight loss measurements.

This can be attributed to the formation of a more robust and wear-resistant boride layer at higher temperatures. The FeB phase, in particular, is known for its superior hardness and abrasion resistance, which likely contributed to the improved wear performance.

In practical applications, borided AISI 1137 steel can be used in components subjected to high wear conditions, such as spline shafts, studs, bolts, and nuts. To prolong the lifetime of these components, it is essential to optimize the boronizing process parameters, such as temperature and time, to achieve the desired layer thickness and hardness. Additionally, the regular maintenance and monitoring of wear surfaces can help identify early signs of wear and prevent catastrophic failures.

4. Optimization of the Boronizing of AISI 1137 Steel

4.1. Taguchi Analysis and ANOVA for Layer Thickness

First, boriding thickness analyses depending on temperature and time were conducted. The results of the analyses are given in Figure 4.

In light of the analysis in Figure 4, it has been determined that the boronizing process performed on AISI 1137 steel yields an optimal layer thickness when the parameters are set to a boronizing temperature of 950 °C and a boronizing time of 4 h. An examination of the ANOVA in Table 3 reveals that the most influential parameter affecting layer thickness is the boronizing time, accounting for 81.7% of the effect ($p = 0.070$, where $p < 0.005$). Conversely, the temperature parameter appears to have an insignificant influence ($p = 0.070$, where $p < 0.05$), with its contribution to the effect being merely 15.7%.

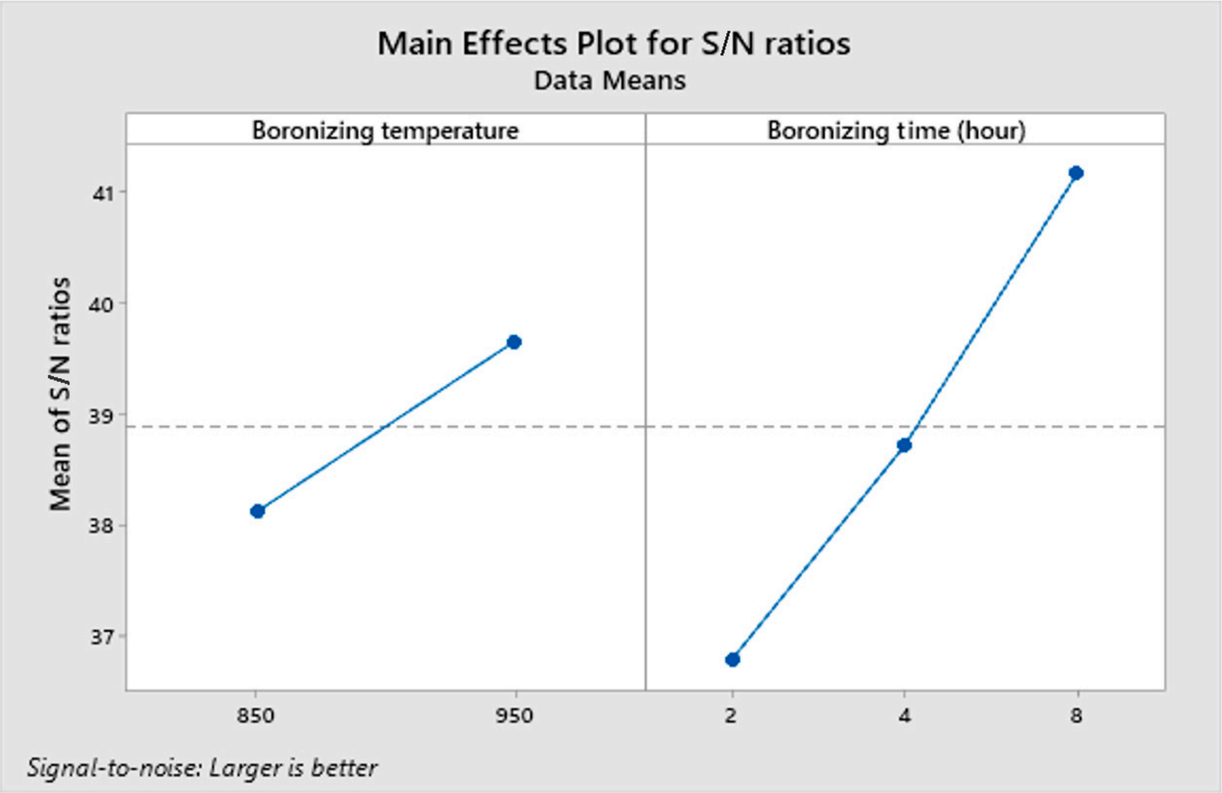


Figure 4. Taguchi analysis: boronizing layer thickness (μm) versus boronizing temperature and boronizing time (h).

Table 3. Analysis of variance for layer thickness.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	% Contribution
Boronizing temperature	1	414.50	414.50	12.71	0.070	15.76381
Boronizing time (h)	2	2149.70	1074.85	32.95	0.029	81.75505
Error	2	65.24	32.62	-	-	2.481137
Total	5	2629.44	-	-	-	100

These findings suggest that the duration of the boronizing process plays a critical role in determining the layer thickness, overshadowing the impact of temperature. The negligible effect of temperature may be attributed to the saturation of the boron diffusion process at higher temperatures, wherein time becomes the dominant factor in facilitating further diffusion and growth of the boride layer.

4.2. Taguchi Analysis and ANOVA for Wear Rate

In the second stage, an analysis of the effect of time and temperature on wear was conducted, and the results are given in Figure 5.

Boronizing treatments were conducted on AISI 1137 steel at temperatures of 850 °C and 950 °C for durations of 2, 4, and 8 h. The analysis in Figure 5, using Taguchi methodology, indicates that the optimal parameters for minimizing wear rate are a boronizing temperature of 950 °C and a boronizing time of 8 h. An examination of the ANOVA results presented in Table 4 demonstrates that temperature significantly affects wear rate (p = 0.027, where p < 0.005), whereas time does not have a significant impact (p = 0.260, where p < 0.005). Specifically, the boronizing temperature accounts for 82% of the influence on wear rate, while the boronizing time contributes only 13%.

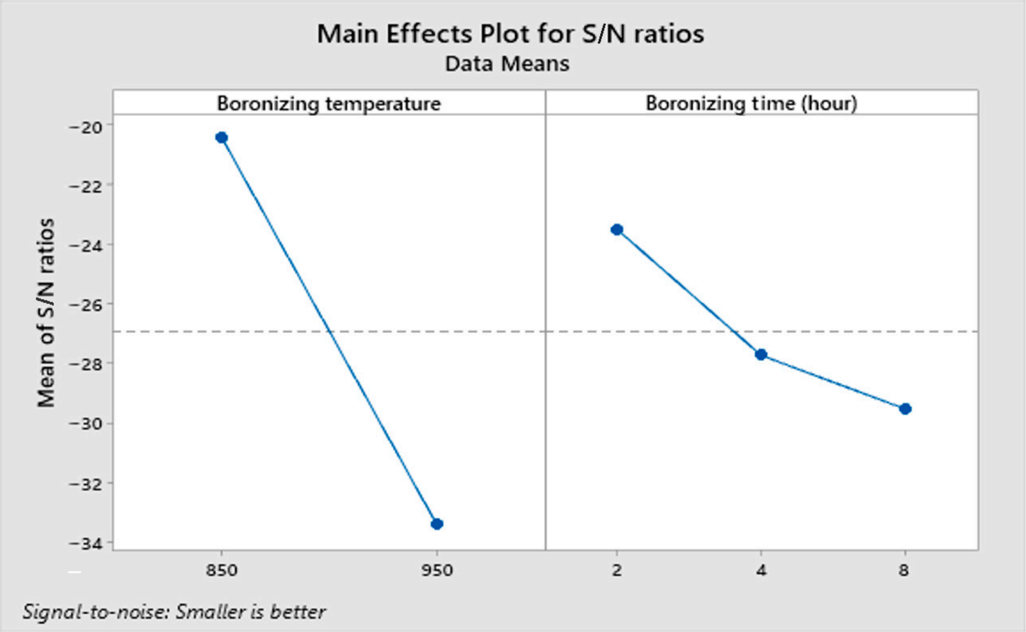


Figure 5. Taguchi analysis: wear rate (mg) versus boronizing temperature and boronizing time (h).

Table 4. Analysis of variance for wear rate.

Source	DF	Adj SS	Adj MS	F-Value	p-Value	% Contribution
Boronizing temperature	1	2128.2	2128.17	35.08	0.027	82.01788
Boronizing time (h)	2	345.3	172.67	2.85	0.260	13.30738
Error	2	121.3	60.67	-	-	4.674734
Total	5	2594.8	-	-	-	100

These findings suggest that the temperature parameter is the dominant factor in reducing wear rate, overshadowing the contribution of time. This significant influence of temperature can be attributed to its effect on the formation and characteristics of the boride layer, which plays a crucial role in wear resistance. Therefore, adjusting the boronizing temperature appears to be a more effective approach to optimizing wear rate compared to modifying the boronizing time within the investigated range.

4.3. Taguchi Analysis and ANOVA for Hardness

In the last stage, the change in hardness was analyzed, and the results are given in Figure 6.

Boronizing treatments were performed on AISI 1137 steel at temperatures of 850 °C and 950 °C for durations of 2, 4, and 8 h. It was observed that the thickness of the boronized layer increased with both time and temperature, which consequently led to an increase in hardness. According to the Taguchi analysis presented in Figure 6, the optimal parameters for achieving the highest hardness are a boronizing temperature of 950 °C and a boronizing time of 8 h. However, the ANOVA results detailed in Table 5 reveal that neither temperature ($p = 0.181$, where $p < 0.005$ is not satisfied) nor time ($p = 0.405$, where $p < 0.005$ is not satisfied) significantly influence hardness. Despite this, their contributions to hardness cannot be entirely dismissed, as it was found that temperature has a 45% influence and time has a 32% influence on hardness.

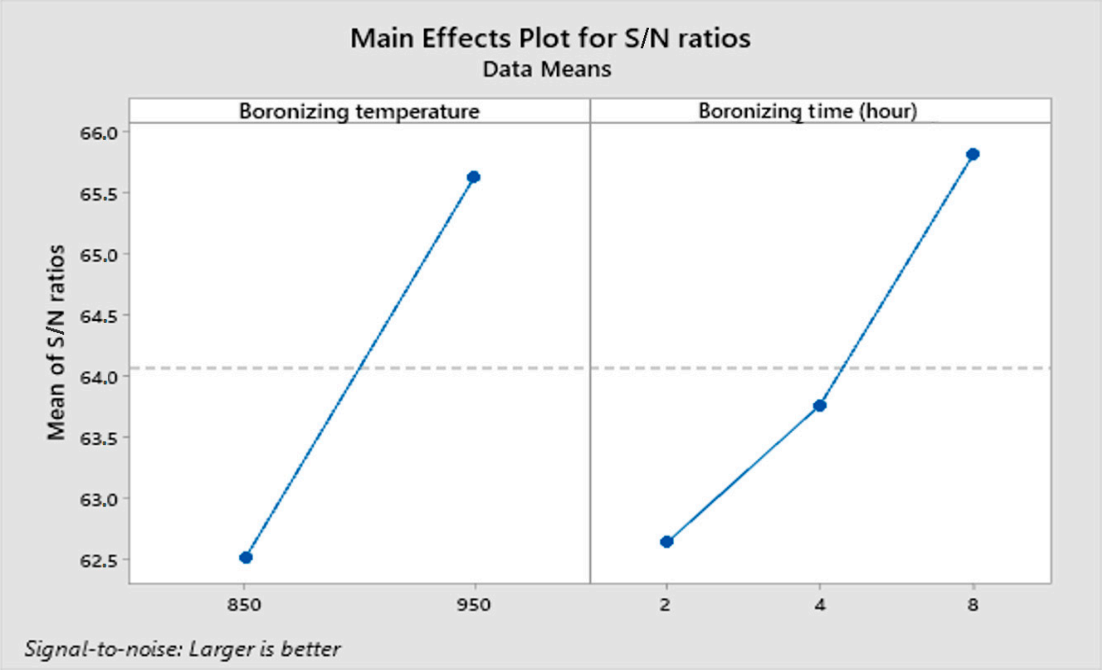


Figure 6. Taguchi analysis: hardness (HV) versus boronizing temperature and boronizing time (h).

Table 5. Analysis of variance for hardness.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	% Contribution
Boronizing temperature	1	407,161	407,161	4.06	0.181	45.14641
Boronizing time (h)	2	294,303	147,152	1.47	0.405	32.6326
Error	2	200,403	100,202	-	-	22.22088
Total	5	901,868	-	-	-	100

These findings suggest that while the boronizing parameters of temperature and time do not show a statistically significant effect on hardness individually, they still contribute substantially to the overall hardness achieved. The increase in hardness with higher temperatures and longer boronizing times can be attributed to the enhanced diffusion of boron atoms, resulting in a thicker and harder boride layer. Thus, optimizing both temperature and time is essential for achieving improved hardness in AISI 1137 steel through the boronizing process.

4.4. *Taguchi Method and ANOVA*

The Taguchi method is a robust statistical technique used for optimizing process parameters and improving quality. It employs orthogonal arrays to systematically vary and test multiple factors, allowing for the identification of optimal conditions with a minimal number of experiments [20]. In this study, an L9 orthogonal array was selected to investigate the effects of two temperatures (850 °C and 950 °C) and three treatment times (2, 4, and 8 h) on layer thickness, wear rate, and hardness.

The signal-to-noise (S/N) ratio was calculated for each response variable to determine the optimal levels of the factors. The S/N ratio helps in identifying the settings that minimize variability and improve performance. For layer thickness and hardness, the "larger-the-better" criterion was used, while for wear rate, the "smaller-the-better" criterion was applied. ANOVA was employed to analyze the significance of the factors and their interactions. This statistical method decomposes the total variability of the data into contributions from each factor and error. The F-value and *p*-value were calculated to determine the statistical significance of the factors. A *p*-value less than 0.05 indicates a significant effect. The percentage contribution of each factor was also computed to understand its impact on the response variables [21].

In this study, the ANOVA results revealed that boronizing time had the most significant effect on layer thickness, accounting for 81.7% of the variation, while temperature had a minor influence. Conversely, temperature was the dominant factor affecting wear rate, contributing 82% to the variation, with time having a lesser impact. For hardness, neither temperature nor time showed a statistically significant effect individually, but their combined influence was substantial. By integrating the Taguchi method and ANOVA, the optimal boronizing parameters were identified as a temperature of 950 °C and a duration of 4 to 8 h. These settings yielded the best combination of layer thickness, hardness, and wear resistance, providing valuable insights for industrial applications.

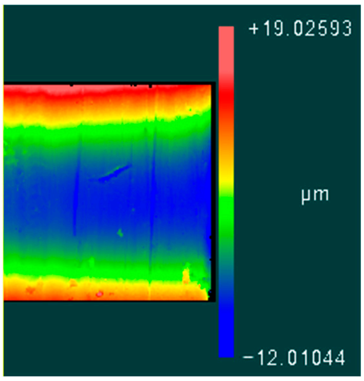
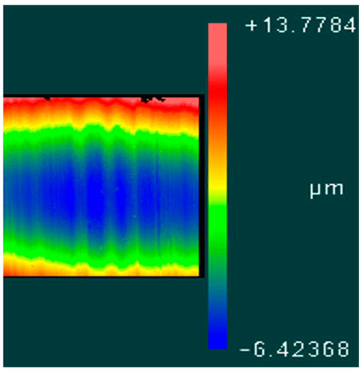
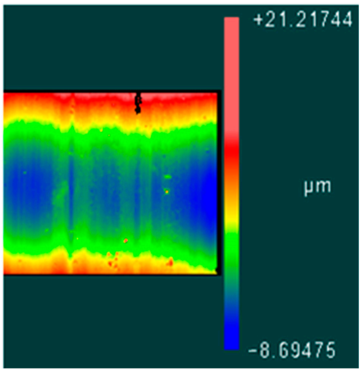
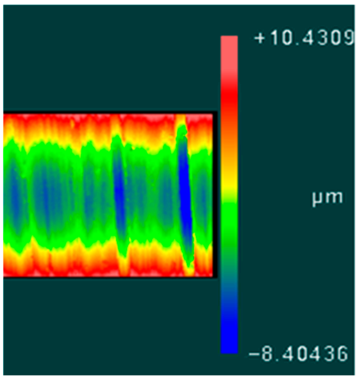
5. Boronizing Surface

The AISI 1137 steel was visualized using the 3D optical imager to determine the surface metrology. In Table 6, optical images are given for 2–6–8 h at a 850 °C temperature. The images presented in the table showcase the surface modifications resulting from boriding processes conducted at varying durations and at a temperature of 850 °C. The data in this table provide a meticulous examination of surface fluctuations based on the duration of the boriding process. Detailed information regarding the temperature and duration of each boriding operation is encapsulated within the Properties column, depicting processes carried out at 850 °C for durations of 30 min, 45 min, 60 min, and 120 min. Each row in the table is accompanied by a corresponding color map in the Change in Surface after Boriding column, visually representing the depth and intensity of surface alterations following the boriding procedure. Noteworthy transformations are observed after the 30 min boriding process, with the color map illustrating the extent of the surface modification. A more profound and intensified alteration is evident after the 45 min boriding process, signifying a noticeable impact on the surface.

The 60 min boriding process results in further deepening and intensification of surface modifications, as depicted in the color map, highlighting its significant influence on the surface. Finally, the 120 min boriding process induces the most substantial and intense surface alterations, with the color map showcasing that the maximum impact was achieved during this duration.

Overall, the data unequivocally demonstrate that prolonging the boriding duration leads to deeper and more intense surface alterations. These insights are invaluable for optimizing the boriding process and effectively achieving the desired surface characteristics.

Table 6. Boridation of the surface depending on time and temperature.

Properties	Change in Surface After Boriding
850 °C—30 min	
850 °C—45 min	
850 °C—60 min	
850 °C—120 min	

6. Conclusions

This study systematically investigated the effects of boronizing temperatures (850 °C and 950 °C) and durations (2, 4, and 8 h) on the structural and mechanical properties of

AISI 1137 steel. The findings provide a comprehensive analysis of the optimal boronizing parameters for enhancing wear resistance and hardness, which has not been extensively covered in previous research. It was determined that the optimal boronizing parameters for AISI 1137 steel are a temperature of 950 °C and a duration of 8 h. These conditions resulted in significantly improved mechanical properties of the steel, likely due to the formation of boride phases, as suggested by the enhanced hardness and wear resistance values observed.

The experimental results demonstrated that boronizing at 950 °C for 8 h improved the wear resistance of AISI 1137 steel by 1.8–3.9 times compared to boronizing at 850 °C, as evidenced by our wear test measurements. These quantitative improvements in wear resistance suggest potential benefits for industrial applications where enhanced surface durability is required. The hardness of the boronized surface layers was measured as being between 1963.7 HV and 219.3 HV, with hardness decreasing from the boronized layer toward the base material. This gradient in hardness can be beneficial for applications requiring a hard surface with a tough core.

Future research could explore the effects of different boronizing atmospheres, cooling rates, and post-treatment processes on the wear mechanisms and overall performance of borided steel. Understanding these factors will provide a more comprehensive approach to enhancing the wear resistance and durability of borided AISI 1137 steel in various industrial applications. Additionally, investigating the impact of varying temperature and pressure conditions on material properties, such as jet flow density and velocity on heat transfer, could further optimize the boronizing process.

The optimized boronizing parameters identified in this study can be applied to medium-carbon steel components used in the automotive industry, such as gears, shafts, and bearings, to enhance their wear resistance and extend their service life. Machinery components subjected to high wear conditions, such as cutting tools and dies, can also benefit from the improved surface properties achieved through the optimized boronizing process. By integrating the Taguchi method and ANOVA, the optimal boronizing parameters were identified as a temperature of 950 °C and a duration of 4 to 8 h. These settings yielded the best combination of layer thickness, hardness, and wear resistance, providing valuable insights for industrial applications.

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References

1. Salman, S.; Köse, R.; Urtekin, L.; Findik, F. An investigation of different ceramic coating thermal properties. *Mater. Des.* **2006**, *27*, 585–590. [CrossRef]
2. Köse, R.; Urtekin, L.; Ceylan, A.; Salman, S.; Findik, F. Three types of ceramic coating applicability in automotive industry for wear resistance purpose. *Ind. Lubr. Tribol.* **2005**, *57*, 140–144. [CrossRef]

3. Urtekin, L.; Kucukturk, G.; Karacay, T.; Uslan, I.; Salman, S. An investigation of thermal properties of zirconia coating on aluminum. *Arab. J. Sci. Eng.* **2012**, *37*, 2323–2332. [CrossRef]
4. Aliofkhazraei, M.; Ali, N. Surface Boriding of Metals for Enhanced Hardness and Wear Resistance: A Review. *Surf. Eng.* **2019**, *35*, 847–864.
5. Gheisari, A.; Sohi, M.H.; Bahrololoom, M.E. A Review on Boronizing of Steels Using the Powder-Pack Method. *Surf. Eng.* **2018**, *34*, 330–343.
6. Chen, X.; Zhang, Y.; Wang, Z.; Liu, Q.; Li, Y. Boronizing of Iron Alloys: Methods, Mechanisms, and Applications. *J. Mater. Sci. Technol.* **2021**, *56*, 105–120.
7. Gräfen, W.; Edenhofer, B. New developments in thermo-chemical diffusion processes. *Surf. Coat. Technol.* **2005**, *200*, 1830–1836. [CrossRef]
8. Martini, C.; Palombarini, G.; Poli, G.; Prandstraller, D. Sliding and abrasive wear behaviour of boride coatings. *Wear* **2004**, *256*, 608–613. [CrossRef]
9. Guler, S.; Calik, M.; Almis, A.; Tasgetiren, E.; Yilmaz, F. Effect of Boronizing Time on the Microstructure and Wear Behavior of AISI 1050 Steel. *Surf. Coat. Technol.* **2018**, *333*, 109–116.
10. Karakoç, E.A.; Celik, O.N.; Calik, M.; Bayramoglu, M.E. Effect of Boronizing Time on the Microstructure and Thickness of Boride Layers Formed on AISI 1045 Steel. *Mater. Sci. Eng. A* **2016**, *652*, 131–138.
11. Silva, S.; Silva, C.A.; Araujo, L.O.; Neto, J.M.D.; Sinatora, A.; Ueda, M. Microstructural Characterization of Borided AISI 1040 Steel. *J. Mater. Eng. Perform.* **2013**, *22*, 445–451.
12. Zhang, S.; Liu, Y.; Shi, L.; Li, M.; Peng, J. Influence of processing parameters on microstructure and properties of boronized layer on H13 steel. *Surf. Coat. Technol.* **2020**, *401*, 126234.
13. Sikka, V.K.; Misra, S. Surface hardening of steels by a new boriding process. *Surf. Eng.* **2018**, *34*, 605–609.
14. Zhang, W.; Sun, L.; Li, C.; Yu, H. Effects of boronizing process on microstructure and mechanical properties of 20CrMnTi steel. *J. Mater. Res. Technol.* **2019**, *8*, 3760–3770.
15. Özkaya, A.; Can, E.; Übeyli, H.; Çolak, M.O. Effect of Boronizing Parameters on the Wear Behavior of Medium Carbon Steel. *Surf. Coat. Technol.* **2020**, *382*, 125132.
16. Jain, V.; Sundararajan, G. Influence of the pack thickness of the boronizing mixture on the boriding of steel. *Surf. Coat. Technol.* **2002**, *149*, 21–26. [CrossRef]
17. Campos-Silva, I.; Ortiz-Domínguez, M.; Tapia-Quintero, C.; Rodríguez-Castro, G.; Jiménez-Reyes, M.Y.; Chávez-Gutiérrez, E. Kinetics and Boron Diffusion in the FeB/Fe_2B Layers Formed at the Surface of Borided High-Alloy Steel. *J. Mater. Eng. Perform.* **2012**, *21*, 1714–1723. [CrossRef]
18. Danışmaz, M.; Demirbilek, M. Assessment of heat transfer capabilities of some known nanofluids under turbulent flow conditions in a five-turn spiral pipe flow. *Appl. Rheol.* **2024**, *34*, 20240002. [CrossRef]
19. Akdag, U.; Akcay, S.; Un, N.; Danismaz, M. Experimental investigation of the heat transfer characteristics of a synthetic annular jet impingement on a flat surface. *Exp. Heat Transf.* **2024**, 1–20. [CrossRef]
20. Şahin, İ.B.; Urtekin, L.; Genç, A.; Özerkan, H.B. Optimization of Machining Parameters for Boron Alloy Steel By Plunge Electro Erosion By Taguchi Technique. *J. Sci. Rep.-A* **2022**, *50*, 169–180.
21. Şahin, İ.B.; Yilan, F.; Urtekin, L. Optimisation on machining parametres by EDM of TiN coated Ti6Al4V alloys. *Adv. Mater. Process. Technol.* **2024**, *10*, 960–970. [CrossRef]