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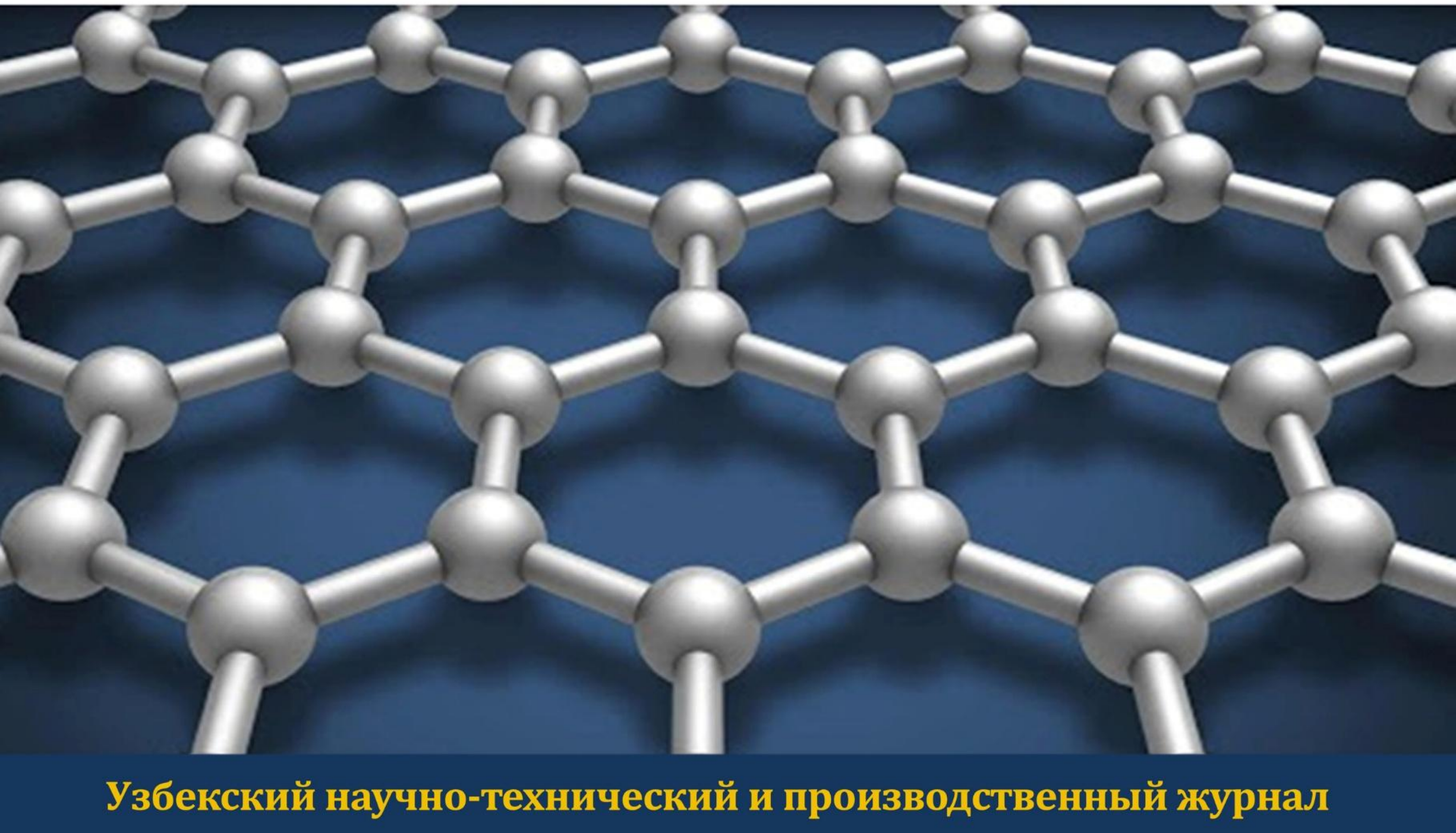

Узбекский научно-технический и производственный журнал

Композиционные материалы

конечный объём образующегося шлама изменяется в широких пределах от 2,47 до 73,13 %. На основе полученных экспериментальных данных была построена номограмма (рис.1), позволяющая определить основные технологические параметры процесса обезмагниевания в зависимости от соотношения «обессульфаченная рапа:известковое молоко».

Выводы. Таким образом, в результате проведённых исследований изучен процесс обессульфачивания рассолов месторождений Караумбет дистиллированной жидкостью содового производства с последующим обезмагниеванием известковым молоком. Установлено, что при расходе $CaCl_2$ и $Ca(OH)_2$ в количестве 100–105 % от стехиометрически необходимого по отношению к ионам SO_4^{2-} и Mg^{2+} соответственно, температуре процесса 20–30 °C и продолжительности обработки 60 мин. Остаточное содержание ионов SO_4^{2-} и Mg^{2+} в очищенном рассоле составляет 0,34–0,09 % и 0,30–0,11% соответственно.

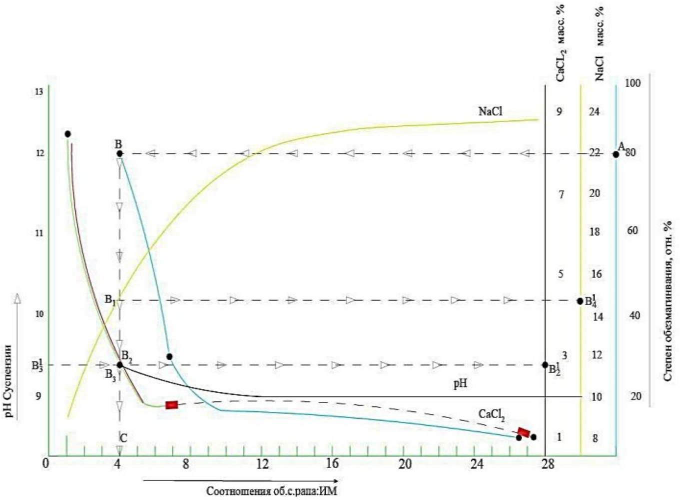

Рис. 1. Номограмма процесса обезмагниевания (обессульфаченная рапа:ИМ)

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MORPHOLOGY OF PHASE CONSTITUENTS AND THEIR STRUCTURAL-FUNCTIONAL IMPLEMENTATION IN CHROMIUM-MOLYBDENUM STEEL AFTER VARIOUS THERMAL TREATMENTS

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Abstract To optimize the microstructural and performance properties of chromium-molybdenum steel in aggressive and low-temperature environments, this study examines the relationship between its phase transformations and heat treatment conditions. The research focuses on analyzing the morphology of primary phase components, structural changes during the doubling process, and the influence of induction heating parameters within the critical intermediate temperature range. It was established that a combined heat treatment regime-consisting of full quenching followed by induction heating-ensures the formation of a dislocation-cell substructure and prevents the formation of un-tempered martensite phases, which negatively affect resistance to sulfide stress corrosion cracking (SSCC). Microstructural and fractographic analyses confirm an improvement in mechanical properties, specifically impact toughness and ductility, compared to traditional single-stage heat treatment. An optimal heating process is proposed that balances recrystallization and substructure preservation, thereby enhancing the operational reliability of chromium-molybdenum steel.

Keywords: chromium-molybdenum steel, phase transformations, critical intermediate temperature range, sulfide stress corrosion cracking, transformation.

Introduction. Chromium-molybdenum steels are widely used in mechanical engineering and the oil and gas industry due to their high strength, excellent toughness, and notable corrosion resistance. These steels are often employed in critical components such as pipelines, pressure vessels, and structural parts that operate under demanding conditions, including high stress, low temperatures, and exposure to aggressive chemical environments. The operational effectiveness and service life of such materials are largely determined by their microstructure, which is primarily formed and controlled during thermal treatment processes [1].

Effective control of phase transformations during heat treatment plays a crucial role in optimizing the microstructure to achieve a balance of strength, ductility, and resistance to sulfide stress corrosion cracking (SSCC). This is especially important for components exposed to hydrogen sulfide (H_2S)-containing environments, where sulfide-induced embrittlement and cracking can lead to premature failure. Moreover, maintaining mechanical integrity at low temperatures requires careful manipulation of phase constituents to prevent brittle fracture mechanisms [2].

Therefore, understanding and controlling the morphology and distribution of phases such as martensite, ferrite, and austenite through precise thermal processing is essential. Advanced heat treatment regimes, including double quenching combined with induction heating in the intercritical temperature range, have shown promise in enhancing both mechanical and corrosion resistance properties. This study focuses on these transformations and their implications for improving the reliability and durability of chromium-molybdenum steels in severe service conditions [3].

Methods. The subject of this investigation was $34CrMo_4$ steel, modified with additional alloying elements including vanadium and chromium, selected for its potential to improve the structural integrity and performance of components operating under abrasive and corrosive conditions. The material was melted and processed under controlled laboratory conditions to simulate industrial practices, and its structural and mechanical behavior was evaluated after various thermal treatments [4].

Chemical Composition and Sample Preparation. The steel used in this study was smelted using a laboratory induction furnace equipped with a graphite crucible. The alloying process was carried out in stages: iron and carbon were melted first, followed by sequential addition of silicon, manganese, chromium, and molybdenum. Copper was added at the final stage to minimize losses due to volatilization. The melt temperature was maintained within the range of 1550–1600 °C to ensure proper dissolution and homogeneity of the alloying elements. Two steel variants were prepared: one experimental composition and one reference alloy for comparative purposes. The final chemical composition was determined using spark optical emission spectroscopy [5].

Heat Treatment Regimes. To investigate the influence of thermal cycles on phase transformations and microstructure, a multistage heat treatment was applied:

1. Complete austenitizing and quenching: heating to 870–900 °C, with a holding time of 1 hour to ensure full austenitization, followed by rapid quenching in oil to form a martensitic matrix.

2. Induction heating in the intercritical temperature range (ITR): controlled heating to 750–780 °C using a medium-frequency induction unit, targeting partial austenite reformation and refinement of the microstructure.

3. Tempering: final thermal exposure at 600 °C for 2 hours, followed by air cooling, to relieve residual stresses and stabilize the microstructure.

The aim of this sequence was to produce a dual-phase microstructure consisting of tempered martensite and finely dispersed carbides, optimizing both hardness and fracture toughness [6].

Microstructural Analysis. Detailed microstructural examination was carried out using both optical microscopy (OM) and scanning electron microscopy (SEM). Metallographic specimens were prepared by standard grinding and polishing procedures, followed by etching in a 4% Nital solution to reveal phase boundaries and carbide morphology. SEM was performed at various magnifications to identify the morphology and distribution of martensitic plates, ferritic regions, and precipitated carbides [7].

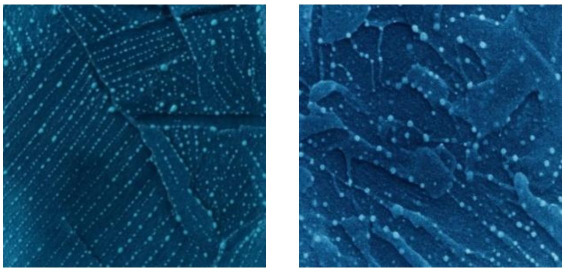
Additional analysis of dislocation substructure and phase interfaces was performed using transmission electron microscopy (TEM) where necessary.

Mechanical Testing. Mechanical properties were evaluated according to standard protocols:

- Ultimate tensile strength, yield strength, and elongation were measured via uniaxial tensile testing at room temperature;
- Impact toughness (KCV) was assessed using Charpy V-notch tests on samples in accordance with ISO 148-1.

All tests were repeated at least three times to ensure statistical significance, and average values were reported.

Results. Complete quenching produces a needle-like low-carbon martensitic structure with noticeable carbon distribution heterogeneity (Fig. 1a).



a b

Fig. 1. Microstructure of 34CrMo4 steel: (a) after complete quenching (needle-like martensite), (b) after induction heating in the intercritical range (dispersed austenite and residual ferrite formation)

Bright needles correspond to regions with low carbon content formed during rapid cooling in the two-phase region.

Induction heating within the ITR (Fig. 1b) results in coherent austenite nuclei forming within the α-phase, while residual ferrite remains in low-carbon areas. Austenite growth via diffusion involves carbon redistribution and impedes phase boundary migration.

Double quenching with heating in the ITR significantly improves impact toughness and ductility compared to single quenching (Table 1).

Table 1.

Comparative evaluation of mechanical properties of chromium-molybdenum steel depending on the heat treatment regime

Heat treatment regime	Ultimate tensile strength, MPa	Yield strength, MPa	Elongation, %	Impact toughness, J/cm²	Ductile fracture portion, %
Complete quenching + itr + tempering	541	431	32.8	225	100
Complete quenching + tempering	597	483	28.2	78.6	20

SSCC testing showed that for double quenching, the threshold stress is 75% of $\sigma_{0.2}$ with less than 5% ductility loss. For single quenching, the threshold decreases to 65% with ductility loss up to 70%. Fractographic analysis revealed a transition from brittle intergranular fracture (single quenching) to ductile dimple fracture (double quenching), as shown in Fig. 2.

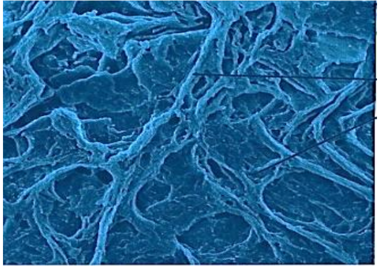


Fig. 2. Fractographic analysis of fracture after quenching above Ac3 and tempering, exposed to H_2S at 65% of $\sigma_{0.2}$; magnification ×1800

Substructure retention. Microstructural analysis demonstrated that after double quenching and heating in the ITR, the dislocation-cell ferrite substructure formed during hot plastic deformation is preserved, while austenite grains do not inherit the needle-like martensitic morphology. This indicates a balance between recrystallization and substructure retention, enabling combined strengthening.

Discussion. The results confirm that complex heat treatment with double quenching and induction heating in the intercritical temperature range is an effective method for controlling phase transformations and structural organization in chromium-molybdenum steel. This regime avoids the formation of unwanted non-martensitic phases and promotes the formation of a dispersed, highly strengthened microstructure with improved ductility and corrosion resistance. The optimal heating temperature range (750–780°C) ensures equilibrium between recrystallization and substructure retention, which is critical for enhancing service reliability.

Conclusion. Comprehensive thermal treatment of chromium-molybdenum steel involving double quenching and subsequent induction heating in the intercritical temperature range forms a microstructure with enhanced mechanical and corrosion-resistant properties. This approach expands the applicability of the steel in low-temperature and aggressive environments.

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