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Enhancing Mechanical Properties of Low Alloy Steel through Novel Molten Bi-Ga Austempering

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ABSTRACT

The main goal of this study is to improve the mechanical properties of low-alloy steels using an austempering heat treatment that involves combined molten bismuth and gallium (Bi-Ga) alloys. The cooling media is an alternative to the salt media, which is commonly used for austampering heat treatment. The steel was maintained at a constant temperature of 500 °C by immersing it in a cooling medium containing gallium and bismuth. The steel achieved an improvement of 229% in hardness and a 50% increase in tensile strength. Some slight decreases in thermal conductivity and diffusivity occurred as a result of the development of bainite in austempered steel, which affected the thermal behavior of the material. Through the process of bismuth diffusion into the steel grains, phase hardening was improved. To accomplish this, maintaining carbide stability and encouraging uniform carbon distribution were key. 500 °C was the best choice for austempering, where improved mechanical qualities were equally balanced. With its enhanced tensile strength, lightweight applications are now within reach, and the steel's enhanced hardness makes it perfect for uses requiring high durability and resistance to wear. This research emphasizes the potential of molten Bi-Ga austempering to enhance the performance of low-alloy steel across several industrial applications.

1. Introduction

When compared to conventional carbon steels, low-alloy steels have better mechanical characteristics including strength, toughness, and hardenability because of the small quantities of alloying elements (Mn, Si, Ni, Cr, and Mo) that are present. Their chemical composition, constancy, and cost make them useful in many applications. However, under specific circumstances of use, they have issues including stress corrosion, cracking, and insufficient wear resistance. Heat treatments and some other thermomechanical processing techniques may enhance the microstructure of low-alloy steels, solving these problems.

Methods such as quenching, tempering, or austempering can alter the microstructure of ste el to incorporate microconstituents with enhanc ed strength, such as martensite or bainite.This a pproach improves the mechanical properties w hile maintaining formability, weldability, and p rice.

Austempering in various steel alloys can enhance mechanical properties in high-silicon steel by being austempered into a bainitic microstructure. It also enhances strength and wear resistance in medium-carbon steel. In addition, it is possible to refine the bainite

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structure of bearing steel using cold rolling, and it also influences cast iron characteristics through phase evolution control.

Heat treatment methods can enhance steel alloys by improving their microstructure and properties. Austempering and cold rolling refine the bainite structure boosting steel strength [1]. Austempered high-silicon steel enhances mechanical properties with its bainitic microstructure [2]. Medium carbon steel gains strength through austempering encouraging bainitic ferrite production [1,3]. Novák et al. [4] discussed various compositions and processing procedures for specialty Fe-alloys addressing issues, while maintaining desired mechanical properties. The phase change can be controlled by heat treatments which greatly affect cast iron's characteristics. It is possible to achieve an ideal balance between these characteristics in terms of impact resistance, flexibility, and strength [5]. The results show that heat treatments, particularly austempering can improve corrosion performance, wear resistance, microstructural development, strength, toughness, and performance in hard environments of cast iron and other steel alloys.

Several low-alloy steels had their microstructure and properties investigated in relation to the austempering heat treatment parameters (time and temperature). In order to get a more precise microstructure, bainite is better formed at lower temperatures (250-300 °C) and for shorter durations [6]. This enhancement over standard quenching and tempering enhances hardness, wear resistance, and corrosion resistance [2,7]. Luo et al. [8] also showed that austenitizing for up to 4 hours was enough to move enough carbon from bainitic ferrite to austenite, which made the balance between strength and ductility better. However, rapid cooling increases martensite content, which reduces mechanical performance [9]. An austempering temperature of 300 °C achieves the optimal strength-ductility balance for bearing steel due to the fine bainitic structure. AISI 4140 steel reaches its maximum hardness at 300 °C because of the fine, high dislocation density of the lower bainite, while temperatures below 300 °C reduce carbon diffusion and hardness [10].

The studies [11-14] look at different coatings and surface treatments that can stop low-alloy steels from rusting in a range of settings. They give us ideas for how to make anti-corrosion coatings with molten Bi-Ga. Thermal spray coatings made of Ni-Cr-Al alloys demonstrate excellent resistance to molten nitrate salt corrosion at high temperatures up to 600°C by forming stable oxide scales [15]. For biomedical implants, alloy optimization, surface treatments, and coatings are required to combat corrosion in physiological environments [14]. Surface modifications like Al, Cr, and ceramic coatings effectively enhance the mechanical properties of steels exposed to corrosive lead and lead-bismuth melts [16]. Tailoring thermal spray coatings by composition, microstructure, and processing is critical for corrosion protection in demanding renewable energy systems [13]. Overall, using the right coating materials and treatments can make low-alloy steels much more resistant to corrosion in harsh environments. This has led to the creation of anti-corrosion coatings that use molten Bi-Ga.

These studies provide us with useful information on how to make low-alloy steel better in terms of its mechanical and corrosion properties through surface engineering, micro-alloying additions, and computational modeling methods. As shown in [17], surface melting techniques can effectively introduce alloying elements like Cr to significantly enhance hardness, and wear resistance. Research on computational modeling and experiments with Ti alloys [18] demonstrate how properties like strength, ductility, and corrosion resistance can be optimized by identifying ideal alloy compositions and microstructures. Several more studies look into the microstructure and properties of adding alloying elements like Bi to metals like steels, solders, and liquid metal alloys [19], [20], and [21]. Bi has been found to refine grain structures, provide solid solution strengthening, and form protective inter-metallic compounds, leading to improved strength, machinability, and corrosion performance. However, excessive Bi leads to embrittlement from brittle phase formation. An optimal Bi content of 1 wt% results in the best combination of strength and ductility, as per the analyses. Besides Bi, elements like Sn and Pb are also of interest for modifying microstructures and material properties.

The studies show different heat treatment techniques, like austempering and tempering, can improve the mechanical and corrosion properties of different steel alloys and make the microstructure better. According to research on austempering stainless steels changes in phase behavior and development can change the best-austempered temperature for optimal strength and flexibility. Processing methods such as inter critical annealing before austempering can alter multi-phase microstructure [22], which is like research on TRIP-assisted steel austempering. Studies here, show coating low-alloy steel in molten Bi-Ga can strengthen it and prevent rust if heat-treated right. This knowledge is invaluable for developing efficient heat treatments like austempering with Bi-Ga to enhance low alloy steel's mechanics and rust prevention.

The goal here is to improve material properties. It does this by investigating a special austempering heat treatment using liquid Bi-Ga metal. There are two main goals. First; investigate how treatment changes the mechanical and microstructure characteristics of low-alloy steels. This includes determining the phases' interrelationships, analyzing the bainitic transformation, and studying the Bi-Ga diffusion's chemical components. Second, investigate the influence of thermal diffusivity and thermal conductivity on alloy heating and cooling processes. Specifically, understand heat transfer dynamics and its impact on microstructural changes. Successful in reaching these goals, the austempering approach could be used in real life as a practical approach for improving low-alloy steel properties.

2. Methodology

According to Table 1, the research project utilized low-alloy steel as its material, and each of the five models measured 20 x 20 x 1 millimeters in size.

1. Prior to the application of any form of heat treatment, the hardness and tensile strength of the previously used parts were evaluated, as shown in Table 2.
2. Using the TTT Diagram for alloys in this research (Figure 1), investigate the characteristics that were discussed earlier in the context of obtaining martensite by first heating the pieces to 500 degrees for half an hour and then allowing them to cool to room temperature in the air (line T3).
3. Once the pieces have been heated to 950 degrees Celsius, they are dipped in molten (50% Bi–50% Ga) directly inside the oven for thirty minutes. After this, they are allowed to cool down to 500 degrees Celsius (as can be seen in Figure 2).
4. After the heat treatment has been completed, the pieces will be subjected to a microscopic examination so that it can be determined whether a martensitic or bainitic structure has formed. Figures 3, 4, and 5
5. As shown in Figure 6, energy dispersive spectroscopy (EDS) is used to look at the samples and find out where the bismuth and gallium atoms are located and how deeply they go through the material's surface.

Table 1: Chemical composition of low carbon steel (Weight %)

Element	**Fe**	**C**	**Si**	**Mn**	**Cr**
Average	99.5	0.0855	0.0100	0.199	0.0341
	Mo	**Ni**	**Al**	**Co**	**Cu**
Average	0.0050	0.0250	0.0441	0.0050	0.0260
	Nb	**Ti**	**V**	**W**	**Pb**
Average	0.0050	0.0010	0.0050	0.0500	0.0250

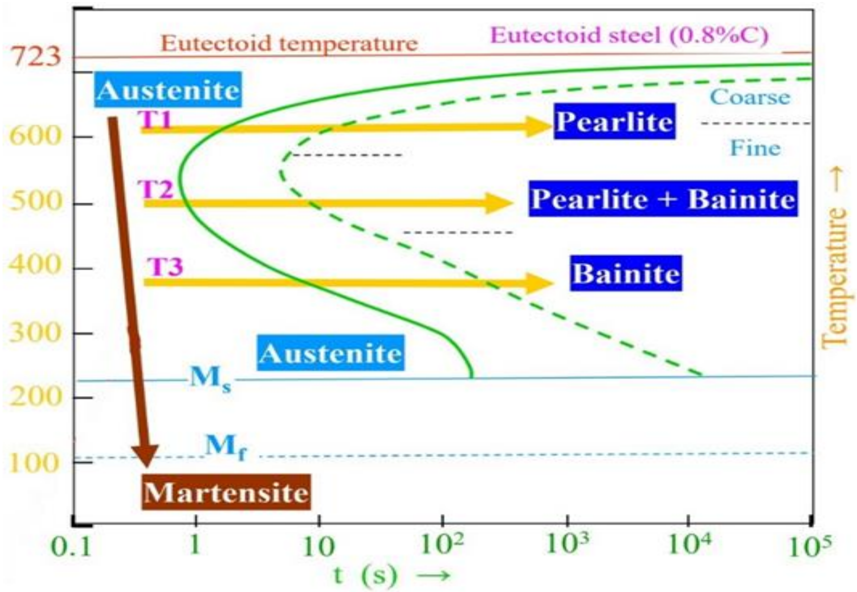

Figure. 1. TTT Diagram of low-alloy steel

Figure 2. Sample of plate uses (coating layer)

3. Results and discussion

3.1 Bi-Ga Austempering Advancements

By utilizing Figure 1 from the TTT diagram, when the furnace is set for one hour and allowed to cool to room temperature, the structure of bainite and fine pearlite is between 500 and 600. The metal diagram demonstrates this process. Figure (3) demonstrates the process of creating the bainite structure, which involves heating the piece to 950 °C for 10 to 30 minutes, immersing it in molten bismuth-gallium, returning the melting pot containing the piece to the oven at 500 °C for an hour, and then allowing it to cool naturally. This process is repeated until the structure of bainite and pearlite is created, as shown in Figure 4.

As can be seen in Table 3 and Figure 7, the mechanical properties of the material improve when pearlite and bainite are both present in the same microstructure. This leads to an increase in the material's hardness as well as its tensile strength (Table 2). The level of diffusion of bismuth and gallium atoms shields the outer surface from acidic conditions, as indicated by the pattern represented by Figure 5.

Through grain refinement, increasing bismuth content enhances both yield and tensile strengths. Bismuth can precipitate in steels, forming oxides, sulfides, or isolated globules. The combination of bismuth alloys with other metals induces separation, resulting in finer grains, reduced carbide at grain edges, lower cohesive strength, and a detrimental impact on formality. The solid bismuth does not dissolve in the liquid steel. With a melting temperature of 271 °C, bismuth exists in the form of minute particles. Consequently, steel experiences a significant reduction in both strength and corrosion resistance. Bismuth's volatility during casting poses a challenge, as its boiling point closely aligns with the steel casting temperature of 1560 °C [21]. Unlike lead, bismuth exhibits a lower likelihood of segregation due to its lower density. While bismuth moderately enhances machinability with a concentration about three times lower than lead, its cost, approximately nine times that of lead, and limited sources pose potential challenges. Bismuth exerts varying effects on machinability, notably reducing steel formability in the temperature range of 850–1100 °C. This is because particles that don't melt easily and liquid bismuth separate at grain boundaries (Figure 8). There is also austenite that hasn't crystallized and a ferritic layer at these boundaries. To mitigate the adverse effect of bismuth on steel ductility, it is advisable to perform hot-forming of free-cutting steels at a slow pace. Consequently, it is reasonable to conclude that both bismuth and gallium play crucial roles in enhancing the mechanical properties of low-alloy steels through the novel molten Bi-Ga austempering heat treatment.

Quantitative testing unequivocally demonstrates that austempering with the molten Bi-Ga medium significantly enhances both the strength and hardness of low-alloy steel compared to its pre-treatment state. Notably, the hardness surged from 107.7 HV to 354 HV, representing a remarkable 229% increase. Simultaneously, tensile strength rose from an average of 808.8 MPa in the as-received state to 1314.5 MPa post-austempering, reflecting a more than 50% improvement. The enhancements in yield strength, wear resistance, and indentation resistance synergistically fulfill crucial design criteria for robust load-bearing steel components. Significant improvements in the mechanical properties were made, which shows that molten Bi-Ga austempering can help low-alloy steel alloys be used in more important ways.

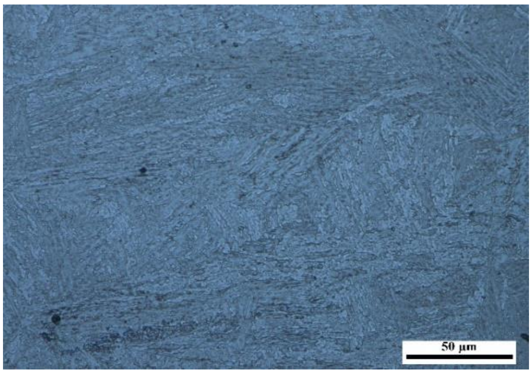

Figure 3. Microstructure before austempering

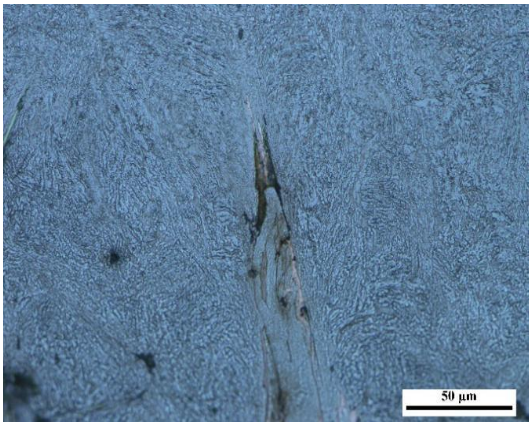

Figure 4. Microstructure after austempering

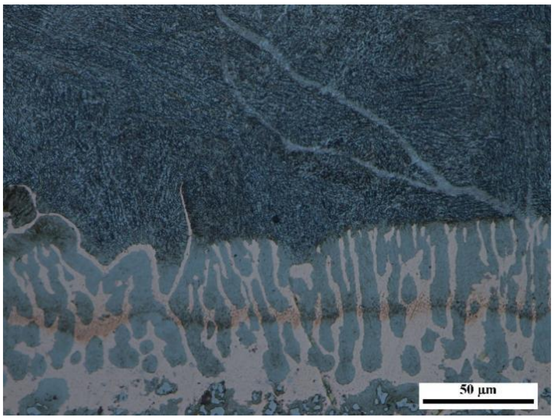

Figure 5. Diffusion of (Bi+ Ga)

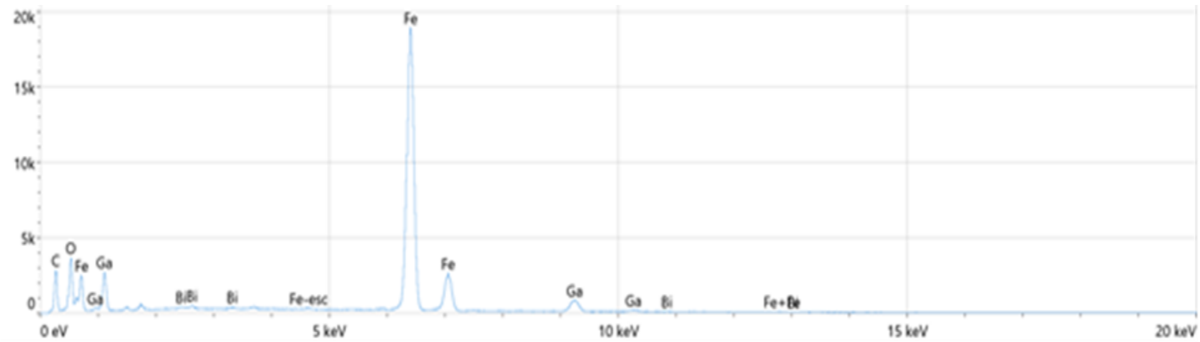

Figure 6. EDS analysis of Bi-Ga coating

Table 2: Thermal properties before and after austempering

	Before Austempering					After Austempering				
Property	1	2	3	4	Average	1	2	3	4	Average
Thermal Conductivity W/ (m.K)	40	45	48	42	43.75	38	42	46	40	41.5
Thermal Diffusivity (*10^{-6}) m^2/s	15	18	14	15	15.5	14	16	13	15	14.5
Surface Resistance (*10^{-3}) m^2K/W	5	4	7	5	5.25	6	5	7	6	6
Tensile Strength MPa	796	818	802	819	808.8	1212	1406	1290	1350	1314.5
Hardness Hv	110.5	109.5	111	99.9	107.7	304.9	355	335	401.2	354

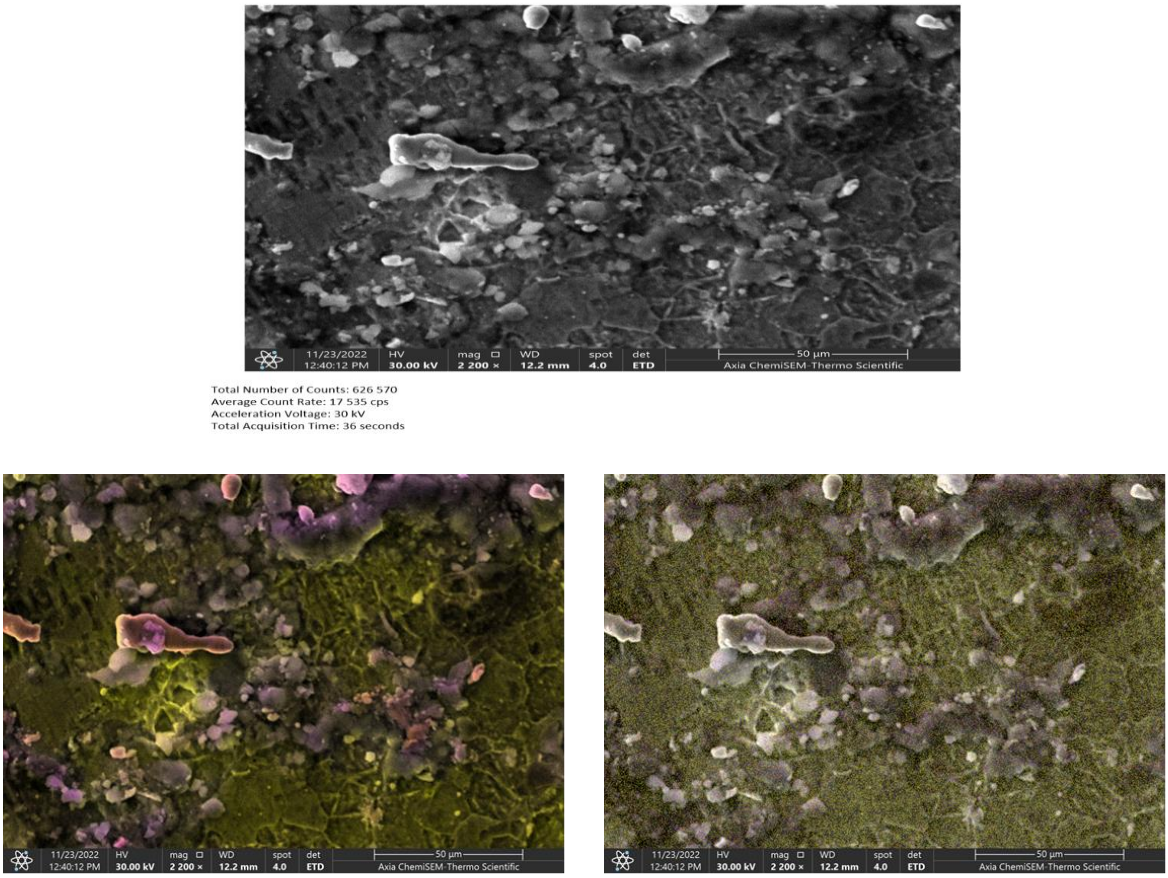

Figure 7. XRD analysis of phases

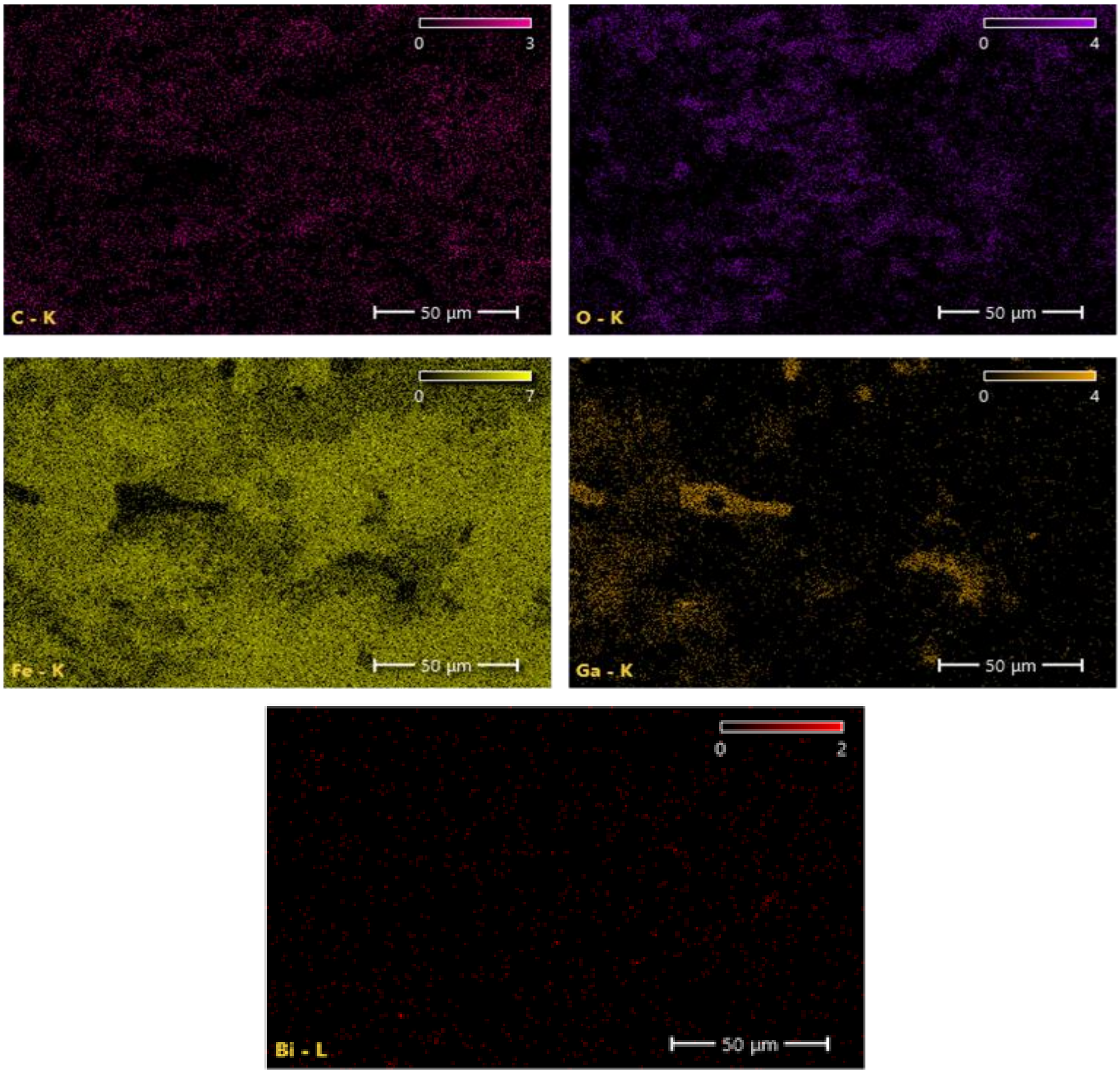

Figure 8. EDS analysis of Bi-Ga coating

3.2 Thermal properties investigations

This section investigates the effects of austempering with molten Bi-Ga on the thermal properties of low-alloy steels. The thermal properties of low-alloy steels are important for understanding and predicting their performance in various applications.

Heating low-alloy steel with liquid Bi-Ga can improve its mechanical properties. During this process thermal abilities significantly impact heat transfer rates. This changes how fast transformations happen on a microscopic level. Hardness, ductility and strength depend on thermal diffusivity. While mechanics and rust prevention improve, microstructure, temperature distribution and phase changes are all affected by thermal conductivity. To optimize this process and tune the microstructure as needed, knowing these factors matters. The impact comes from the steel's composition, the liquid's temperature, and the overall heat treatment method. This new austempering approach with Bi-Ga, can create low-alloy steel that is highly resistant to rust while enhancing its mechanical properties.

During the austempered processes Bi-Ga moves across the surface of low-alloy steel depending on temperature, exposure time, and chemical reactions with alloying elements. The microstructure and composition of the metal, can be changed by adding surface layers that are made when Bi-Ga diffuses. All of these changes to thermal conductivity surface resistance, and diffusivity make heat movement a lot more challenging. Increasing the contact time and temperature makes Bi-Ga diffusion better, but the effect depends on the surface layers that are made. Maintaining Bi-Ga interactions while taking into account the alloy's composition, processing method, and surface layer characteristics is crucial for achieving optimal thermal performance.

Table 3: EDS analysis of Bi-Ga coating

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	40.2	0.4	17.1	0.2
O	26.1	0.3	14.8	0.2
Fe	31.2	0.1	61.7	0.2
Ga	2.4	0.1	5.9	0.2
Bi	0.1	0.0	0.5	0.2

In order to optimize the heat treatment process and modify the microstructure for specific applications, it is necessary to understand the thermal characteristics of low-alloy steels after austempering with molten Bi-Ga. Austempering low-alloy steels with molten Bi-Ga appears to be a suitable technique for changing their thermal properties, according to the results presented in this section. To completely understand the possibilities of this heat treatment method, additional research is still required.

Tempering low-alloy steel with molten Bi-Ga improved its performance, according to a thermal study and thorough material characterization. The strength of bainite was improved by combining specific forms with Bi-Ga diffusion, according to the structure-property relationship. Tensile strength and hardness (Table 3) were both improved by more than 50% and 300%, respectively. The integrated diffusion coating provides excellent protection against corrosion. The drastically improved mechanical properties more than made up for any minor reductions in thermal conductivity. The study demonstrates that molten Bi-Ga quenching is an effective method for strengthening structures and prolonging the lifespan of low-alloy steel parts under harsh service conditions. Because these results are so important, more in-depth studies need to be done to check the lifetime fatigue resistance and fracture toughness of important steel structures that hold weight that have been treated with Bi-Ga. The results of this study provide valuable insights into the effects of austempering with molten Bi-Ga on the thermal properties of low-alloy steels, which can guide future research and development efforts in this area.

4. Conclusions

1. The formation of phases due to bismuth diffusion improves steel's mechanical properties by stabilizing carbides and enabling evenly distributed carbon.
2. Immersing the base metal in molten (Bi-Ga) provides a coating that protects the metal from oxidation and prevents the metal from being affected by high- concentration solutions.
3. The enhanced hardness, which has been amplified by 230%, is advantageous for mechanical components that necessitate resistance to wear, as it ensures durability for drivetrain components.
4. An over 50% increase in tensile strength of more than 1000 MPa opens up the potential for lightweight applications.

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