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IDENTIFYING OF CHEMICAL COMPOSITION CHANGES DURING THE CARBURIZING PROCESS OF CARBON STEEL UNDER TENSION

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Carburizing is a commonly employed technique used to improve carbon steel's surface characteristics, specifically its hardness and ability to resist wear. The introduction of tension during the carburizing process adds complexities that affect the distribution of elements in the material. The research methodology includes subjecting carbon steel samples to carburizing temperatures and applying tensile stress. This approach allows for analyzing the effects of carburization and stress on the carbon steel samples. The focus of the investigation was to analyze the use of the pack carburizing technique at lower temperatures, specifically 700 °C and 750 °C, while also applying proportional-voltage tensile stresses. The study focuses on conducting a comprehensive analysis of changes in the chemical composition throughout the cross-section of the material. Advanced analytical techniques perform mapping and elemental spectrum analysis, such as scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS). These techniques enable a thorough investigation of the distribution and composition of elements such as carbon, iron, silicon, magnesium, and phosphorus. According to the research findings, carbon elements were added within the temperature range of 700 °C to 750 °C during the carburization process. The carbon content in the material increased from 0.15 % in its unprocessed state to 0.73 % at a temperature of 700 °C, followed by a further increase to 1.26 % at a temperature of 750 °C. According to the study, it was found that applying tensile loads and reducing carburizing temperatures can enhance the carburizing process and result in higher carbon steel content. This can bring about cost savings and improve overall industrial efficiency

Keywords: carbon steel, load tensile, carburizing, chemical composition, scanning electron microscopy

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1. Introduction

Low-carbon steel, characterized by its comparatively low carbon content, is a flexible and extensively used material across several sectors. The carbon concentration of this material, which is generally less than 0.25 % by weight, imparts distinct characteristics that render it appropriate for various applications [1, 2]. Although it may exhibit lower strength and hardness than steels with greater carbon content, it offsets these limits by possessing many other advantageous properties. One notable benefit associated with low-carbon steel pertains to its exceptional ductility. This property enables it to endure deformation without fracturing, making it suitable for applications that need bending, shaping, and forming, such as automobile components, pipelines, and building materials [3].

Additionally, the decrease in carbon content enhances the weldability and machinability of the material. Welding low-carbon steel is characterized by simplicity and reduced vulnerability to problems like brittleness. As a result, it produces robust and reliable welds. The heightened machinability of the material allows for easy cutting, drilling, and shaping of various components [4]. The chemical composition of carbon steel consists of essential elements such as carbon (C), manganese (Mn), silicon (Si), phosphorus (P), and sulfur (S) [5]. Carbon plays a crucial role as the main component, influencing mechanical characteristics and hardness. The addition of manganese enhances the strength and hardness of the material while maintaining its ductility. Silicon exhibits significant advancements in the areas of tiling, malleability, wear resistance, and resilience. The presence of phosphorus and sulfur in small amounts can negatively impact steel properties, highlighting the importance of controlling their levels. In addition, small amounts of nickel, chrome, and copper can be added to achieve specific goals, such as enhancing corrosion resistance [6].

Surface hardening is a kind of heat treatment that is most often applied to steel. This treatment aims to improve the outside layer of the metal's hardness and wear resistance while maintaining the core's strength and resiliency. The purpose is to generate a surface layer that has been toughened, often known as a "case," with the ability to endure abrasion, friction, and wear under difficult working circumstances [7]. Pack carburizing is one of the most common methods employed among the many case hardening procedures. In this procedure, the steel components that are going to be carburized are placed within a container that is sealed, and this container also contains a carbon-rich substance, typically in the form of powder or granules. Following this step, the container is placed in a furnace and heated to a certain temperature. This step makes it possible for the carbon to diffuse through the steel surface [8].

The pack carburizing process utilizes a carburizing material consisting of either pure carbon or a combination of carbon with other organic components, such as wood, bone, leather, or wheat. These things naturally contain carbon [9]. During the heat treatment process, the carbon atoms derived from the carburizing material undergo a migration process, resulting in their incorporation into the surface of the steel. This transformation leads to the formation of a carbon-enriched layer [5]. The increased concentration of carbon in the steel results in significant improvements in its hardness and wear resistance in the treated area, making it very durable.

Hardness is a fundamental mechanical property of a material that quantifies its ability to withstand deformation or resist penetration by external entities. From a technical standpoint, the term "hardness" pertains to the capacity of a substance to resist scratching or piercing. Various scales and testing methodologies are used to quantify and contrast the hardness of diverse materials. These include the widely employed Vickers, Rockwell, and Brinell scales, each with its distinct testing procedure [4]. The process of carburizing is known to enhance the hardness of a material by inducing changes in its microstructure and elemental content. The term "microstructure" refers to the spatial configuration and organization of matter at the minuscule scale, comprising the arrangement of atoms, crystals, and phases that constitute its overall structure. The microstructure has a crucial role in influencing several material characteristics, including strength, hardness, ductility, and thermal and electrical conductivity [10].

The method of carburizing is still used in many research projects to improve the mechanical properties of a wide variety of different kinds of materials. Carbon steel is a type of steel that has a carbon component that is present in a quantity that is relatively low. As a consequence, carbon steel's tensile strength is significantly lower when compared to the tensile strength of other types of steel. It is to be anticipated that the application of the carburizing process will result in a modification to the fundamental chemical composition of carbon steel. Therefore, research devoted to analyzing the carburizing process for changes in the chemical composition of carbon steel is still relevant.

2. Literature review and problem statement

The carburizing process stands as a cornerstone in metallurgy, revered for its ability to elevate the surface attributes of carbon steel, imbuing it with heightened hardness and an impressive resistance to wear and tear [11]. Beyond its fundamental application, the introduction of tension during the carburizing process unfurls a tapestry of intricate complexities that subtly steer the course of chemical composition changes within the material. The interaction between tension and carburization emerges as an avenue of captivating exploration, where the amalgamation of mechanical forces and chemical transformation yields fascinating revelations. Within this nexus, researchers have delved, peering through the lens of scientific inquiry to unravel the intricate dance of stress and carburization's interplay. The symphony of these influences orchestrates a dance that orchestrates the evolution of microstructure and composition in carbon steel [12, 13].

The paper [14] investigates the relationship between carbon particle size, the carburizing process of ST-40 steel, and its effect on surface hardness. This research topic is of great interest and has important implications for material science and engineering. Investigating the relationship between carbon particle size and surface hardness in carburized steel is significant for industries that depend on improved material properties to enhance wear resistance and strength. The study lacks an in-depth analysis of possible external factors that may impact the surface hardness of carburized steel. Various factors, including temperature, carburizing time, and the composition of the carburizing atmosphere, may influence the observed hardness.

The study [15] investigates the biaxial pressure pack carburizing method's impact on altering the mechanical properties of local low-carbon steel. This research holds significant relevance and practical implications. The implementation of a biaxial pressure pack carburizing method indicates advancements in the realm of surface modification techniques. The novelty of this method has the potential to open up new possibilities for applications and advances in the mechanical properties of low-carbon steel. The analysis primarily emphasizes the improvement of mechanical properties. However, conducting a comprehensive study that considers potential environmental impacts, including energy consumption, waste generation, and emissions associated with this method is crucial.

The review [11] provides valuable insights into the wear analysis of treated Duplex Stainless Steel (DSS) material using carburizing. This analysis is significant for improving the wear resistance of DSS material. The review examines the various wear mechanisms that may be affected by the carburizing process, aiming to enhance our comprehension of how this treatment can potentially modify the material's performance in diverse wear scenarios. The review appears to lack a comprehensive explanation of the specific methodology employed in conducting the review. The selection criteria for studies, the search strategy, and the process of evaluating the quality of the selected papers play a crucial role in maintaining the review's credibility. The examination may have missed a significant chance to propose potential areas for future research. Identifying areas of limited understanding and possible avenues for further research can help researchers focus on addressing unresolved inquiries.

The study [16] investigates the impact of strain rate and temperature on the mechanical properties of medium carbon steel S48C through hot tension testing. This research holds scientific significance and has practical implications. The investigation of how strain rates and temperatures influence mechanical properties offers valuable insights into the behavior of materials in varying conditions. Understanding this knowledge can provide valuable insights for making informed choices regarding material selection and engineering decisions. The study's findings may have limited generalizability if it has a small sample size or lacks diversity in material sources. The variability in the composition or production processes of S48C steel makes it especially significant. The study ought to analyze potential external factors that could impact mechanical properties, strain rate, and temperature. The results may be influenced by factors such as sample preparation, variations in microstructure, and testing conditions.

The article [17] explores the mechanical properties and cracking behavior of low-temperature gaseous carburized austenitic stainless steel, a significant and intricate topic in materials science. The study analyzes the effects of low-temperature gaseous carburization on austenitic stainless steel. The specific focus of this study enables a more thorough examination of the impact of this treatment on mechanical properties and cracking behavior. The study's emphasis on cracking behavior is significant. However, for a thorough analysis, it is essential to consider the various types of cracks, such as intergranular and transgranular, as well as their possible causes. The comprehension of crack initiation and propagation mechanisms holds significant importance.

The author's objective is to develop a new method for pack carburizing that works at lower temperatures compared to existing techniques commonly used. Buffalo bone charcoal possesses energizing properties, while $BaCO_3$ functions as a catalyst. The conventional carburization process at high temperatures requires a longer time and higher financial expenditure. The application of stresses to carbon steel at high temperatures results in the stimulation of random atomic motion, which subsequently facilitates the diffusion of carbon. The study involves the application of pack carburizing at two discrete temperatures, precisely 700 °C and 750 °C. The procedure will include the application of proportionate stress loads, together with the use of buffalo bone charcoal and $BaCO_3$. This research investigates changes in chemical composition using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and mapping analysis. The main goal is to reduce the time and temperature required for heating while also improving the efficiency of the carburizing process.

3. The aim and objectives of the study

The aim of the study is identifying the change the chemical composition of carbon steel using carburizing process under tension.

To achieve this aim, the following objectives are accomplished:

– to analyze the chemical composition of carbon steel before carburizing process;

– to analyze the variations in the chemical composition of carbon steel under a carburizing temperature of 700 °C while subjecting it to tension;

– to analyze the variations in the chemical composition of carbon steel under a carburizing temperature of 750 °C while subjecting it to tension.

4. Materials and methods of experiment

4. 1. Object, hypothesis of the study and materials

The primary focus of this study is to examine and analyze the changes that transpire in the chemical composition of carbon steel throughout the carburization process when subjected to tensile stress. The main emphasis lies in comprehending tensile stress application's impact on the distribution and composition of different elements inside the carbon steel material during carburizing. This study aims to investigate the alterations in the elemental composition of steel, with a special focus on the concentrations of carbon, iron, and other pertinent elements, under the combined conditions of carburizing temperatures and stress. This work aims to employ sophisticated material characterization techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) to delineate the spatial arrangement of components within the surface and subsurface layers of the material.

The primary hypothesis of this study is that strain during carbon steel carburization changes its chemical makeup, particularly the organization and quantity of carbon and other vital components. The idea states that tensile tension during carburizing affects carbon atom migration into steel surface layers. This creates a carbon-rich layer with better hardness and wear resistance. The present work hypothesizes that advanced material characterization methods like scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) can detect chemical composition changes. These methods will identify distinctive elemental mapping and spectrum patterns, revealing the spatial arrangement of carbon, iron, and other relevant elements throughout the material's surface and underlying strata. The hypothesis is that the data will show that stress helps carbon diffuse and affects material properties.

The study assumes that the carburizing process attains a condition of equilibrium whereby the diffusion of carbon into the material is balanced. The potential impact of transient impacts or fluctuations in carburizing states during the procedure is not considered. The research may include simplified depictions of material characterization methodologies, supposing idealized results from scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) methods. The investigation might be simplified by excluding any potential phase shifts or transformations that may arise due to the carburizing process.

In this study, the researchers chose carbon steel as the primary material for the pack carburizing process. The carburization process was optimized by utilizing a specific combination of carburizing materials. The composition of the mixture was analyzed and found to contain 80 % buffalo bone charcoal, which served as an energizer, and 20 % $BaCO_3$, acting as a catalyst. These components were selected to improve the efficiency of carburization and facilitate the development of favorable material properties. The primary energizer in the mixture was buffalo bone charcoal, which is well-known for its high carbon content. The carbon-rich composition of the steel played a crucial role in allowing carbon atoms to spread throughout its surface layers during the carburizing process. The energizer significantly impacted increasing the carbon concentration at the surface, resulting in improved hardness and wear resistance. Fig. 1 in the study illustrates the specimens selected for analysis using Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS). Advanced techniques enable an extensive examination of the microstructure and elemental composition of the carburized samples. The observations obtained from these analyses are anticipated to provide a more comprehensive understanding of the underlying mechanisms and further confirm the effectiveness of the selected carburizing method.

Furthermore, the researchers used a carburizing material with a precise mesh grain size of 20. The meticulous choice of grain size is crucial to achieve homogeneity and regularity throughout the carburization process. A mesh grain size of

20 facilitates a uniform dispersion of carburizing material particles, promoting a more homogeneous diffusion of carbon inside the steel. The researchers aimed to maximize the advantages of the pack carburizing process by combining carbon steel's distinctive characteristics and an optimum mixture of buffalo bone charcoal and $BaCO_3$ with a mesh grain size of 20. This study aimed to generate a resilient carburized layer exhibiting enhanced surface characteristics, hence rendering the steel material appropriate for challenging applications across diverse sectors such as automotive, aerospace, and equipment.

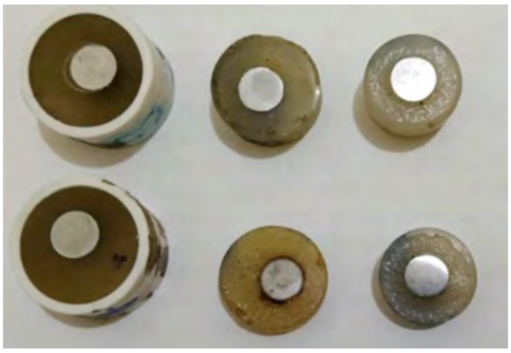


Fig. 1. Visual inspection of a specimen with energy-dispersive X-ray spectroscopy (EDS) with scanning electron microscopy (SEM)

Fig. 2, *a* illustrates the experimental setup used to apply tension to the carbon steel specimens during carburizing. This setup involves the use of a furnace and a tensile load test. The design of this specialized setup plays a critical role in accurately simulating real-world conditions and studying the impact of tension on the carburization process. Fig. 2, *b* appears to depict an experimental setup that exhibits a high level of organization and precision, particularly in its tension application mechanism. It is common practice to securely fix the carbon steel specimens within the furnace during the carburizing process to ensure accurate and consistent tension application.

The furnace plays a critical role in maintaining the desired carburizing temperature, ensuring uniform heat distribution to enable successful and controlled carburization. The temperature settings and duration of the test are carefully controlled to achieve the desired level of carbon diffusion into the steel. The tensile load test shown in Fig. 2 is a vital component of the research, as it allows researchers to explore how the application of tension influences the carburization process and the resulting chemical composition changes. By subjecting the carbon steel samples to specific tensile loads within the furnace, the researchers can evaluate how mechanical stress affects the diffusion of carbon atoms and other alloying elements into the steel's surface layers.

In Fig. 3, the state-of-the-art JEOL JCM 6000 plus microscope tool is showcased, representing a cutting-edge instrument employed for Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) testing on the samples. This advanced microscopy tool is a crucial asset in the research, providing valuable insights into the microstructural features and elemental composition of the carburized samples under tension.

Combining SEM and EDS testing using the JEOL JCM 6000 plus microscope ensures a comprehensive examination of the carburized samples, offering a detailed understanding of the microstructural changes and chemical composition variations induced by tension-assisted carburizing. These observations are essential for validating the success of the experimental setup and understanding the mechanisms by which tension influences the carburization process. Moreover, utilizing this advanced microscopy tool demonstrates the researchers' commitment to employing state-of-the-art equipment for their investigation. The precise and reliable data generated from the JEOL JCM 6000 plus microscope contributes to the scientific rigor of the research and ensures the accuracy of the findings.

a

b

Fig. 2. Experimental setup of carburizing process: *a* – load tester for tensile strength; *b* – data collection instrument

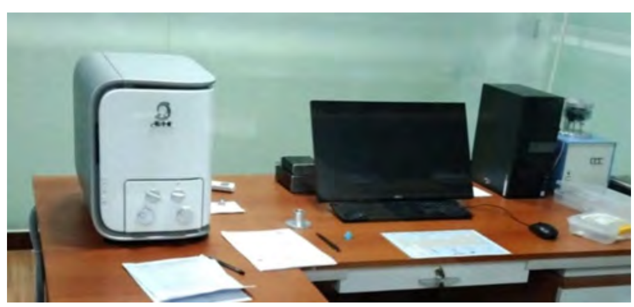


Fig. 3. Microscope for Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS)

4. 2. Methods and sample testing

The research methodology utilized in this study is experimental, with a specific emphasis on non-destructive testing techniques. Metallographic tests are employed as the primary means of analysis. The study primarily employed metallographic tests such as Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS). The utilization of advanced techniques is crucial in analyzing carburized samples as it provides significant insights into the microstructure of the material, its elemental composition, and the presence of various elements. Scanning Electron Microscopy (SEM) is utilized as a powerful imaging tool by researchers to observe the microstructure of carburized samples at high magnifications. The researchers can analyze the tension-assisted carburized samples by capturing detailed SEM images. This allows them to examine the surface morphology, grain boundaries, and other microstructural features. Understanding the impact of applying tensile stresses during carburization on the material's microstructure and mechanical properties is essential.

On the other hand, energy-Dispersive X-ray Spectroscopy (EDS) is employed to perform elemental analysis on the carburized samples. EDS provides quantitative data about the material's elemental composition, including the percentage of elements present within the carburized layer. This analysis is invaluable in assessing the effectiveness of the carburization process and understanding how the presence of tensile stresses affects the diffusion and distribution of carbon and other alloying elements in the steel. Furthermore, EDS allows researchers to conduct element mapping, providing spatial distribution information about the elements in the carburized samples. This mapping helps identify variations in elemental composition across the material's surface and subsurface layers, offering critical insights into the uniformity and homogeneity of the carburized layer.

The metallographic examination is comprised of a set of procedures that are carried out in order. These steps include sectioning, grinding, polishing, etching, and photographing. Following the first stage of the procedure, which consists of sectioning the specimen to the appropriate dimensions, a sequence of systematic surface refining is carried out to eradicate imperfections. After that, a process known as polishing is carried out to give the item a shiny look. Etching is carefully performed in some areas to improve the target's visibility. In the end, the microstructures are seen using advanced imaging techniques like scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and mapping. These techniques are used to examine the surface of the sample.

5. Results of the experiment carburizing process on carbon steel with tension

5. 1. Results of non-destructive testing of carbon steel before carburizing process

In the raw materials analysis, mapping and elemental spectrum reveal the distribution and content of various elements within the material. By examining the microstructure, distinct color variations and gradients can be observed for elements such as carbon (C), iron (Fe), magnesium (Mg), silicon (Si), and phosphorus (P). Fig. 4 vividly illustrates these variations, showcasing the unique distribution patterns of each element across the material.

In the mapping analysis, different colors and intensities represent elements' spatial arrangement and concentration. This valuable information helps researchers comprehend the composition and interactions between other parts in the material. By identifying these elemental patterns, valuable insights can be gained into the material's properties, behavior, and potential applications.

The mapping and spectrum analysis contribute significantly to materials science and engineering, aiding in developing innovative materials with enhanced performance and tailored characteristics. Such detailed elemental data assists in refining manufacturing processes, optimizing material properties, and ensuring the materials' suitability for specific industries and applications. By harnessing the power of advanced imaging techniques and elemental analysis, researchers can unlock the full potential of materials, leading to continuous advancements across a wide range of technological fields.

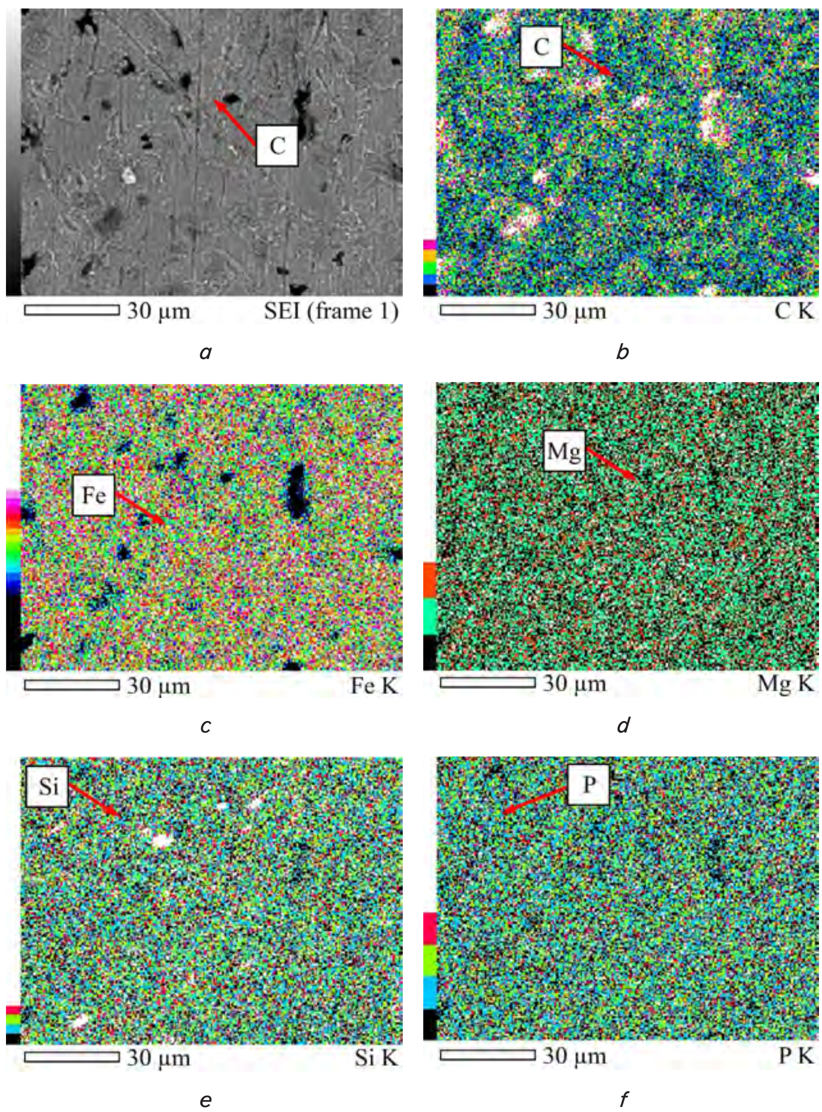


Fig. 4. Energy-Dispersive X-ray Spectroscopy observation image for the location and spectrum of elements in raw material: *a* – Scanning Electron Microscopy image; *b* – carbon; *c* – iron; *d* – magnesium; *e* – silicon; *f* – phosphorus

Fig. 5 and Table 1 present the elemental content found in the raw materials. The analysis reveals the following elemental composition: carbon content is 0.15 %, iron (Fe) constitutes 99.04 % of the material, manganese (Mn) accounts for 0.07 %, silicon (Si) makes up 0.58 %, and phosphorus (P) is present at 0.06 %.

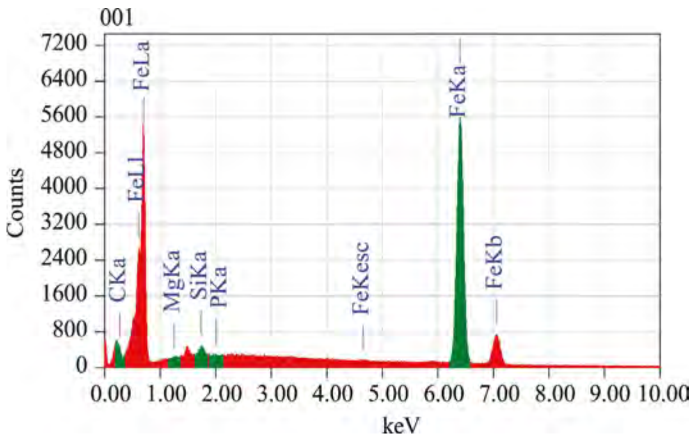


Fig. 5. Graph of the percentage of basic material elements

Table 1

Data on the elemental composition of basic materials

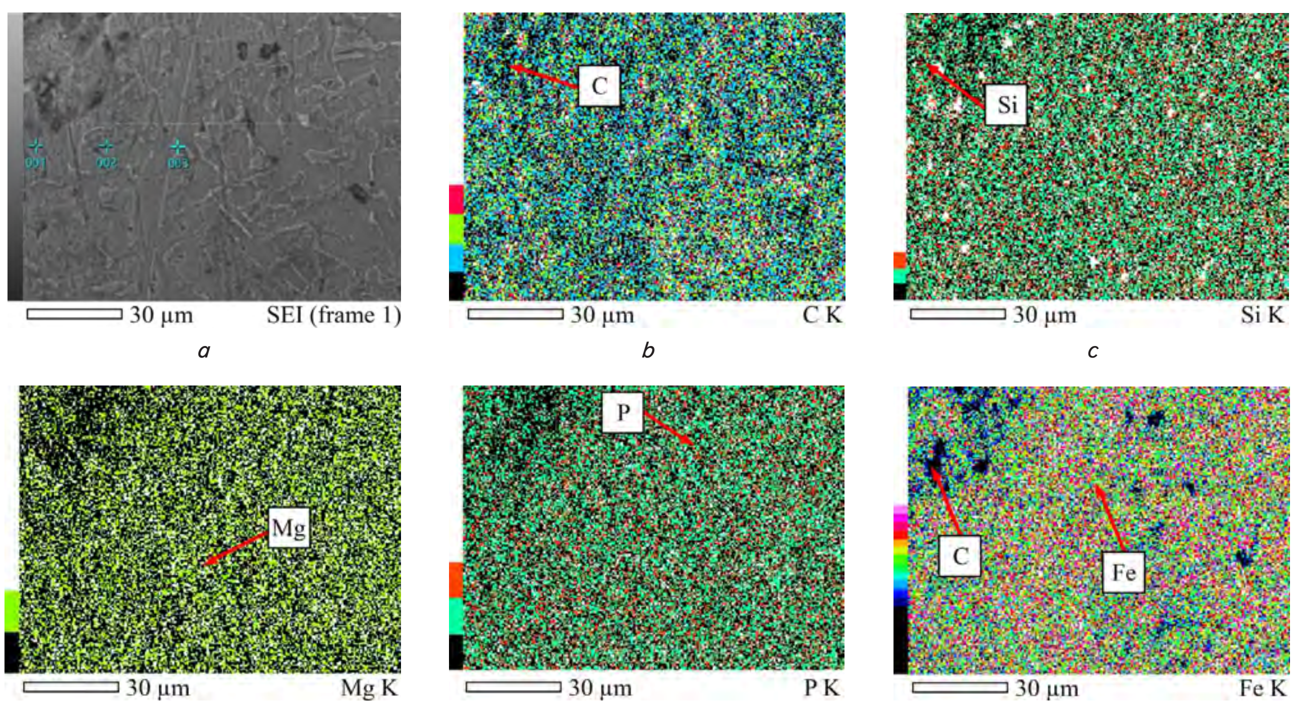
Element	(keV)	Mass (%)	Counts	Sigma	Mol (%)	Compound	Mass (%)	Cation
C	0.277	0.15	173.15	0.01	0.87	C	0.15	0.00
O	–	22.45	–	–	–	–	ND	–
Mg	1.253	0.04	175.38	0.02	0.13	MgO	0.07	0.03
Si	1.739	0.27	1013.14	0.04	0.69	SiO_2	0.58	0.16
P	2.013	0.03	86.39	0.03	0.03	P_2O_5	0.06	0.02
Fe	6.398	77.06	75174.77	0.50	98.29	FeO	99.04	23.60
Total	11.68	100.00	76622.8	0.6	100.00	–	100.00	23.81

These precise measurements of elemental percentages are crucial for understanding the material's properties and characteristics. The high iron content suggests the material is predominantly composed of iron. At the same time, the presence of other elements, such as carbon, manganese, silicon, and phosphorus, plays a significant role in influencing the material's mechanical and chemical attributes.

5. 2. Results of non-destructive testing of carbon steel during carburizing process at 700 °C

At carburizing temperatures of 700 °C under tensile conditions, a comprehensive mapping and elemental spectra analysis reveal intriguing patterns in each element's content. The mapping technique vividly illustrates distinct colors and distribution patterns, while the spectral analysis provides quantitative information about the elemental composition. In Fig. 6, the captivating visual representation showcases the intricate variations in color and distribution across the material. These contrasting patterns highlight the selective diffusion of elements, especially carbon, into the steel's surface layers during the carburizing process. The enriched carbon concentration at the surface enhances hardness and wear resistance, making it ideal for demanding engineering applications.

The results of an element map performed on the carbon steel after it had been carburized at a high temperature of 700 °C are shown in Fig. 7. Energy-Dispersive X-ray Spectroscopy (EDS) findings are fascinating and enlightening. The graph acts as a living canvas, bringing the surface's basic steel composition to life. A notable change is seen when looking closely at the EDS results. Carburization is accompanied by a complex series of chemical events, the most visible manifestation of which is an increase in silicon (Si) content (shown by a sharp peak in the graph). The carburization process at the higher temperature is likely responsible for the noticeable increase in silicon concentration, which marks a crucial change in the steel's composition.



a *b* *c* *d* *e* *f*

Fig. 6. Energy-Dispersive X-ray Spectroscopy mapping at a carburizing temperature of 700 °C: *a* – Scanning Electron Microscopy image; *b* – carbon; *c* – silicon; *d* – magnesium; *e* – phosphorus; *f* – iron

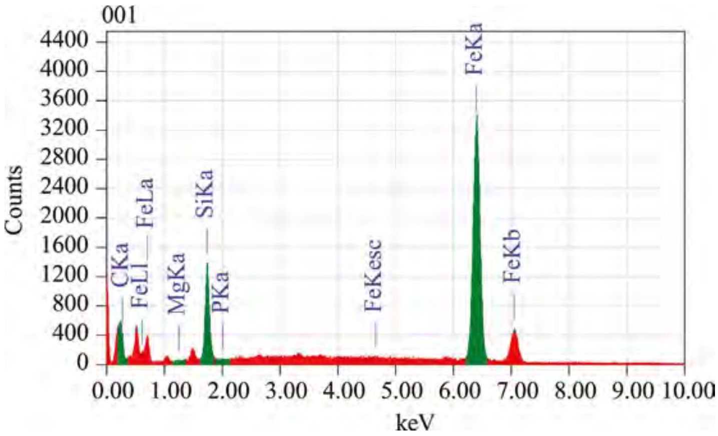


Fig. 7. Graph of elemental elements on the outermost carburizing 700 °C tensile point (1)

The subtle modification of silicon has significant repercussions for both the characteristics of the material and the range of possible uses for it. The interaction of silicon with carbon and other alloying elements may cause changes in the behavior of hardness, wear resistance, and even corrosion. This alteration in elemental composition kicks off a chain reaction of molecular alterations that have the potential to provide the surface layers of carbon steel with an increased resistance to wear and tear.

Table 2 presents a comprehensive and detailed analysis of the constituent composition of the carburized material. This analysis was conducted at a temperature of 700 °C, focusing primarily on tensile load point 1, corresponding to the surface layer. The table serves as a valuable source of knowledge, delivering a detailed analysis of the material's elemental composition. It provides a complete understanding of the changes brought about by the carburization process. Upon closer examination of the findings, a plethora of quantitative data is revealed, shedding light on the complex structure of the carburized material's surface layers. The focus is on the precise existence of each element inside the matrix. The profound impact of the method becomes readily evident by a notable increase in carbon content to a substantial 0.73 %. The observed increase in elevation emphasizes the efficient penetration of carbon into the surface of the material, which is a characteristic feature of effective carburization. This process imparts improved hardness and resistance to wear to the material.

Table 2

Data about the material's elemental makeup tensile carburization at 700 °C

Element	(keV)	Mass (%)	Counts	Sigma	Mol (%)	Compound	Mass (%)	Cation
C	0.277	0.73	567.16	0.02	4.16	C	0.73	0.00
O	–	24.77	–	–	–	–	ND	–
Mg	1.253	0.03	93.16	0.02	0.10	MgO	0.06	0.02
Si	1.739	3.94	9717.99	0.14	9.57	SiO_2	8.43	2.17
P	2.013	0.06	120.46	0.03	0.06	P_2O_5	0.13	0.03
Fe	6.398	70.46	45216.15	0.59	86.11	FeO	90.65	19.56
Total	11.68	100.00	55714.9	0.8	100.00	–	100.00	21.78

Iron (Fe) is the most abundant elemental constituent, making up 90.65 % of the material. The consistent presence of this material demonstrates its inherent steel composition, even after undergoing carburizing. The resilience of steel is a significant characteristic that highlights its essential role in the material matrix. Steel serves as the backbone of its mechanical properties. Furthermore, it is vital to consider the significance of other alloying elements in this context. Manganese (Mn) is present in a relatively small amount, accounting for 0.06 % of the material. Its presence contributes to the overall behavior of the material. Silicon (Si) is significantly present in the composition, accounting for 8.43 % of the total. The increase in silicon usage highlights its essential role in the carburization process, which could lead to changes in properties like increased corrosion resistance or improved surface durability. Phosphorus (P) is included in the elemental ensemble, accounting for 0.13 % of the material's composition. Phosphorus, despite its small quantity, can influence material properties subtly, providing valuable information about the composition of the alloy as a whole.

5. 3. Results of non-destructive testing of carbon steel during carburizing process at 750 °C

At carburizing temperatures of 750 °C under tensile conditions, a comprehensive analysis of mapping and elemental spectra reveals remarkable changes in the elemental composition. The mapping technique vividly illustrates a more pronounced variation in color, distribution, and radiation across the material's surface. These distinctive patterns are clear evidence of the successful addition and diffusion of elements during the carburizing process. In Fig. 8, the captivating visual representation showcases the enriched distribution of elements, particularly carbon, in the surface layers of the material. The intensified color gradients affirm the significant increase in carbon content, resulting in a thicker and more uniform carburized layer. This transformation enhances surface hardness and wear resistance, making the material well-suited for challenging engineering applications.

Fig. 9 and Table 3 present a detailed analysis of the elemental content at carburizing temperature 750 °C under tensile load spot 1 (surface). The results reveal the precise percentages of various elements in the carburized material. Notably, the carbon content has significantly increased to 1.26 %, indicating a successful and substantial diffusion of carbon into the material's surface layers during carburizing. Iron (Fe) is the dominant element, constituting 97.74 % of the material. This reaffirms the steel's primary composition, even after undergoing carburization. Additionally, manganese (Mn) comprises 0.04 %, silicon (Si) accounts for 0.90 %, and phosphorus (P) is present at 0.06 %.

Table 4 provide essential data regarding the composition of carbon (C) and ferrous (Fe) elements in raw materials, carburizing temperatures of 700 °C and 750 °C under tensile loads. These tables show that a significant addition of carbon elements occurs on the material's surface (spot 1) during the carburizing process. The carbon content is initially measured at 0.15 % in the raw material. After carburizing at a temperature of 700 °C with a tensile load, the carbon content increases remarkably by 0.73 %. Similarly, at the carburizing temperature of 750 °C with a tensile load, there is a notable rise in carbon elements, reaching 1.26 %.

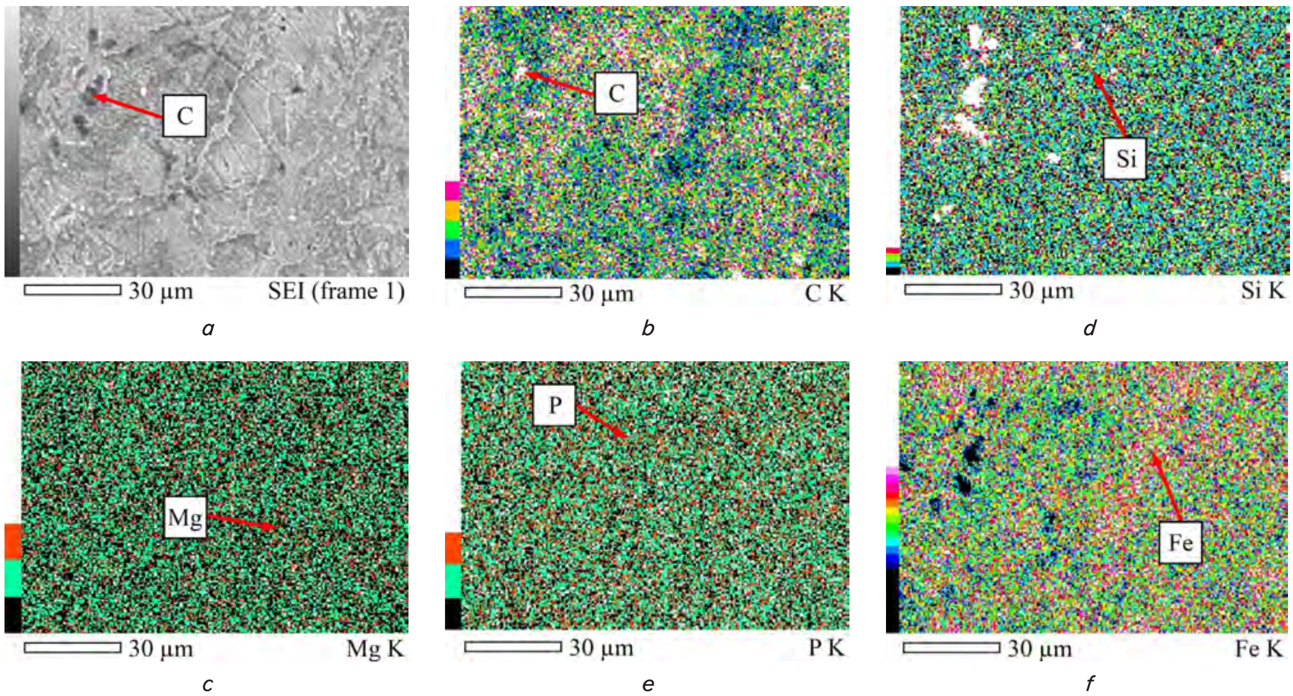


Fig. 8. Energy-Dispersive X-ray Spectroscopy mapping at a carburizing temperature of 750 °C: *a* — Scanning Electron Microscopy image; *b* — carbon; *c* — silicon; *d* — magnesium; *e* — phosphorus; *f* — iron

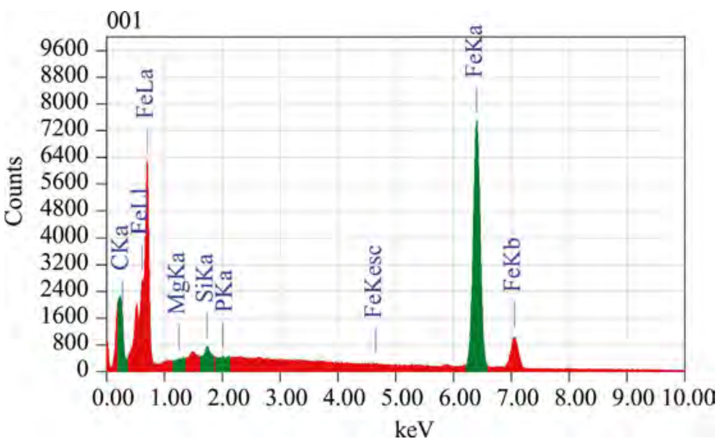


Fig. 9. Graph of elemental elements on the outermost carburizing 750 °C tensile point (1)

Table 3

Data about the material's elemental makeup tensile carburization at 750 °C

Element	(keV)	Mass (%)	Counts	Sigma	Mol (%)	Compound	Mass (%)	Cation
C	0.277	1.26	2031.37	0.02	7.10	C	1.26	0.00
O	–	22.29	–	–	–	–	ND	–
Mg	1.253	0.02	125.14	0.02	0.06	MgO	0.04	0.02
Si	1.739	0.42	2159.75	0.04	1.01	SiO_2	0.90	0.26
P	2.013	0.02	105.21	0.03	0.03	P_2O_5	0.06	0.01
Fe	6.398	75.97	101043.30	0.43	91.79	FeO	97.74	23.43
Total	11.68	100.00	105465	0.54	100.00	–	100.00	21.78

The elemental analysis in Table 5 reveals that iron (Fe) is the dominant element in the carbon steel base material. The data indicates that there is a remarkable change in the Fe content as a result of the carburizing process at different temperatures. Fe constitutes the majority of the composition in the raw material, accounting for 99.14 %. However, after carburizing at 750 °C under tensile conditions, there is a noticeable decrease in the Fe content, which reduces to 97.74 %. Similarly, at the carburizing temperature of 700 °C with tensile load, the Fe content further decreases to 90.65 %.

Table 4

Data on the chemical composition of elements C and Fe of carburizing materials with tensile on the outermost surface

Unsure	Raw Material (%)	700 °C (%)	750 °C (%)
C	0.15	0.73	1.26
Fe	99.14	90.65	97.74

Table 5

Elemental chemical composition data Fe material carburizing on the surface to core

Temperature (°C)	Spot from surface to core unsure Fe		
	1	2	3
700	90.65	98.78	97.91
750	97.74	92.59	98.29

These observations are significant evidence of carbon diffusion into the material during carburizing. Introducing carbon atoms into the material causes a displacement of Fe atoms from the surface layer into the core of the material. This phenomenon, known as carbon migration or diffusion, is the primary mechanism responsible for transforming the material's microstructure and mechanical properties during carburization.

6. Discussion of the experiment carburizing process on carbon steel with tension

The study's results indicate that carburizing is a highly effective method for case hardening. This process focuses explicitly on surface hardening by introducing carbon into the surface layers of the material. The data presented clearly demonstrates that the temperature and duration of the holding time significantly impact the success of carburization. The addition of carbon to the material's surface during the carburizing process creates a durable and resistant carburized layer. The layer's hardness is enhanced with higher carbon content, making it well-suited for applications requiring wear resistance and abrasion resistance [18].

The outcomes derived from this study harmoniously resonate with the principles expounded in pertinent references, including the seminal work outlined in [19]. These references serve as beacons of knowledge, shedding light on the intricate mechanisms underlying the carburizing process and its profound influence on the material's innate properties. The alignment between this study's findings and the insights expounded in these references corroborates the integrity of the research and reinforces the broader understanding of surface modification techniques. The significance of carburizing transcends time, engrained as a stalwart technique renowned for its capacity to bestow an armored resilience upon engineering components. The principles encapsulated within [19] and similar references unveil the artistry of this process, elucidating how carbon, a molecular protagonist, deftly infiltrates the material's atomic tapestry, effecting transformations that resound with enhanced mechanical attributes.

Fig. 4, 6, 8 collectively unveil a visual panorama of the elemental mapping results, each capturing a distinct phase in the material's journey—its raw state, the carburization process at 700 °C under tensile load, and the analogous process at 750 °C under tensile load. In this symphony of imagery, the elemental composition of the material, marked by the presence of carbon (C), iron (Fe), silicon (Si), magnesium (Mg), and phosphorus (P), takes center stage, offering insights into the material's atomic choreography. Fig. 4, as a prologue, paints a vivid portrait of the raw material's elemental distribution. Here, the grandeur of iron (Fe) is illuminated, its atomic landscape widespread and densely clustered across the sample's surface. The raw material's elemental character is assertive, with Fe atoms dominating the visual narrative, overshadowing the sparser scattering of carbon (C) atomic constituents. While black cavities punctuate the canvas, the prevailing theme remains the iron-rich texture, evoking a sense of the material's core identity.

Fig. 6, 8 reveal a subtle progression in the representation of elemental mapping. The material undergoes a carburization process at different temperatures and is subjected to a tensile load, resulting in a series of changes that can be described as symphonies. Within the intricate dance of these elements, a narrative of change unfolds, brought to light by the fluctuating proportions of carbon (C), iron (Fe), and their respective counterparts. Fig. 6 highlights a significant point where carbon (C) becomes the focal point. The mass percentage of carbon increases gradually, indicating a substantial change in the elemental composition. However, iron (Fe) plays a prominent role in this transition, maintaining its dominance within the composition. The combination of these elements results in a complex interaction, setting the stage for the development of the material.

As we continue our exploration of Fig. 8, it is essential to analyze the information and implications associated with this figure. The mass percentage of carbon (C) reaches a significant 1.26 % at an elevated temperature of 750 °C under tensile load, marking the peak of its journey. At this critical point, the material is recognized as hyper-eutectoid steel [20]. The emergence of hyper-eutectoid steel highlights the significant impact of carburization on the material's composition as it surpasses its natural equilibrium boundary. The canvas in this context portrays a transformation narrative, where the material's fundamental nature is reshaped through the impact of heat, stress, and carbon diffusion. The mapping observations reveal a significant correlation between carbon content and material hardness in woven tapestry. The rise in carbon mass leads to a change reflected in increased hardness values of the material. The observations made in this study align with the findings of previous research conducted by [21], which emphasized the relationship between carbon content and hardness. The alignment emphasizes the universal principles that serve as the foundation for the material world, going beyond the limitations of individual fields of study.

The successful carburizing process is confirmed by identifying higher carbon content on the material's surface. The diffusion of carbon atoms into the steel matrix results in the formation of iron carbides, which contributes to an increase in the surface hardness of the material. The knowledge of designing materials with superior wear resistance and increased durability for applications subjected to high stress and friction is precious [13, 22]. Low-carbon steel is an alloy widely acknowledged for its composition primarily comprising iron (Fe) and carbon (C). The presence of two key elements [23] significantly influences the mechanical properties of low-carbon steel, including hardness. High percentages of Fe and C characterize the chemical composition of low-carbon steel compared to other elements. The analysis of the microstructure testing conducted has provided valuable insights into the impact of the carburizing process on the material's properties [24]. To gain insights into the carbon diffusion process in carburization, conducting comprehensive composition testing and mapping across the material, spanning from its surface to its core is crucial.

The testing process for analyzing chemical composition changes during the carburizing process of carbon steel under tension is complex and sensitive, which can be seen as a potential drawback. Conducting accurate chemical analysis, especially when studying microstructures, poses challenges and is prone to potential inaccuracies. Accurately measuring different elements and their diffusion patterns often requires using advanced equipment and techniques for detection and analysis. The complex nature of this complexity presents difficulties in accurately quantifying the extent of chemical changes and their distribution within the substance.

The study reveals that while it illuminates a crucial aspect of the subject, there is a significant avenue for further research. Focusing on chemical composition changes gives a compelling glimpse into the transformative nature of the processes under study. However, a thorough microstructural analysis could enhance this effort. The current research illuminates chemical composition changes but opens the door to profound insights from microstructural intricacies. By studying microstructure, composition change mechanisms may become more precise. Chemical and microstructural analysis can reveal a complete material evolution story.

Future research endeavors present a promising opportunity to bridge the gap by integrating chemical transformations with microstructural arrangements. This approach makes it possible to unravel the intricate dynamics involving atomic interactions, crystallographic alterations, and elemental diffusion, thereby providing insights into the underlying factors that govern the observed variations in composition. This integrated approach surpasses the limitations of individual phenomena, resulting in a more comprehensive and nuanced understanding of the material's trajectory.

Furthermore, it is crucial to consider potential limitations regarding the research's scalability and practical applicability. The potential limitations of testing conditions and equipment in a controlled laboratory setting should be acknowledged, as they may not fully replicate the complexities of real-world industrial scenarios. The findings of this research may require cautious interpretation and extrapolation to practical applications. The tension-assisted carburizing process investigated in this study may not accurately replicate all the variables and conditions in suitable manufacturing processes. As a result, disparities between the outcomes observed in the laboratory and those experienced in real-world scenarios are possible. In addition, the research focuses on investigating the chemical composition changes in the carburized material. However, it may not provide a thorough analysis of the overall mechanical properties of the material. An overly narrow emphasis on chemical changes may result in neglecting critical mechanical properties, such as ductility, impact resistance, and structural stability. The importance of these attributes is equal when considering the suitability of carburized carbon steel for different applications.

7. Conclusions

1. The results obtained from the non-destructive testing performed on the carbon steel prior to the commencement of the carburizing process have shown distinct elemental compositions. The study has identified the existence of carbon, silicon, and iron in the material, with reported content percentages of 0.15 %, 0.58 %, and 99.04 %, respectively.

2. Carburizing adds carbon atoms to steel's surface layers. The mapping and spectroscopic data showed that iron (Fe) was the central element in the base material. After carburizing, the carbon element grew, resulting in hyper-eutectoid steel at higher temperatures. Carburizing at 700 °C increases carbon content by 0.73 %.

3. Carburizing is a procedure that increases the carbon content of steel by introducing carbon atoms into the surface layers of the metal. According to the mapping and spectroscopy findings, iron (Fe) was the most abundant element in the starting material. At the same time, carbon (C) grew significantly throughout the carburizing process, leading to hyper-eutectoid steel at higher temperatures. Carbon content might rise to 1.26 % at 750 °C during carburizing.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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