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Recent Advances in Surface Hardening Techniques for Improving the Mechanical Properties of Low Carbon Steel: A Literature Review

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ABSTRACT
The increasing demand for high-performance engineering materials has driven significant advancements in surface hardening techniques for low carbon steel. Despite its excellent ductility and cost-effectiveness, low carbon steel exhibits limited hardness and wear resistance, restricting its application in demanding environments. This study presents a comprehensive literature review on recent advances in surface hardening technologies, including carburizing, nitriding, boriding, induction hardening, and laser surface treatment.
The review highlights the fundamental mechanisms of diffusion-driven surface modification and the resulting microstructural transformations that enhance mechanical properties. Recent developments such as plasma-assisted processes, hybrid carburizing carbonitriding treatments, and laser-based techniques demonstrate substantial improvements in hardness, wear resistance, and fatigue performance. In addition, emerging eco-friendly carburizing methods utilizing biomass-derived carbon sources show promising potential in reducing environmental impact while maintaining competitive material performance. Furthermore, this study identifies key challenges related to process optimization, microstructural control, and sustainability. Future directions emphasize the integration of hybrid surface engineering techniques and advanced modeling approaches to achieve superior performance. Overall, this review provides critical insights into state-of-the-art surface hardening strategies and serves as a valuable reference for the development of efficient and sustainable material processing technologies.

Key Words: *Low carbon steel, Surface hardening, Carburizing; Nitriding, Plasma treatment, Laser surface hardening, Hybrid surface engineering.*

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I. INTRODUCTION

The demand for improved performance of engineering materials has significantly increased in modern industrial applications, particularly in sectors such as automotive, manufacturing, and construction. Low carbon steel is widely used due to its excellent ductility, weldability, and cost-effectiveness. However, its relatively low hardness and poor wear resistance limit its application in environments requiring high surface strength and durability. Therefore, enhancing the mechanical properties of low carbon steel has become a critical focus in materials engineering.

Surface hardening techniques have emerged as effective approaches to overcome these limitations by modifying the surface layer without compromising the bulk properties of the material. These techniques aim to improve hardness, wear resistance, and fatigue strength while maintaining the inherent toughness of the core. Among the commonly used surface hardening methods are carburizing, nitriding, induction hardening, and boriding, each offering distinct mechanisms and advantages depending on the application requirements.

In recent years, significant advances have been made in surface hardening technologies, driven by the need for higher efficiency, improved performance, and environmental sustainability. Modern carburizing processes, for instance, have evolved from conventional gas carburizing to more advanced methods such as vacuum and plasma carburizing, which provide better control over carbon diffusion and microstructural evolution. Similarly, nitriding techniques have been enhanced through plasma-assisted processes, enabling lower processing temperatures and reduced distortion.

Despite these developments, challenges remain in optimizing process parameters, achieving uniform case depth, and minimizing environmental impact. Additionally, the relationship between processing conditions, microstructural transformations, and resulting mechanical properties is still an area of ongoing research.

Understanding these aspects is essential for selecting appropriate surface hardening techniques tailored to specific industrial applications.

This literature review aims to provide a comprehensive overview of recent advances in surface hardening techniques for improving the mechanical properties of low carbon steel. The review focuses on the fundamental mechanisms, process developments, and comparative performance of various methods, while also identifying current research gaps and future directions in the field.

II. LITERATURE REVIEW

2. Literature Review

2.1. Fundamental Mechanisms of Surface Hardening

Surface hardening mechanisms fundamentally involve modifying the chemical composition, microstructure, and stress state of the steel surface to enhance hardness and wear resistance, while preserving a tougher and more ductile core. This dual-property structure is essential for improving the mechanical performance of low-carbon steels in demanding engineering applications. One of the primary mechanisms is the diffusion of interstitial alloying elements such as carbon, nitrogen, or boron into the surface layer. Processes such as carburizing, nitriding, and boriding facilitate the diffusion of these atoms into the crystal lattice, increasing their concentration near the surface and promoting the formation of hard phases such as carbides, nitrides, and borides. These compound layers significantly improve surface hardness and wear resistance.

In addition to diffusion, phase transformation plays a critical role in surface hardening. During treatments like carburizing, the steel is heated to the austenitic region, allowing carbon to dissolve into the lattice. Upon rapid cooling (quenching), the austenite transforms into martensite hard and brittle phase characterized by a supersaturated carbon structure and lattice distortion while the core remains relatively soft and ductile. This transformation results in a hardened outer layer supported by a tough interior, thereby enhancing both strength and impact resistance. The effectiveness of carburizing is strongly influenced by processing parameters such as temperature, time, and carbon potential, which govern carbon diffusion kinetics and subsequent microstructural evolution [1], [3], [19], [21].

Another important strengthening mechanism is precipitation hardening, particularly evident in nitriding and boriding processes. In these treatments, fine precipitates such as iron nitrides or borides form within or near the surface layer, acting as obstacles to dislocation movement and thereby increasing hardness and wear resistance. Nitriding, in particular, offers the advantage of producing hard nitride phases without the need for quenching, thus minimizing distortion. Advanced techniques such as plasma nitriding enable more precise control over nitrogen diffusion and compound layer formation, resulting in improved hardness, wear resistance, and surface stability [3], [4], [5], [6], [24].

Mechanical surface treatments also contribute to hardening through work hardening (strain hardening). Techniques such as shot peening induce localized plastic deformation, generating a high density of dislocations within the surface layer. The interaction and entanglement of these dislocations restrict further movement, thereby increasing hardness and enhancing fatigue resistance. Furthermore, both thermal and mechanical treatments can introduce compressive residual stresses into the surface layer, which play a crucial role in improving fatigue strength by inhibiting crack initiation and propagation.

Grain refinement is another contributing mechanism, where certain surface treatments produce finer microstructural grains. According to the Hall-Petch relationship, smaller grain sizes increase resistance to dislocation motion, leading to higher hardness and strength. Collectively, these mechanisms diffusion, phase transformation, precipitation, work hardening, residual stress induction, and grain refinement—work synergistically to create a hardened surface layer with superior wear resistance, supported by a ductile and tough substrate. This combination is particularly advantageous for low-carbon steels, enabling their application in components subjected to high stress, wear, and cyclic loading conditions.

2.2. Advances in Carburizing Techniques

Recent advances in carburizing techniques have been driven by the need to improve process efficiency, enhance mechanical performance, and promote environmental sustainability in modern steel processing. Conventional gas carburizing, although widely adopted in industry, is often constrained by prolonged cycle times, high energy consumption, and environmental concerns associated with carbon-rich emissions. Consequently, contemporary developments have shifted toward more controlled, rapid, and eco-friendly carburizing methodologies that offer superior surface integrity and process reliability.

One of the most significant innovations is low-pressure carburizing (LPC), also known as vacuum carburizing, which operates under reduced pressure using hydrocarbon gases. This technique enables precise control of carbon potential, minimizes oxidation and intergranular oxidation defects, and produces deeper, more uniform case depths within shorter processing times. As a result, LPC significantly improves surface quality while reducing distortion and eliminating the need for extensive post-treatment cleaning, making it particularly suitable for high-precision engineering components [7].

In parallel, plasma carburizing has emerged as an advanced surface engineering technique that utilizes ionized gas to enhance carbon diffusion into the steel surface. The plasma environment activates the material surface and accelerates diffusion kinetics, enabling improved hardness and wear resistance at relatively lower temperatures. This process not only enhances surface properties but also reduces gas consumption and emissions, contributing to more sustainable manufacturing practices [8].

Recent research has also highlighted the development of hybrid carburizing-based treatments, particularly carburizing carbonitriding processes, which combine the diffusion of carbon and nitrogen to produce refined martensitic structures with superior hardness and wear resistance. These duplex and hybrid approaches offer synergistic improvements in surface performance, including enhanced fatigue strength and resistance to abrasive wear, thereby expanding the applicability of carburized steels in demanding service conditions [20].

To meet industrial demands for higher productivity, rapid carburizing techniques have been introduced, focusing on optimizing parameters such as temperature, carbon potential, and cycle duration. These approaches significantly reduce processing time without compromising case depth or hardness, while also contributing to improved fatigue performance through refined and uniform microstructural development.

In line with global sustainability initiatives, eco-friendly carburizing methods utilizing biomass-derived carbon sources have gained increasing attention. Agricultural wastes such as coconut shells and palm kernel residues are being explored as alternative carburizing media, offering a renewable and cost-effective substitute for conventional fossil-based carbon sources. Experimental studies have demonstrated that these bio-based materials can achieve comparable hardness and case depth when properly optimized, while simultaneously reducing environmental impact [13], [14], [26]. This trend strongly aligns with the principles of green manufacturing and sustainable materials engineering [27].

Furthermore, the integration of digitalization and process modeling has significantly advanced carburizing technology. Computational simulations now enable accurate prediction of carbon diffusion behavior, phase transformations, and residual stress evolution, facilitating precise optimization of process parameters and reducing reliance on empirical trial-and-error methods. This leads to improved consistency, efficiency, and scalability in industrial applications.

Overall, modern carburizing techniques represent a substantial evolution from traditional methods, incorporating innovations such as vacuum and plasma-assisted processes, hybrid diffusion treatments, rapid cycle technologies, and sustainable carbon sources. These advancements collectively contribute to enhanced surface performance, reduced environmental impact, and greater adaptability to the increasingly stringent demands of advanced manufacturing industries.

2.3. Developments in Nitriding and Advanced Surface Hardening Methods

The latest developments in nitriding and sophisticated surface hardening technologies have considerably enhanced steel surface treatments' performance, accuracy, and efficiency. Nitriding technology, in particular, has advanced through plasma-assisted procedures that allow for fine control over nitrogen diffusion and compound layer development. These developments result in the production of strong nitride layers with improved wear resistance, fatigue strength, and surface stability, while reducing distortion caused by the lack of quenching. Plasma nitriding and its derivatives, such as active screen nitriding, offer improved uniformity and faster processing times, making them ideal for complicated and high-precision components [4], [15], [24].

In addition to nitriding, laser surface hardening has emerged as a high-precision technique capable of producing localized hardened layers with minimal thermal distortion. This method allows controlled microstructural transformation, typically forming martensitic structures with refined grain size, thereby significantly improving surface hardness and wear performance [10], [23]. Similarly, induction hardening remains an efficient and widely used technique for localized treatment, offering rapid heating, controlled hardening depth, and high process efficiency, which are advantageous for large-scale industrial applications [16].

Furthermore, boriding continues to be recognized as an effective thermochemical treatment for achieving extremely high surface hardness through the formation of FeB and Fe_2B layers. These boride phases provide excellent wear and corrosion resistance; however, their inherent brittleness remains a key limitation that must be carefully managed in engineering applications [11], [18], [25].

Overall, the integration of advanced nitriding techniques with modern surface hardening methods such as laser hardening, induction hardening, and boriding demonstrates a significant progression in surface engineering. These developments enable the production of components with superior hardness, wear resistance, and fatigue performance, while maintaining process efficiency and dimensional stability, making them highly relevant for modern industrial and manufacturing demands.

2.4. Comparative Analysis of Surface Hardening Techniques

A comparative analysis of surface hardening techniques reveals that each method offers distinct advantages depending on the required mechanical performance, cost, and application conditions. Carburizing is widely applied for low-carbon steels due to its ability to produce a deep hardened case combined with a tough core, resulting in improved fatigue strength and load-bearing capacity. However, it generally requires high temperatures and longer processing times, which may lead to distortion. In contrast, nitriding provides superior surface hardness and wear resistance at lower processing temperatures without the need for quenching, thereby minimizing distortion and maintaining dimensional stability [12].

Advanced thermochemical treatments further enhance performance. Boriding, for instance, produces extremely hard surface layers (FeB and Fe_2B) with excellent wear and corrosion resistance, although its brittleness can limit applications requiring high toughness. Meanwhile, modern developments such as plasma carburizing and plasma nitriding enable better control of diffusion processes, resulting in improved surface uniformity, reduced processing time, and enhanced efficiency.

Recent studies also emphasize that hybrid and duplex treatments outperform conventional single-process methods. Combined techniques such as carburizing carbonitriding and nitriding–boriding introduce multiple diffusing elements, leading to synergistic improvements in hardness, wear resistance, and fatigue performance [20], [25]. These approaches allow the formation of complex microstructures that are more resistant to mechanical and tribological degradation.

In addition, advanced localized hardening methods such as laser and induction hardening provide high precision and process efficiency. Laser surface hardening enables controlled microstructural transformation with minimal thermal distortion, while induction hardening offers rapid heating and suitability for mass production. Plasma- and laser-based techniques, in particular, provide superior control over process parameters, allowing tailored surface properties for specific industrial applications [22], [23], [24]. However, despite their advantages, these advanced methods often face challenges related to higher operational costs and scalability in large-scale manufacturing.

In general, the choice of an acceptable surface hardening technology is based on balancing criteria such as needed hardness, case depth, distortion tolerance, cost, and production scale. While traditional procedures remain useful, new and hybrid approaches are becoming increasingly popular due to their ability to provide optimal and application-specific surface performance.

2.5. Research Gaps and Future Directions

Despite significant advancements, several research challenges remain. One major gap is the development of environmentally sustainable surface hardening processes that can match the performance of conventional methods. Eco-friendly carburizing approaches show promising results but require further validation for industrial applications [13], [14], [26].

Another challenge is understanding the relationship between process parameters, diffusion behavior, and microstructural evolution, particularly in advanced techniques such as plasma and hybrid treatments [8], [24].

Future research directions include: Hybrid surface engineering techniques, Integration of computational modeling and AI-based optimization, Development of sustainable and low-energy processes. Recent studies on green heat treatment and advanced microstructural design highlight the potential for significant improvements in performance and sustainability [27], [28], [29].

III. CONCLUSIONS

This study has comprehensively reviewed recent advances in surface hardening techniques for improving the mechanical properties of low carbon steel. Conventional methods such as carburizing and nitriding remain effective; however, modern advancements have significantly enhanced their efficiency and performance. Techniques such as plasma carburizing, laser surface hardening, and hybrid thermochemical treatments demonstrate superior control over diffusion processes and microstructural evolution, resulting in improved hardness, wear resistance, and fatigue strength.

The integration of hybrid surface treatments, particularly carburizing carbonitriding and nitriding boriding, has shown promising results in achieving synergistic improvements in mechanical properties. In addition, the development of environmentally friendly carburizing methods using biomass-derived carbon sources represents an important step toward sustainable manufacturing.

Despite these advancements, challenges remain in optimizing process parameters, controlling microstructure, and scaling advanced techniques for industrial applications. Therefore, future research should focus on combining experimental and computational approaches to better understand diffusion mechanisms and microstructural transformations.

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