https://doi.org/10.53360/2788-7995-2025-3(19)-22

IRSTI: 53.49.05

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PHYSICAL FOUNDATIONS OF THE FORMATION OF A STRENGTHENED STRUCTURE OF STRUCTURAL STEELS DURING ELECTROLYTIC-PLASMA HARDENING

Abstract: *This article presents the results of a comprehensive study on the effect of electrolytic-plasma hardening (EPH) on the microstructure and mechanical properties of structural steel grade St4. This steel is widely used in heavy engineering and railway transport, where components operate under conditions of severe wear and variable loads, which highlights the relevance of developing effective strengthening methods. The experiments were carried out on specimens cut from a railway wheel rim, which makes the obtained results practically significant. The treatment was performed in an electrolyte consisting of 10% urea + 20% sodium carbonate + 70% water. The EPH regime included a voltage of 280 V, a current of 40 A, and a treatment duration of 9 seconds. This regime provided rapid heating of the surface layer to the austenitic state followed by instantaneous quenching in the electrolyte. Investigations carried out using scanning electron microscopy and metallographic analysis revealed that after EPH, the surface layer with a thickness of 1.0–1.5 mm consisted of a characteristic needle-shaped martensitic structure. Microhardness measurements confirmed a significant strengthening effect: the hardness increased fourfold from 200 HV to 800 HV. The substantial increase in hardness was accompanied by improved wear resistance and crack resistance, while maintaining the plastic properties of the material core. The obtained results demonstrate the high efficiency of EPH as an environmentally friendly and energy-saving local heat treatment method, which can be recommended to enhance the operational reliability and service life of critical components made of St4 structural steel.*

Key words: *electrolytic-plasma hardening, St4 steel, microstructure, microhardness, martensite, wear resistance.*

Introduction: Structural steels hold a key position among the materials used in mechanical engineering, construction, and related industries. This is due to their optimal combination of strength, ductility, processability, and relatively low cost. However, during operation, these materials are subjected to intense mechanical and corrosive influences, including abrasive wear, cyclic loads, and aggressive environments. This significantly reduces the service life of machine parts and components, necessitating the search for effective surface hardening methods aimed at enhancing their durability and operational reliability [1].

In recent decades, the method of electrolytic-plasma hardening (EPH), based on the high-speed heating of the metal surface layer due to the formation of a vapor-gas envelope when an electric current is passed through an electrolyte [2], has been actively developed. Micro-discharges occur on the sample surface, causing local heating, followed by rapid cooling in the same electrolyte. This mechanism ensures the formation of a fine-dispersion hardened structure, particularly martensite, while simultaneously preserving the ductile properties of the material's core. The method is advantageously different from traditional heat treatment methods: it allows for local hardening of specific zones of a part, is characterized by high heating and cooling rates (on the order of seconds), low energy consumption, environmental friendliness, absence of deformation, and the ability to process parts of complex shapes and large-sized products.

For example, in study [3], hardening of steel 45 was carried out using an electrolyte based on a 20% sodium carbonate solution. The authors applied a voltage of 270-280 V and a holding time of 7-8 seconds. As a result of the treatment, the microhardness of the surface layer increased by 3.1-3.62 times compared to the initial state, and wear resistance increased by 7 times. The structure of the hardened layer consisted of uniformly distributed martensite, the formation of which was due to the high heating and quenching rates. This research demonstrated that EPH ensures not only an improvement in the surface strength characteristics but also a significant increase in the part's resistance to wear during operation.

In another study [4], the subject of research was steel 40KhN. Experiments were conducted using an electrolyte containing 15% sodium carbonate, with a holding time of about 3 seconds. The authors recorded a twofold increase in the microhardness of the treated samples compared to the initial state, as well as a 70% reduction in wear intensity. It was additionally noted that under such conditions, uniform formation of the hardened layer is achieved without thermal damage to the core, which is an important factor for the operation of structural parts.

Thus, electrolytic-plasma hardening is an effective and promising method for the surface hardening of structural steels [5]. It allows for combining high hardness, wear resistance, and corrosion resistance of treated parts with the preservation of the core's ductile properties. However, the task of studying the physical mechanisms underlying the formation of the hardened structure during EPH remains relevant. Establishing the patterns of phase transformations and the influence of processing parameters on the formation of hardened layers is a necessary condition for developing optimal hardening regimes for various grades of structural steels, including widely used cast alloys such as St4.

Research Methods

Experimental research and testing were conducted at the Engineering Center of the "Шәкәрім Университет" Non-Commercial Joint-Stock Company, Kazakhstan. The subject of the research was St4. The steel sample was cut from the bandage of a railway wheel in the form of a parallelepiped with dimensions of 15×15×10 mm³. At low cutting speeds and low load, the sample did not experience deformation or thermal impact. According to GOST 380-2005, the chemical composition of St4 is given below in Table 1. Surface hardening was carried out in an electrolyte with the composition: 10% urea $(NH_2)_2CO$ + 20% sodium carbonate Na_2CO_3 + 70% water for 9 seconds, at a temperature of 850-900 °C, a voltage of 280 V, and a current of 40 A.

Table 1

C	Si	Mn	P	S	Cr	Ni	Cu	As	Fe
0,18-0,27	0,15-0,3	0,4-0,7	< 0,05	< 0,05	< 0,30	< 0,30	< 0,30	< 0,08	Balance

Scanning Electron Microscopy (SEM) on a TESCAN VEGA Compact instrument was used to study the microstructure and phase composition of St4 after EPH treatment. This instrument allows for a detailed study of the material's surface morphological changes, including the identification of characteristic structural elements, phase inclusions, and the distribution of alloying elements.

The microhardness measurement of the samples in their initial state, as well as after hardening, was performed on an HV-1 DT Vickers microhardness tester with an indenter load of P=1 N and a dwell time under load of t = 10 s for all samples.

A metallographic microscope Altami 5C (Russian Federation) with adjustable lighting capabilities was used to study the microstructure of the samples.

Results and Discussion

The surface of the St4 steel in its initial state is characterized by a typical equilibrium ferrite-pearlite structure formed during the slow cooling process after hot rolling. The microstructure presents a distinct two-phase structure, consisting of light ferritic and dark pearlitic areas (Fig. 1).

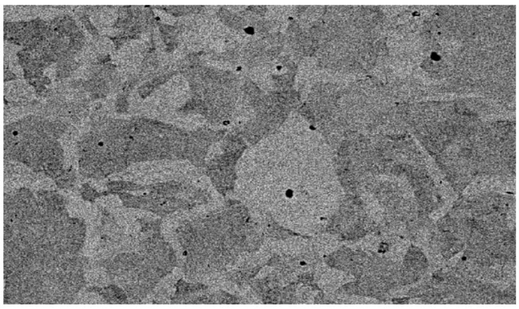

Figure 1 – Microstructure of St4 before EPH

The ferritic regions, which constitute the main matrix of the material, appear light in color after etching and represent a solid solution of carbon in α-iron with a body-centered cubic lattice. These areas are characterized by low hardness and high ductility.

The pearlitic formations, appearing as dark zones, are a mixture consisting of alternating plates of ferrite and cementite. This structural constituent provides higher strength characteristics compared to ferrite.

The microstructure demonstrates a pronounced banding (rolling texture), where the structural constituents are elongated in the direction of deformation. This type of structure is characteristic of the hot-rolled condition and is determined by the manufacturing technology of the initial product – the bandage of a railway wheel.

The absence of signs of thermal impact and deformation confirms the preservation of the initial structure after sample cutting, which ensures the correctness of subsequent studies on the influence of electrolytic-plasma hardening on microstructure transformation.

After electrolytic-plasma hardening conducted at 850-900°C for 9 seconds with subsequent intensive cooling in the electrolyte medium, the surface microstructure of St4 steel undergoes complete transformation (Fig. 2). The initial ferrite-pearlite structure is replaced by acicular martensite with characteristic lath morphology.

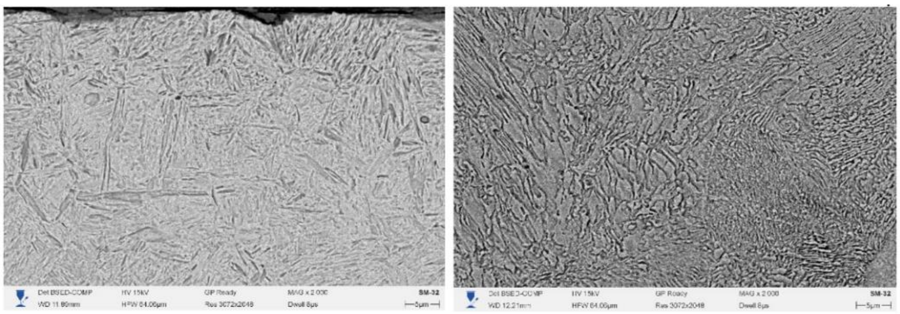

Figure 2 – Microstructure of St4 after EPH

Heating the surface to temperatures of 850-900 °C for 9 seconds leads to a phase transition of α-iron (ferrite) into γ-iron (austenite) with the dissolution of carbide phases. The subsequent intensive cooling in the electrolyte medium ensures a high rate of heat removal, which is critical for suppressing the diffusion processes of austenite decomposition.

As a result, a diffusionless martensitic transformation occurs, characterized by a shear mechanism of crystal lattice rearrangement from face-centered cubic (austenite) to body-centered tetragonal (martensite). The martensitic structure manifests itself in the form of characteristic acicular or plate-like formations observed during microscopic analysis.

The conducted studies showed that electrolytic-plasma hardening of St4 steel leads to significant strengthening of the surface layer. According to the data presented in Figure 3, the initial microhardness of the material was approximately 200 HV. After treatment by the EPH method, the microhardness value reached 800 HV, demonstrating an almost fourfold increase in this indicator.

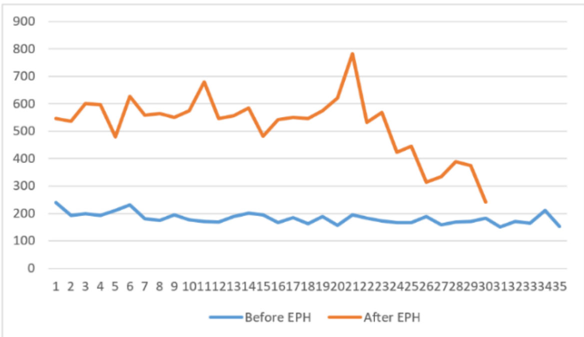

Figure 3 – Microhardness HV

The conducted studies have shown that electrolytic-plasma hardening of St4 steel leads to significant strengthening of the surface layer. According to the data presented in Figure 3, the initial microhardness of the material was approximately 200 HV. After treatment using the EPH method, the microhardness value reached 800 HV, demonstrating an almost fourfold increase in this indicator.

Such a substantial increase in hardness is accompanied by an improvement in a complex of operational characteristics, including enhanced crack resistance and wear resistance of the treated surface. The established pattern confirms the effectiveness of using electrolytic-plasma hardening for the surface strengthening of low-carbon St4 steel.

The microhardness measurement results are consistent with microstructural studies, which revealed the formation of a martensitic structure in the surface layer after treatment. The obtained data demonstrate the promise of applying EPH to improve the operational characteristics of products made from St4 steel.

Conclusion

The conducted research confirmed the high efficiency of electrolytic-plasma hardening for strengthening the surface layer of St4 steel. Treatment in the mode of 280 V, 40 A, 9 s at a temperature of 850-900 °C ensured the formation of fine-acicular martensite and complete disappearance of the initial ferrite-pearlite structure.

The microhardness measurement results showed an increase from 200 HV to 800 HV, indicating a fourfold growth in hardness. This was accompanied by improvements in operational characteristics, including wear resistance and crack resistance of the surface.

EPH is a promising method for processing critical components operating under conditions of wear and cyclic loads. The method combines high processing speed, environmental friendliness, and the capability of hardening complex-shaped parts. Further research should be directed toward optimizing treatment parameters for other grades of steel.

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КОНСТРУКЦИЯЛЫҚ БОЛАТТАРДЫҢ ЭЛЕКТРОЛИТ-ПЛАЗМАЛЫҚ ШЫНЫҚТЫРУ КЕЗІНДЕ НЫҒАЙТЫЛҒАН ҚҰРЫЛЫМЫНЫҢ ҚАЛЫПТАСУЫНЫҢ ФИЗИКАЛЫҚ НЕГІЗДЕРІ

Аңдатпа: *Мақалада Ст4 маркалы конструкциялық болаттың микроструктурасы мен механикалық қасиеттеріне электролит-плазмалық шынықтырудың (ЭПШ) әсерін кешенді зерттеу нәтижелері келтірілген. Бұл болат ауыр машина жасау мен теміржол көлігінде кеңінен қолданылады, онда бөлшектер қарқынды тозу мен ауыспалы жүктемелер жағдайында жұмыс істейді, бұл оны тиімді шынықтыру әдістерін әзірлеудің өзектілігін айқындайды. Тәжірибелер теміржол дөңгелегінің бандажынан кесіп алынған үлгілерде жүргізілді, бұл алынған нәтижелерді практикалық маңызды деп қарастыруға мүмкіндік береді. Өңдеу құрамы: 10 % карбамид + 20 % натрий карбонаты + 70 % су болатын электролитте жүргізілді. ЭПШ режимі 280 В кернеуді, 40 А ток күшін және 9 секундтық әсер ету уақытын қамтыды. Мұндай режим беткі қабатты аустениттік күйге дейін жоғары жылдамдықпен қыздыруды және электролитте лезде салқындатуды қамтамасыз етті. Сканирлеуші электрондық микроскопия және металлографиялық талдау әдістерімен жүргізілген зерттеулер ЭПШ-дан кейін қалыңдығы 1,0–1,5 мм болатын беткі қабатта инелі мартенситтің құрылымы қалыптасатынын көрсетті. Микроқаттылықты өлшеулер беріктіктің айтарлықтай артқанын растады: көрсеткіш 200 HV-ден 800 HV-ге дейін төрт есе өсті. Қаттылықтың айтарлықтай өсуі материал өзегінің пластикалық қасиеттерін сақтай отырып, тозуға және жарықшаққа төзімділіктің артуымен қатар жүрді. Алынған нәтижелер ЭПШ-ның экологиялық таза және энергия үнемдейтін жергілікті термоөңдеу әдісі ретінде жоғары тиімділігін дәлелдейді және оны Ст4 болатынан жасалған жауапты бөлшектердің сенімділігі мен ұзақ қызмет ету мерзімін арттыру үшін қолдануды ұсынады.*

Түйін сөздер: *электролит-плазмалық шынықтыру, Ст4 болаты, микроструктура, микроқаттылық, мартенсит, тозуға төзімділік.*

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ФИЗИЧЕСКИЕ ОСНОВЫ ФОРМИРОВАНИЯ УПРОЧНЁННОЙ СТРУКТУРЫ КОНСТРУКЦИОННЫХ СТАЛЕЙ ПРИ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОЙ ЗАКАЛКЕ

Аннотация: *В статье представлены результаты комплексного исследования влияния электролитно-плазменной закалки (ЭПЗ) на микроструктуру и механические свойства конструкционной стали марки Ст4. Данная сталь широко используется в тяжёлом машиностроении и железнодорожном транспорте, где детали эксплуатируются в условиях интенсивного износа и переменных нагрузок, что определяет актуальность разработки эффективных методов её упрочнения. Эксперименты проводились на образцах, вырезанных из бандажа железнодорожного колеса, что позволяет рассматривать полученные результаты как практически значимые. Обработка осуществлялась в электролите состава: 10 % карбамид + 20 %*

карбонат натрия + 70 % вода. Режим ЭПЗ включал напряжение 280 В, силу тока 40 А и продолжительность воздействия 9 секунд. Такой режим обеспечил высокоскоростной нагрев поверхностного слоя до аустенитного состояния с последующим мгновенным охлаждением в электролите. Исследования, выполненные методами сканирующей электронной микроскопии и металлографического анализа, показали, что после ЭПЗ в поверхностном слое толщиной 1,0-1,5 мм формируется характерная игольчатая структура мартенсита. Измерения микротвёрдости подтвердили значительный эффект упрочнения: показатель увеличился в четыре раза – с 200 HV до 800 HV. Существенный рост твёрдости сопровождался повышением износостойкости и трещиностойкости при сохранении пластичных свойств сердцевины материала. Полученные результаты демонстрируют высокую эффективность ЭПЗ как экологичного и энергосберегающего метода локальной термообработки, который может быть рекомендован для повышения эксплуатационной надёжности и долговечности ответственных деталей из конструкционной стали Ст4.

Ключевые слова: *электролитно-плазменная закалка, сталь Ст4, микроструктура, микротвёрдость, мартенсит, износостойкость.*

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Received 26.07.2025
Revised 28.08.2025
Accepted 03.09.2025