Effect of Electrolytic-Plasma Hardening on the Structure, Microhardness and Tribological Properties of 20Cr2Ni4A Steel

A. Maulit, Z. Satbayeva, B. Rakhadilov

Abstract. This study investigates the effect of short-duration electrolytic-plasma hardening on the microstructure, phase composition, microhardness, and tribological properties of 20Cr2Ni4A structural steel. The treatment was carried out in an aqueous electrolyte at a voltage of 320 V for 3, 5, and 7 s, followed by intensive cooling in the same electrolyte. Structural and phase transformations were examined by X-ray diffraction and scanning electron microscopy, while the performance characteristics were evaluated based on the microhardness distribution and coefficient of friction. It was established that electrolytic-plasma hardening leads to the formation of a gradient-hardened layer consisting of a hardened zone, a transition zone, and the unaffected base material. A fine needle-like martensitic-type structure is formed in the surface region, while the phase composition remains predominantly α-Fe with the presence of carbide and oxide phases. With increasing treatment duration, both the maximum microhardness and the depth of the hardened layer increase. After 7 s of treatment, the microhardness reaches 971.6 HV, while the depth of the zone with increased hardness is approximately 2 mm. Following hardening, the coefficient of friction decreases from approximately 0.748 to 0.574. The obtained results demonstrate the effectiveness of electrolytic-plasma hardening as a rapid method for local surface hardening of 20Cr2Ni4A steel.

***Index Terms*:** Electrolytic-Plasma Hardening, Microstructure, Microhardness, X-Ray Diffraction Analysis, Coefficient of Friction, Surface Hardening.

I. Introduction

Structural steels are widely used in mechanical engineering due to their favorable combination of strength, manufacturability, and relatively low cost. However, wear and fatigue damage in engineering components predominantly initiate in the surface layers, where the highest contact and thermal stresses occur [1,2]. Therefore, improving the service life of such materials is largely associated with the formation of a hardened surface layer while maintaining a tough and ductile core.

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Various surface-hardening techniques are used for steels, including carburizing, nitriding, induction hardening, laser hardening, and other thermochemical and heat-treatment methods [3-7]. Despite their effectiveness, conventional technologies may involve long processing times, relatively high energy consumption, complex equipment, and a risk of thermal distortion [8,9]. In this regard, electrolytic-plasma hardening (EPH) is considered a promising approach because it provides high-rate localized heating of the steel surface in an electrolyte followed by intensive cooling [10,11].

During EPH, a vapor-gas envelope is formed at the metal-electrolyte interface, within which a plasma discharge develops and rapidly heats the surface layer to the austenitizing temperature within several seconds [12-16]. Subsequent rapid cooling promotes the formation of a martensitic structure and a substantial increase in hardness. The thickness and properties of the hardened layer depend on the applied voltage, treatment duration, electrolyte composition, and hydrodynamic conditions [17-19]. Studies on various carbon and low-alloy steels have shown that electrolytic-plasma treatment can increase surface microhardness several times and improve wear resistance due to the formation of a fine martensitic structure [20-26].

Nevertheless, the relationships between short-duration EPH conditions, phase and structural transformations, and the resulting tribological characteristics remain insufficiently understood. Therefore, the aim of this study is to investigate the effect of short-duration electrolytic-plasma hardening on the microstructure, phase composition, microhardness, and tribological properties of 20Cr2Ni4A steel. The novelty of the work lies in establishing the relationship between treatment duration, the formation of a gradient-hardened surface layer, and changes in the mechanical and tribological characteristics of 20Cr2Ni4A steel under rapid electrolytic-plasma heating and subsequent quenching.

II. Materials and Methods

For electrolytic-plasma hardening, 20Cr2Ni4A structural steel, which is compositionally similar to 3316H steel, was used. The specimens were prepared as cubes with dimensions of 20 × 20 × 20 mm. Prior to treatment, the specimen surfaces were ground and polished using an HYMP-2 grinding and polishing machine to a surface roughness of $Ra = 1.0 \pm 0.1$ μm.

Electrolytic-plasma hardening was carried out in an aqueous electrolyte containing 20 wt.% $Na_2 CO_3$ and 10 wt.% urea using a 40 kW installation equipped with a specialized treatment chamber and plasmatron (Fig. 1). The electrolyte was circulated through the plasmatron at a flow rate of 4-7 L/min, while the cooling water circulated through the heat exchanger at 3-6 L/min, maintaining the electrolyte temperature within the range of 50–60 °C. The specimen, connected as the cathode, was positioned 2-3 mm from the plasmatron outlet, while the anode was connected to the positive terminal of the power supply. Hardening was performed at an applied voltage of 320 V for 3, 5, and 7 s, followed by cooling of the specimens in the electrolyte [27].

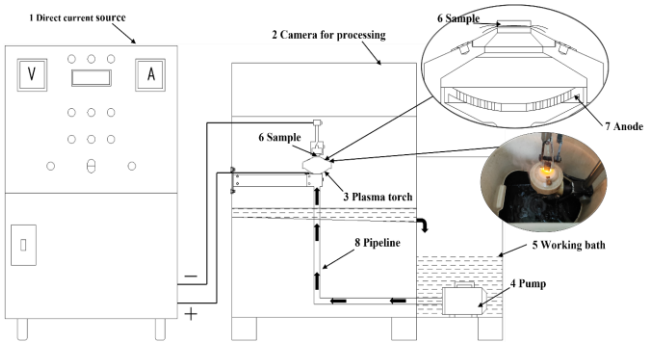


Fig. 1. Experimental setup for electrolytic-plasma hardening of steels.

The phase composition was investigated by X-ray diffraction using an X'Pert PRO PANalytical diffractometer with Cu-Kα radiation (λ = 1.541 Å) over a 2θ range of 30–90° with a step size of 0.02°. The diffraction patterns were processed and analyzed using HighScore Plus software. The surface and cross-sectional microstructures were examined by scanning electron microscopy (SEM) using an SEM3200 microscope after etching in a 4% HNO_3 solution in ethanol.

Microhardness was measured by the Vickers method using a Metolab 502 tester under a load of 10 g and a dwell time of 10 s in accordance with GOST R ISO 6507-1-2007. Tribological tests were carried out on a TRB3 tribometer (Anton Paar) using a ball-on-disk configuration under dry sliding conditions at 25 ± 1 °C, an applied normal load of 10 N, and a sliding speed of 0.05 m/s. A 100Cr6 steel ball was used as the counterbody, and the total sliding distance was 60 m.

III. Results and Discussion

Comparison of the X-ray diffraction patterns of the untreated 20Cr2Ni4A steel, shown in Fig. 2, and the specimen after 7 s of electrolytic-plasma hardening indicates that α-Fe remains the dominant phase in both cases. In the untreated condition, weak diffraction peaks corresponding to the carbide phases Fe_3 C and FeC are also observed. After treatment, in addition to the α-Fe reflections, peaks attributed to Fe_2 C and FeO appear, indicating structural and phase transformations in the surface layer caused by short-duration plasma heating followed by intensive cooling. The formation of the oxide phase is likely associated with interaction of the heated surface with the electrolyte and the vapor–gas envelope. These results indicate the formation of a hardened surface layer, while the presence of a martensitic component should be further confirmed by microstructural observations and microhardness measurements.

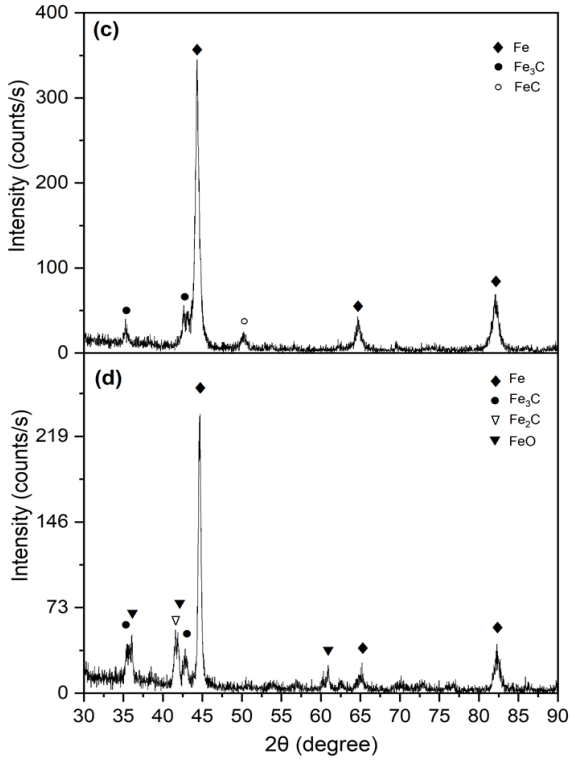


Fig. 2. X-ray diffraction patterns of 20Cr2Ni4A steel: (a) untreated condition; (b) after electrolytic-plasma hardening for 7 s.

SEM analysis of the cross section of 20Cr2Ni4A steel (Fig. 3) after electrolytic-plasma hardening for 7 s revealed the formation of three distinct zones: the hardened zone (I), the transition zone (II), and the unaffected base metal (III). Zone I exhibits a fine needle-like dispersed morphology characteristic of martensitic-type hardened structures. Zone II is characterized by a mixed and heterogeneous structure, reflecting the incomplete phase transformations through the layer thickness. Zone III retains the morphological features of the initial steel condition. These observations indicate the gradient nature of the structural changes occurring under conditions of short-duration plasma heating followed by intensive cooling.

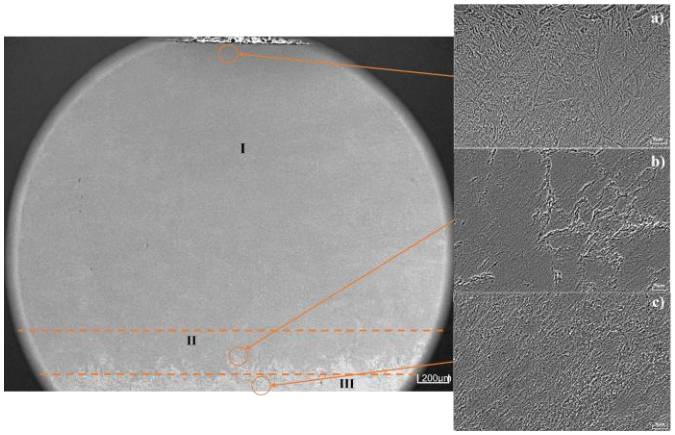


Fig. 3. SEM image of the cross section of 20Cr2Ni4A steel after electrolytic-plasma hardening for 7 s: I – hardened zone; II – transition zone; III – unaffected base material; (a) microstructure of zone I; (b) microstructure of zone II; (c) microstructure of zone III.

As shown in Fig. 4, the microhardness of 20Cr2Ni4A steel increases significantly with increasing electrolytic-plasma hardening duration. After 3 s of treatment, the maximum microhardness is approximately 698 HV; after 5 s, it reaches about 791 HV; and after 7 s, it increases to approximately 971,6 HV. At the same time, the depth of the hardened layer also increases, from about 0.6–0.7 mm after 3 s to approximately 2.0 mm after 7 s. At greater depths, the microhardness gradually decreases to 250–300 HV, corresponding to the untreated base material. These results confirm the formation of a gradient-hardened layer and are in good agreement with the SEM observations of the hardened zone, transition zone, and unaffected base material.

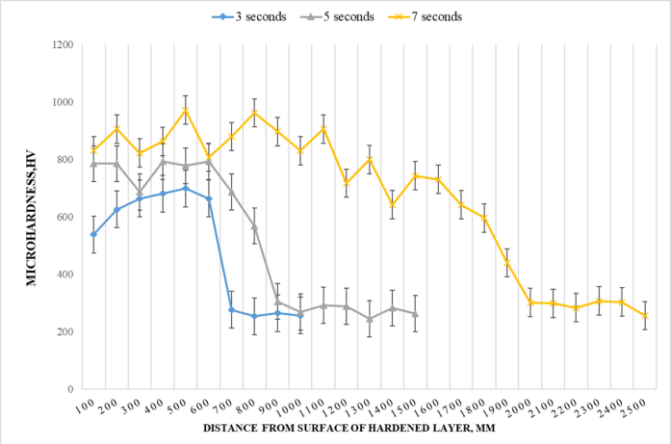


Fig. 4. Microhardness distribution as a function of depth in 20Cr2Ni4A steel after electrolytic-plasma hardening for 3, 5, and 7 s.

After electrolytic-plasma hardening, the coefficient of friction of 20Cr2Ni4A steel decreases compared with the untreated condition (see Fig. 5). For the untreated specimen, after the running-in period, the coefficient of friction stabilizes at approximately $\mu = 0.748$, whereas for the hardened specimen it is predominantly around $\mu = 0.574$. The reduction in the coefficient of friction is associated with the formation of a high-hardness surface layer and a decrease in plastic deformation within the contact zone. These results are consistent with the observed increase in microhardness and the formation of a hardened martensitic-type structure after electrolytic-plasma hardening.

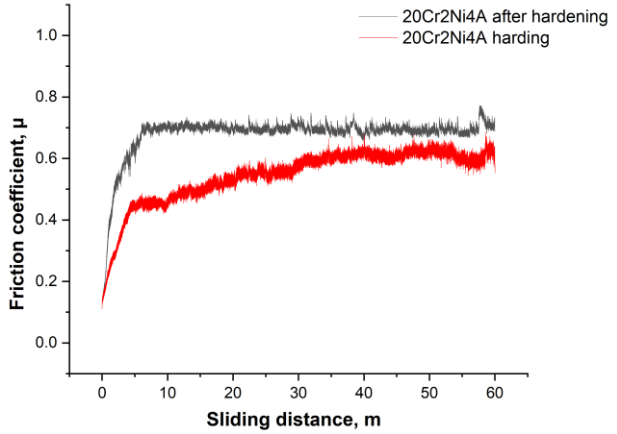


Fig. 5. Coefficient of friction as a function of sliding distance for 20Cr2Ni4A steel in the untreated condition and after electrolytic-plasma hardening.

IV. Conclusion

This study investigated the effect of short-duration electrolytic-plasma hardening on the structural and phase state, microhardness, and tribological characteristics of 20Cr2Ni4A structural steel. It was established that electrolytic-plasma treatment leads to the formation of a pronounced gradient-hardened layer consisting of a hardened zone, a transition zone, and the unaffected base material. SEM analysis revealed the formation of a fine needle-like martensitic-type structure in the surface region, while X-ray diffraction analysis showed changes in the phase composition, with the α-Fe matrix retained and carbide and oxide phases present.

With increasing treatment duration, both the microhardness and the depth of the hardened layer increased. After hardening for 7 s, the maximum microhardness reached approximately 971.6 HV, while the depth of the zone with increased hardness was about 2 mm. In comparison, the microhardness of the untreated material was approximately 255 HV. Tribological tests also demonstrated a beneficial effect of the treatment: after electrolytic-plasma hardening, the coefficient of friction decreased to approximately 0.574 compared with 0.748 for the untreated steel.

Electrolytic-plasma hardening provides rapid local strengthening of 20Cr2Ni4A steel, simultaneously increasing the hardness of the surface layer and improving its tribological characteristics. The most pronounced effect within the investigated range of processing conditions was obtained at a treatment duration of 7 s. Therefore, this regime can be considered promising for the surface hardening of machine components operating under conditions of intensive friction and wear.

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