Research Paper

Analysis of the Carburizing Process Using a Batch Atmosphere Furnace

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Abstract

The carburizing process is a heat treatment method aimed at enhancing the surface hardness, wear resistance, and corrosion resistance of materials by adding carbon at high temperatures. This study analyzes the impact of this process on low-carbon steels (STKM 13A and SPCC) and an alloy steel (SCM 435). Carburization was conducted at 900°C for 100 minutes. The tests performed included a Micro Vickers hardness test and microstructural characterization following the ASTM E-407 standard. The results showed a significant increase in the surface hardness of all materials. Critically, carbon diffusion in both STKM 13A and SPCC reached a consistent and defined depth of 0.48 mm, while in SCM 435, it diffused uniformly across the entire material thickness. Microstructural analysis revealed a phase transformation from pearlite and ferrite before carburization to martensite afterward. For STKM 13A and SPCC, the martensite phase formed up to a depth of 0.48 mm, while SCM 435 underwent a total transformation to the martensite phase, resulting in full hardening. This research provides specific quantitative data on the critical case depth (0.48 mm) achievable in STKM 13A and SPCC under these conditions, offering a clear reference point for industrial applications requiring controlled surface hardening.

Keywords *Carburization; Hardness; Phase Transformation*

INTRODUCTION

In modern industries such as automotive, aviation, equipment manufacturing, and construction, the use of metal components with specific and optimal mechanical properties is essential. Metals produced from smelting, typically in the form of slabs or billets, require further forming and additional treatment to be properly applied. One of the most effective methods for modifying the physical and mechanical properties of a material is through heat treatment (Rajan et al., 2023). This process involves heating the material to a controlled temperature, followed by cooling using a specific medium, such as water, oil, or air. Its purpose is to increase hardness, ductility, and wear resistance, while also relieving internal stress and refining the crystalline grain size, allowing the material to meet demanding functional requirements (Froes, 1994).

Carburizing is a highly important type of heat treatment, primarily utilized to improve the surface properties of materials (Boumediri et al., 2024). This case-hardening process involves adding carbon to the surface layer of a metal at high temperatures, allowing for the diffusion of carbon atoms into the material's crystal structure. The increased carbon content at the surface leads to a significant phase transformation, which directly results in increased hardness and wear resistance (Sultan et al., 2022; Dai et al., 2022). The success of the carburizing process is highly dependent on various factors, including the initial chemical composition of the material, temperature, heating duration, and the cooling rate (Yamamoto et al., 2023). The chemical composition of the material, particularly the content of alloying elements such as chromium and nickel, plays a crucial role, as it can significantly influence the carbon diffusion rate and the formation of the desired hard phases (Xu et al., 2021). Therefore, selecting the appropriate material is a determining factor for achieving optimal carburizing results, ensuring the component can perform as intended under severe operational conditions (Baykara & Atik, 2025).

A literature review indicates that low-carbon steels, such as those researched by Ballem et al. (2023) and Hiremath et al. (2024), are often subject to carburization due to their low cost. However, the achieved case depth in these steel types is generally limited and highly sensitive to cooling parameters. Low-alloy steels, conversely, such as SCM 435, are known to have superior hardening capability because their alloying elements promote the formation of stable martensite (Xu et al., 2021). Despite numerous individual studies on these two material groups, the current literature lacks detailed and validated comparative data that directly evaluate the differences in carbon diffusion mechanisms and maximum hardening performance when low-carbon steels (STKM 13A and SPCC) and alloy steel (SCM 435) are subjected to identical carburizing conditions. This research gap creates ambiguity in the practical guidelines for material selection.

Therefore, this study aims to comprehensively analyze the impact of the carburization process on STKM 13A, SPCC, and SCM 435, focusing on carbon diffusion depth, microstructural transformation, and hardness improvement, in order to provide clear quantitative references for industrial applications. This study utilized a batch atmosphere furnace with specific process parameters, a carbon potential of 0.9% for 100 minutes. The rapid cooling process was performed using cold oil at a temperature of 60°C, followed by a tempering process at 180°C for 90 minutes. Testing was conducted rigorously using a Micro Vickers hardness tester for hardness and an optical microscope for microstructural characterization, in accordance with the ASTM E-407 standard.

LITERATURE REVIEW

Extensive research has investigated the efficacy of the carburization process across various ferrous materials, demonstrating its crucial role in enhancing surface hardness and wear resistance in industrial components (Xu et al., 2021; Dai et al., 2022). Studies on low-carbon steels (e.g., SPCC and similar grades) consistently confirm that while the process significantly improves surface properties, the achieved case depth is highly sensitive to processing parameters, particularly temperature and cooling rate (Ballem et al., 2023; Hiremath et al., 2024). These findings highlight a predictable limitation in carbon diffusion kinetics within low-carbon matrices, often resulting in superficial hardening. Conversely, investigations focusing on low-alloy steels (e.g., SCM 435), which contain stabilizing elements like Chromium and Molybdenum, report superior hardening capabilities and deeper effective case depths, attributed to the alloy elements promoting the formation of stable, high-hardness martensite phases (Boumediri et al., 2024; Baykara & Atik, 2025). This difference in behavior emphasizes that material chemistry is a determinant factor in achieving optimal, predictable hardening results (Yamamoto et al., 2023).

Despite the established understanding of material-specific carburization kinetics, a significant research gap remains in the comparative assessment of these material groups under precisely controlled and identical conditions. The current literature primarily presents data from individual studies or varying process parameters, which limits the ability to directly quantify and contrast the critical carbon diffusion behavior and maximum achievable hardening performance between commodity low-carbon steels (STKM 13A and SPCC) and standard low-alloy steel (SCM 435). The lack of direct comparative data under a uniform thermal cycle (e.g., 900°C for 100 minutes) hinders the development of clear, quantitative guidelines for industrial material selection. Therefore, this study fills this void by providing a rigorous comparative analysis of the microstructural transformation and mechanical responses of these three materials, aiming to establish clear benchmarks for optimizing industrial carburization practice

RESEARCH METHOD

Carburizing Procedure

The heat treatment procedure was conducted in a sequential process comprising specimen preparation, cleaning, preheating, carburizing, quenching, secondary cleaning, and tempering. Three distinct material specimens were employed: low-carbon steels STKM 13A and SPCC, and alloy steel SCM 435. Specimen preparation involved sectioning the materials using a coolant to mitigate thermally induced deformation. The edges were subsequently deburred, and the specimens were secured together to ensure dimensional stability. Prior to carburizing, samples were cleaned of contaminants using a vacuum degreaser. The specimens were then preheated in a batch atmosphere furnace via an electric heater until the target carburizing temperature was achieved. During preheating, Rx gas was introduced to maintain an inert environment and prevent surface oxidation.

Carburization was performed at a constant temperature of 900°C with a target carbon potential of 0.9%. Liquefied Petroleum Gas (LPG) served as the carbon source, with the chamber atmosphere regulated by an oxygen sensor to control carbon ingress. Following the carburizing phase, samples were briefly soaked to minimize thermal stress and distortion. Quenching was executed rapidly using cold oil maintained at 60°C. Post-quench, specimens were washed to remove residual oil. An initial hardness measurement was taken before the final tempering stage, which was conducted at 180°C for 90 minutes.

Testing Materials

After the carburizing and tempering processes, two main characterization tests were performed:

Hardness Test

Hardness testing was conducted using a Micro Vickers hardness tester. The prepared samples were polished with 1500-grit sandpaper prior to measurement. Hardness measurements were taken at three different points on the cross-section.

Metallography

Microstructural observation was conducted via metallographic analysis. The specimen was first mounted and then ground using a Kenma machine with #500 and #1500 grit paper to achieve the requisite surface quality. Grinding was succeeded by polishing with alumina powder. To delineate the microstructure, the polished surface was etched with a Nital solution (composed of 5% nitric acid and 95% alcohol). The final sample was dried to remove residual moisture and observed using a digital optical microscope.

FINDINGS AND DISCUSSION

Surface Hardness

Surface hardness testing was conducted at three different points on each sample using a Micro Vickers hardness tester with a load of 0.3 HV. The results, as shown in Table 1, indicate a significant difference between the raw material condition (before carburizing) and after carburizing.

Table 1. Results of Surface Hardness Test

Sample	Hardness (HV)

STKM 13A	213,33 ± 6,65
SCM 435	193,33 ± 2,08
SPCC	136,67 ± 2,51
STKM 13A Carburized	713,33 ± 10,40
SCM 435 Carburized	747,33 ± 2,35
SPCC Carburized	737,67 ± 10,96

In the raw material condition, STKM 13A had the highest average hardness at 213.33 HV, followed by SCM 435 at 193.33 HV, and SPCC at 136.67 HV. The higher hardness of STKM 13A compared to SCM 435 before carburization was due to the forging metal-forming process applied to STKM 13A. According to Boumediri et al. (2024), forging can improve the microstructure by compacting and refining the grains, which directly increases the material's hardness. Following the carburizing process, a drastic increase in surface hardness occurred in all samples. SCM 435 recorded the highest hardness value at 747.33 HV, followed by SPCC at 737.67 HV, and STKM 13A at 713.33 HV. The highest hardness increase in SCM 435 was attributed to its chemical composition as an alloy steel, which contains elements like chromium. This alloying element, combined with carbon diffusion from the atmosphere, enhances the surface of SCM 435, making it richer in elements and substantially increasing its hardness. In contrast, although SPCC had a lower hardness than STKM 13A before carburization, it showed a higher surface hardness after the process. This is because SPCC has a lower initial carbon content, which creates more interatomic space in its crystal structure, thus facilitating the diffusion of carbon from the atmosphere (Khajuria et al., 2023). Conversely, STKM 13A has a higher initial carbon content, which reduces the interatomic space and limits carbon entry, so its hardness increase was not as high as that of SPCC.

Hardness Distribution

Hardness distribution testing was conducted by measuring the hardness from the surface to the core of the material at every millimeter of depth. The results showed different patterns for each material, as presented in Table 2.

Table 2. Results of Hardness Distributions

Depth (mm)	Hardness (HV)					
	STKM 13A	SCM 435	SPCC	STKM 13A Carburized	SCM 435 Carburized	SPCC Carburized
0,05	187	175	111	640	710	680
0,1	189	165	114	629	710	639
0,2	188	178	110	532	707	530
0,3	184	172	107	342	685	429
0,4	189	179	107	300	687	216
0,5	196	187	102	190	685	162
0,6	200	172	103	156	692	127
0,7				141	680	

Depth (mm)	Hardness (HV)					
	STKM 13A	SCM 435	SPCC	STKM 13A Carburized	SCM 435 Carburized	SPCC Carburized
0,8				143	705	
Core				138	705	

For STKM 13A and SPCC, the highest hardness was observed at the surface and decreased continuously with increasing depth, in accordance with the law of diffusion. A significant change in value occurred at a depth of 0.4-0.5 mm for STKM 13A and 0.3-0.4 mm for SPCC. This decrease occurred because the area is a transition zone where the martensite phase formed on the surface begins to mix with the ferrite phase in the material's core. Hardness material decreases as the carbon content diminishes toward the core. In contrast to these two materials, SCM 435 showed a relatively uniform hardness value, ranging from 710-680 HV from the surface to the core. This uniformity indicates that the carburizing process has affected the entire material, a phenomenon known as full hardening. This is possible because SCM 435 contains alloying elements, such as chromium, throughout its entire body. According to Werner et al. (2022), chromium atoms can become trapped in carbides, which alters the steel's overall function. The rapid cooling process (oil quenching) after carburizing helps the martensite phase transformation occur throughout SCM 435, preventing the decrease in hardness seen in low-carbon steels.

Analysis of Microstructural Characterization

Microstructural characterization aims to observe the phase changes that occur as a result of carburization. Observations were made using a microscope with 1000X magnification after etching with a 5% nital solution. The microstructures of the three samples before and after carburization are shown in Figure 1.

Before carburization, all raw material samples showed a microstructure consisting of the pearlite phase (dark areas) and the ferrite phase (light areas). In STKM 13A, the grain structure appeared long and small, which was a result of the forging process that compacts the grains. After carburization, a significant phase transformation occurred. In STKM 13A and SPCC, the martensite, pearlite, and ferrite phases were formed. According to Verhoeven et al. (2005), the martensite phase forms because the high carburization temperature provides energy for atoms to move into empty spaces. The smaller size of carbon atoms compared to iron atoms allows carbon to enter the iron lattice as interstitial solute atoms.

This characterization also found that the carburization depth in both materials reached 0.48 mm. This diffusion rate is influenced by the diffusion coefficient and the concentration gradient, where the highest carbon concentration at the surface promotes rapid diffusion to areas with lower concentration (Xu et al., 2025). For SCM 435, microstructural observation revealed that the martensite phase formed entirely from the surface to the core. This is consistent with the uniform hardness test results. The presence of chromium in SCM 435 chemically alters its function. This total phase change is known as full hardening.

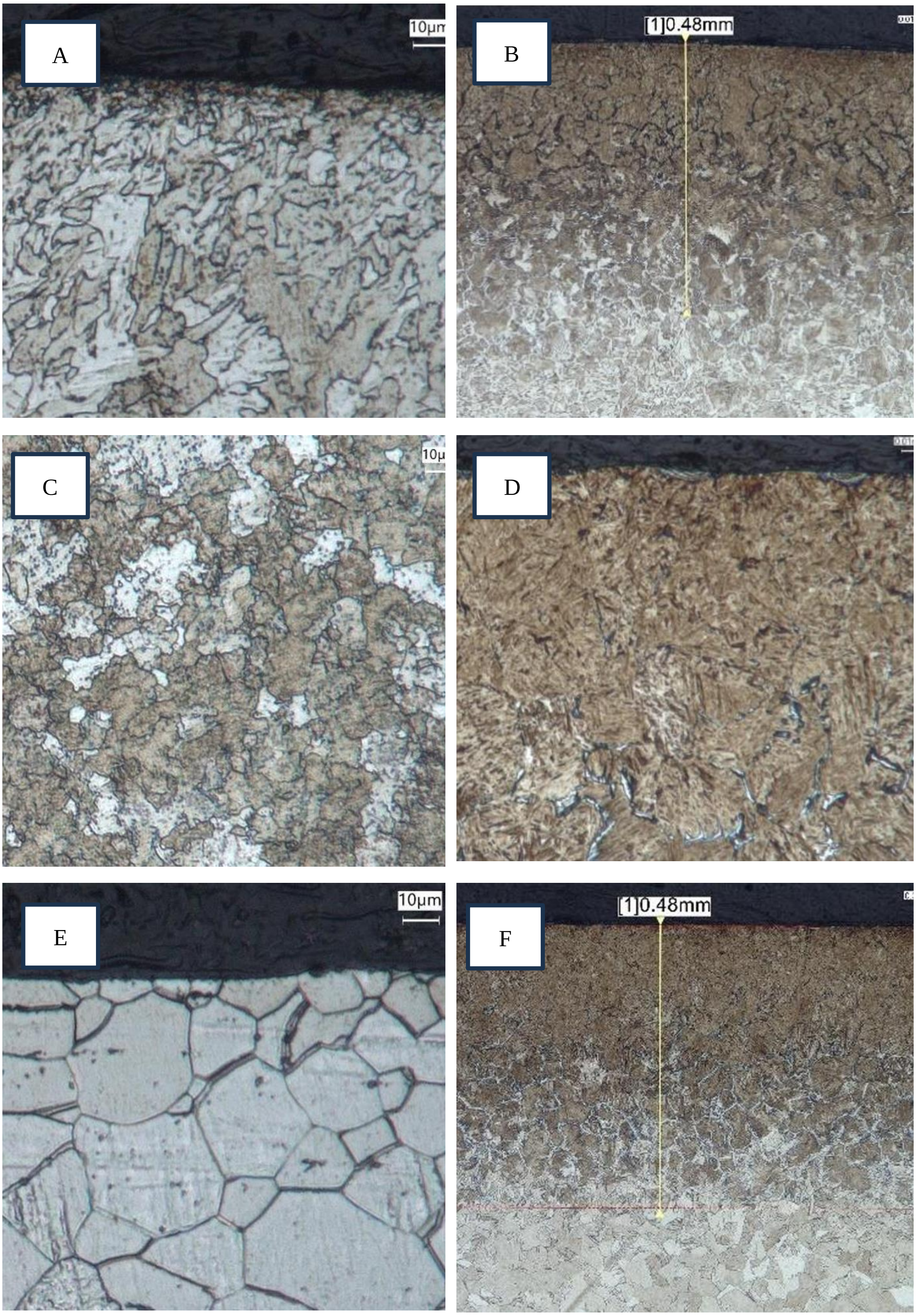

Figure 1. Microstructure of samples (a) STKM 13A, (c) SCM 435, (e) SPCC, and carburized (b) STKM 13A, (d) SCM 435, (f) SPCC

CONCLUSIONS

Based on the results and discussion, several key points can be concluded regarding the impact of the carburizing process on STKM 13A, SCM 435, and SPCC steels:

1. The carburizing process significantly increases the surface hardness of all three materials, proving that carbon diffusion has successfully occurred.
2. The hardness distribution test results show different patterns for each material. In STKM 13A and SPCC steels, the highest hardness is at the surface and gradually decreases towards the core. A sharp decrease in hardness for STKM 13A occurs at a depth of 0.4-0.5 mm, while for SPCC it occurs at 0.3-0.4 mm. This is due to the difference in the initial carbon composition of the two materials. Meanwhile, SCM 435 shows a relatively stable hardness value from the surface to the core, indicating that carbon diffusion has occurred throughout.
3. A significant phase change was observed through microstructural characterization. Before carburizing, all three materials had a pearlite and ferrite phase. After carburizing, STKM 13A and SPCC showed the formation of a martensite phase up to a depth of 0.48 mm. In contrast, SCM 435 underwent a total transformation from the martensite phase to the core, demonstrating the phenomenon of full hardening.

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