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Effect of multi-stage heat treatment regime parameters on the structure and mechanical properties of modified 35HML chromium-molybdenum steel

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Abstract: This paper presents the results of a comprehensive experimental study of the effect of multi-stage heat treatment regime parameters on the structure and mechanical properties of modified cast chromium-molybdenum steel 35HMЛ, used in the manufacture of cast parts for mining excavators at JSC “Almalyk Mining and Metallurgical Combine”. The melt was modified with a complex Fe-V-Al-Ca ferroalloy composition (V 25–30 %, Al 15–20 %, Ca 5–10 %, balance Fe) in an amount of 0.15–0.18 wt. %, introduced into the ladle onto the metal stream at a temperature not below 1520 °C. A four-stage heat treatment scheme was developed: homogenizing annealing at 880 °C → normalization at 880 °C → quenching from 850 °C in preheated water at 60 °C → high tempering at 600–650 °C. The choice of preheated water at 60 °C as the quenching medium is experimentally justified by comparison with industrial oil И-20A: both media provide practically identical hardness (62 HRC versus 61.5 HRC), while preheated water reduces the proportion of castings rejected due to cracks from 12 % to 2 %. The dependence of hardness on tempering temperature in the range of 450–650 °C was established, and the recommended range of 600–650 °C was justified, excluding the zone of type II temper embrittlement (450–550 °C). The developed technology was implemented at the Central Repair and Mechanical Plant (CRMZ) of JSC “AMMC” (Implementation Certificate No. SL-355/1 dated April 16, 2025), providing a 35 % increase in Charpy impact toughness (from 540 ± 22 to 730 ± 31 kJ/m²) and an increase in the service life of ЭКГ-10 excavator support wheels from 2800 to 4200 hours.

Keywords: 35HML steel, complex modification, Fe-V-Al-Ca ferroalloy, multi-stage heat treatment, quenching in preheated water at 60 °C, high tempering, Charpy impact toughness, abrasive wear resistance, cast parts for mining excavators

1. Introduction

Increasing the service life and operational reliability of cast parts for mining excavators, crushing-and-grinding and ore-dressing equipment operating under conditions of intense impact-abrasive wear is one of the priority engineering tasks of the mining and metallurgical industry of Uzbekistan. At JSC “Almalyk MMC” — the country’s largest mining and metallurgical enterprise — the bulk of cast parts for ЭКГ-type excavators and ball-mill liners are made of chromium-molybdenum steel 35HML (analogous to AISI 4135).

In the as-cast state, this steel is characterized by a coarse dendritic structure, segregation heterogeneity, and uneven distribution of the carbide phase, which significantly limits its service life. Traditional single-stage heat treatment does not ensure uniformity of structure and properties across the cross-section of massive cast parts of complex configuration.

A promising approach is the combination of complex melt modification with the Fe-V-Al-Ca ferroalloy composition, which provides a synergistic combination of modifying (V), deoxidizing (Al), and refining (Ca) effects, with a scientifically substantiated multi-stage heat treatment scheme. The choice of quenching medium plays a critically important role: industrial oils are environmentally unsafe and expensive, while cold water leads to high quenching stresses and crack formation in massive castings.

The aim of this work is the experimental substantiation of the multi-stage heat treatment regime parameters of modified chromium-molybdenum steel 35HMЛ — including homogenizing annealing, normalization, quenching in preheated water at 60 °C, and high tempering — ensuring an optimal combination of strength, hardness, and impact toughness of cast parts for mining equipment.

2. Research methodology

Material and complex modifier. The object of the study is cast chromium-molybdenum steel 35HML of average chemical composition (wt. %): 0.40 C; 0.51 Si; 0.73 Mn; 1.05 Cr; 0.20 Mo. The melt was modified with the Fe-V-Al-Ca ferroalloy composition (Fe 35–40 %, V 25–30 %, Al 15–20 %, Ca 5–10 %), introduced into the ladle onto the metal stream at T ≥ 1520 °C in an amount of 0.15–0.18 wt. % with subsequent holding for 3 min. Spectral analysis confirmed the multifunctional action of the modifier: sulfur content decreased by 43 % (from 0.028 to 0.016 wt. %), total oxygen by 61 % (from 0.0072 to 0.0028 wt. %); the steel was enriched with V (0.033 %), Al (0.029 %), and Ca (0.0025 %).

Multi-stage heat treatment. A four-stage scheme was applied: (1) homogenizing annealing at 880 °C with slow furnace cooling at a rate of 30–50 °C/h down to 500 °C; (2) normalization at 880 °C (1 min per 1 mm of cross-section, air cooling); (3) quenching from 850 °C in preheated water at 60 °C; (4) high tempering at 600–650 °C with air cooling. The temperature of the quenching water was monitored with a submersible electronic thermometer (±0.5 °C).

Mechanical testing. Hardness was measured by the Rockwell (HRC) and Brinell (HB) methods. Charpy impact toughness with a V-notch (KCV) was measured on a PIT320T pendulum impact tester (maximum energy 300 J) at +25 °C. Abrasive wear resistance was determined by the Brinell–Haworth scheme on an LR-130B abrasimeter at a load of 78.4 N, a rubber-wheel rotation speed of 200 rpm, and a friction path of 720 m. The abrasive was a mixture of pyrite, chalcopyrite, and molybdenite from the "Kalmakyr" deposit (grain size 0.4 mm, pyrite microhardness up to 1510 kgf/mm²).

Flaw detection and statistics. Quenching cracks were monitored by three methods: visual inspection, the capillary (dye-penetrant) method (GOST 18442-80), and ultrasonic testing on a УД2-70 flaw detector (GOST R 55724-2013). All mechanical test results are presented as the mean ± standard deviation over three parallel specimens in each series. Confidence intervals were calculated at a confidence probability of 0.95 using the Student coefficient $t = 4.303$ for $n - 1 = 2$ degrees of freedom.

3. Results and Discussion

Hardness evolution along the multi-stage route. Fig. 1 shows the change in hardness of modified 35HML steel at the characteristic stages of multi-stage heat treatment. In the as-cast state, the hardness was 53.5 HRC. After homogenizing annealing it decreased to 24.5 HRC. Normalization restored the hardness to 47.5 HRC. Quenching from 850 °C in preheated water at 60 °C provided 62 HRC, which exceeds the value for oil quenching (61.5 HRC). Subsequent high tempering at 650 °C reduced the hardness to 33.5–38.2 HRC depending on the cooling rate.

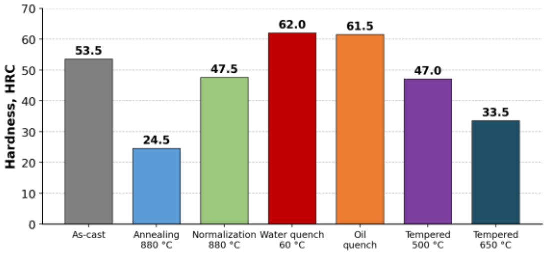

Fig. 1. Hardness evolution of modified 35ХМЛ steel at various stages of multi-stage heat treatment

Comparison of quenching media. A direct experimental comparison of two quenching media was carried out: industrial oil I-20A (from 900 °C) and preheated water at 60 °C (from 850 °C). The microstructure after oil quenching consists of fine-acicular martensite with a hardness of 61.5 HRC. The microstructure after quenching in preheated water at 60 °C exhibits predominantly lath martensite with a hardness of 62 HRC, owing to the increased cooling rate of 200–300 °C/s versus 80–100 °C/s for oil.

The use of preheated water at 60 °C has decisive advantages over cold water. First, heating the water destroys the vapor film, shortening the duration of the film-boiling stage and stabilizing heat removal. Second, the cooling rate in the martensitic transformation range (300–200 °C) is reduced, which decreases quenching stresses and the risk of crack formation in massive castings. Industrial verification confirmed a reduction in the proportion of castings rejected due to cracks from 12 % (cold water) to 2 % (preheated water at 60 °C).

Fig. 2. Monitoring of the quenching medium temperature: thermometer reading of 63.0 °C in the bath with preheated water

Effect of tempering temperature. A detailed series of experiments with tempering temperatures from 450 to 650 °C established a monotonic dependence of hardness on tempering temperature (Fig. 3): 51 HRC at 450 °C, 47 HRC at 500 °C, 36 HRC at 550 °C, and 33.5 HRC at 650 °C. The decrease is associated with the progressive coagulation of the carbide phase and the decomposition of tetragonal martensite. The recommended tempering range of 600–650 °C is justified by two factors: it ensures complete coagulation of the carbide phase and keeps the steel out of the zone of type II temper embrittlement (450–550 °C). For applications where increased hardness is critical, reduced tempering at 450–500 °C with a hardness of 47–51 HRC is permissible.

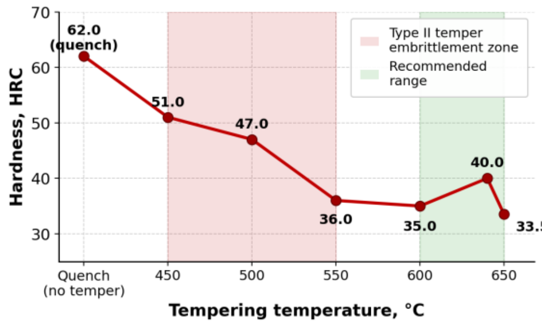

Fig. 3. Dependence of the hardness of modified 35ХМЛ steel on tempering temperature after quenching in preheated water at 60 °C

Comparative mechanical properties. Comparative tests of four groups of specimens (without modifier, FeV, Fe-V-Al-Ca, FeMo) confirmed the pronounced positive effect of complex modification on the mechanical properties of 35HMЛ steel (Table 1). All specimens underwent an identical multi-stage heat treatment cycle: annealing 880 °C → normalization 880 °C → quenching from 850 °C in preheated water at 60 °C → high tempering 600–650 °C.

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Table 1

Mechanical properties of 35ХМЛ steel modified with various ferroalloys (mean ± σ, n = 3)

Modifier	Specific wear, mg/m	ε (rel.)	KCV, kJ/m²	+KCV, %
Without modifier	0.149 ± 0.006	1.000	540 ± 22	—
FeV	0.134 ± 0.005	1.117 ± 0.044	680 ± 28	+26 %
Fe-V-Al-Ca	0.120 ± 0.004	1.244 ± 0.045	730 ± 31	+35 %
FeMo	0.116 ± 0.004	1.289 ± 0.046	800 ± 34	+48 %

The complex Fe-V-Al-Ca modifier provides an optimal combination of properties at moderate cost: although FeMo demonstrates marginally better individual indicators, its cost is substantially higher and its modifying effect is monofunctional. Fe-V-Al-Ca simultaneously refines the primary structure (via V(C,N) carbonitrides), deeply deoxidizes the melt (Al → Al_2O_3), and modifies the morphology of non-metallic inclusions (Ca → globular sulfides).

Industrial implementation and economic effect. The developed technology was introduced into the production practice of the CRMZ of JSC "Almalyk MMC" (Implementation Certificate No. SL-355/1 dated 16.04.2025). Technological Regulation TR 001.18-04:2025 was developed and approved. The service life of ЭКГ-10 excavator support wheels was increased from 2800 to 4200 hours (+50 %). The annual economic effect per ЭКГ-10 excavator amounts to 31.6 million UZS due to the reduction in the number of replacements from 2.32 to 1.55 per year. The total annual economic effect for the ЭКГ-10 excavator fleet (12 units) is about 380 million UZS, with a payback period for the capital investment (50 million UZS) of 1.6 months.

4. Conclusion

The parameters of the multi-stage heat treatment regime of cast chromium-molybdenum steel 35XML modified with the complex Fe-V-Al-Ca ferroalloy composition were experimentally substantiated:

1) A scientifically substantiated four-stage heat treatment scheme was developed: homogenizing annealing 880 °C → normalization 880 °C → quenching from 850 °C in preheated water at 60 °C → high tempering 600–650 °C.

2) The use of preheated water at 60 °C as the quenching medium provides hardness equivalent to oil quenching (62 versus 61.5 HRC) at a higher cooling rate (200–300 versus 80–100 °C/s) and reduces the proportion of castings rejected due to cracks from 12 % to 2 % compared with cold water.

3) The dependence of hardness on tempering temperature in the range of 450–650 °C was established. The recommended range of 600–650 °C ensures complete coagulation of the carbide phase and keeps the steel out of the zone of type II temper embrittlement.

4) Comparative tests of four modifier variants confirmed the advantages of Fe-V-Al-Ca: a 35 % increase in impact toughness (540 → 730 kJ/m²) and a relative abrasive wear resistance of up to 1.244 ± 0.045.

5) The technology was implemented at JSC "Almalyk MMC". The annual economic effect is about 380 million UZS with a payback period of 1.6 months.

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