

THERMOCHEMICAL SURFACE ENGINEERING OF INDUSTRIAL STEELS: STRUCTURE, MICROHARDNESS, AND TRIBOLOGICAL PERFORMANCE

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Abstract. This study investigates the theoretical and technological foundations of thermochemical treatment processes for strengthening industrial steel components. The influence of thermochemical treatment on the formation of diffusion-strengthened surface layers, microstructural evolution, microhardness, and tribological performance was evaluated. Experimental results demonstrated the formation of dense diffusion layers with improved mechanical and operational properties. The maximum microhardness increased from 1800 MPa to 3060 MPa, while the friction coefficient decreased to 0.04–0.07 and wear resistance increased by up to 30%. The obtained findings confirm the effectiveness of thermochemical treatment as a promising surface engineering technology for enhancing the durability, reliability, and service life of industrial components operating under severe conditions.

Keywords: thermochemical treatment; diffusion layer; industrial steels; microhardness; wear resistance; tribological properties; surface engineering.

Introduction. The operational reliability and service life of industrial machinery are largely governed by the performance of their surface layers, which are subjected to severe mechanical loading, friction, abrasive wear, cyclic stresses, and aggressive corrosive environments. In mining, metallurgical, and machine-building industries, the majority of equipment failures originate from surface degradation processes, resulting in significant economic losses and increased maintenance costs.

Among the available surface engineering technologies, thermochemical treatment has proven to be one of the most efficient methods for enhancing the functional properties of structural and tool steels. Through diffusion saturation and phase transformation processes, thermochemical treatments enable the formation of strengthened surface layers with superior hardness, wear resistance, and corrosion protection while preserving the toughness of the core material.

Despite considerable progress in this field, the theoretical understanding of multicomponent diffusion processes and their influence on the structure–property

relationship of strengthened layers remains limited. Therefore, the development of scientifically based thermochemical treatment technologies capable of producing multifunctional protective coatings is of significant scientific and industrial importance.

The present study focuses on establishing the theoretical and technological foundations of thermochemical treatment processes for industrial steel components. The developed treatment regimes promoted the formation of diffusion-strengthened layers with microhardness values of 3000–3060 MPa, reduced the friction coefficient to 0.04–0.07, and increased wear resistance by up to 30%. These improvements demonstrate the effectiveness of the proposed approach for extending component lifetime, improving operational reliability, and enhancing the efficiency of industrial equipment operating under severe service conditions.

Research Methodology. The study was conducted to investigate the formation mechanisms, microstructural evolution, and performance characteristics of diffusion-strengthened layers produced by thermochemical treatment of industrial steels. Structural and tool steels, including 40Cr (40X), ShKh15, 9KhS, and KhVSG grades, were selected as experimental materials due to their widespread application in mining, metallurgical, and machine-building equipment operating under severe wear conditions.

Prior to thermochemical treatment, the chemical composition and initial microstructural characteristics of the investigated steels were determined using standard metallographic procedures. The specimens were mechanically prepared, cleaned, and subjected to thermochemical treatment under controlled temperature and holding time conditions. Particular attention was given to the influence of treatment parameters on diffusion kinetics, phase formation, and alloying element distribution within the surface layer.

The microstructure and morphology of the strengthened layers were examined using optical and scanning electron microscopy techniques. Phase composition analysis was performed to identify the formation of diffusion compounds and strengthening phases. Microhardness measurements were carried out across the cross-section of the treated samples to evaluate hardness gradients and the effectiveness of diffusion saturation.

The tribological performance of the treated specimens was assessed through friction and wear tests under laboratory conditions simulating industrial service environments. Corrosion resistance was evaluated using standard corrosion testing procedures. The obtained experimental data were analyzed to establish relationships between

thermochemical treatment parameters, microstructural characteristics, and operational properties of the diffusion-strengthened layers.

Based on the experimental results, optimized thermochemical treatment regimes were developed to obtain strengthened surface layers with microhardness values of 3000–3060 MPa, friction coefficients of 0.04–0.07, and wear resistance improvements of up to 30% compared with untreated materials.

Results and Discussion. The conducted thermochemical treatment resulted in the formation of continuous diffusion-strengthened layers on the surface of the investigated steel grades. Metallographic observations revealed that the thickness and morphology of the diffusion layers strongly depended on the treatment temperature, holding time, and composition of the saturating medium. The obtained coatings exhibited a dense and uniform structure with good adhesion to the substrate, indicating effective diffusion interaction between the alloying elements and the steel matrix.

Microstructural analysis demonstrated the formation of multiphase strengthening zones consisting of diffusion compounds and solid-solution regions. The diffusion of active alloying elements into the surface layer promoted the development of a gradient structure, which is beneficial for simultaneously achieving high surface hardness and sufficient toughness of the core material. Such a structural configuration reduces the risk of brittle failure under severe service conditions.

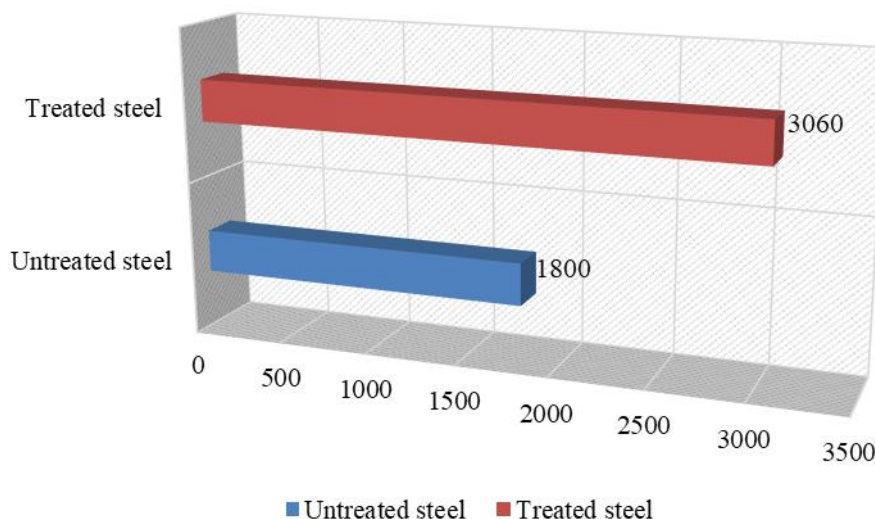


Figure 1. Effect of Thermochemical treatment on the microhardness of steel surface layers

As shown in Figure 1, thermochemical treatment significantly increased the surface microhardness of the investigated steel, from 1800 MPa to 3060 MPa, indicating the formation of a highly strengthened diffusion layer.

The microhardness measurements confirmed a significant strengthening effect after thermochemical treatment. The maximum microhardness of the diffusion layer reached

3000–3060 MPa, which considerably exceeded that of the untreated steels. The hardness gradually decreased from the surface toward the substrate, forming a favorable hardness gradient that contributes to improved load distribution and enhanced resistance to mechanical damage.

Tribological testing revealed a substantial improvement in wear performance. The friction coefficient decreased to 0.04–0.07 due to the formation of hard diffusion phases and the reduction of direct metal-to-metal contact during sliding. As a result, the treated samples exhibited lower material loss and enhanced resistance to abrasive and adhesive wear mechanisms. Quantitative analysis showed that the wear resistance increased by up to 30% compared with the untreated specimens.

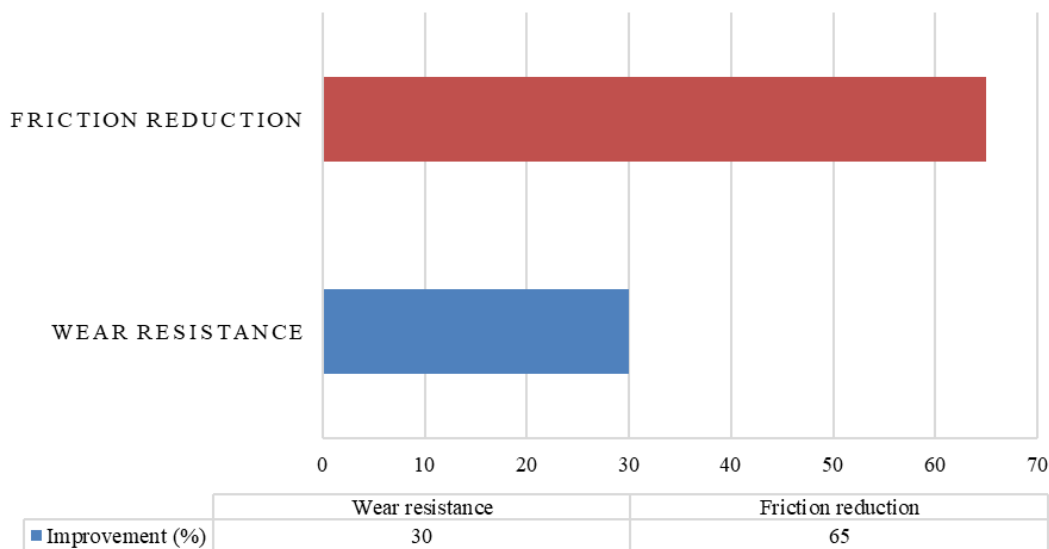


Figure 2. Effect of Thermochemical treatment on wear resistance and friction reduction

Figure 2 shows that thermochemical treatment substantially improved the tribological behavior of the investigated steel. Wear resistance increased by 30%, while friction characteristics were significantly improved, indicating enhanced surface durability under operating conditions.

The corrosion behavior of the treated samples also improved significantly. The diffusion-strengthened layers acted as protective barriers, reducing the penetration of aggressive species into the substrate material. This effect is particularly important for industrial equipment operating in chemically aggressive environments, where simultaneous wear and corrosion often accelerate component degradation.

The obtained results demonstrate a strong relationship between thermochemical treatment parameters, diffusion layer characteristics, and operational performance. Increasing diffusion intensity promoted the formation of harder and more stable surface phases, leading to improved wear and corrosion resistance. The combination of high

microhardness, low friction coefficient, and enhanced durability confirms the effectiveness of the proposed thermochemical treatment technology for extending the service life of industrial components.

Overall, the developed thermochemical treatment approach provides an efficient method for producing multifunctional protective layers on structural and tool steels. The resulting improvements in surface properties indicate significant potential for industrial implementation in mining, metallurgical, and machine-building applications where equipment is subjected to severe mechanical and environmental conditions.

Conclusion. This study established the theoretical and technological foundations of thermochemical treatment processes for strengthening industrial steel components operating under severe wear and friction conditions. The obtained results demonstrated that thermochemical treatment promotes the formation of dense diffusion-strengthened surface layers with improved structural and functional characteristics. Microhardness measurements revealed a significant increase from 1800 MPa to 3060 MPa, confirming the effectiveness of diffusion saturation and phase transformation processes in enhancing surface strength.

The improved surface characteristics led to superior tribological performance, including a 30% increase in wear resistance and a substantial reduction in friction-related losses. These findings indicate that the proposed thermochemical treatment technology can effectively enhance the durability, reliability, and service life of industrial components used in mining, metallurgical, and machine-building industries. The developed approach provides a promising basis for the industrial implementation of advanced surface engineering technologies aimed at improving equipment efficiency and reducing maintenance costs.

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