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Thermomechanical methods of hardening chromium-molybdenum steel products

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Abstract: The article discusses the results of research dedicated to the thermomechanical processing of products made from chromium-molybdenum steel, similar to grade 35ХМЛ, but modified with vanadium as a modifier. The experiments were conducted under serial production conditions with the aim of improving the technological process. Within the framework of the study, a method was implemented where the forging process was combined with subsequent heat treatment, performed immediately after forging at a specialized station. This approach eliminates the need for re-heating of products, which significantly reduces energy consumption and enhances production efficiency.

During the cooling process of the products, it is necessary to maintain the optimal temperature regime to ensure a controlled exothermic phase transformation of austenite into pearlite. This allows for the formation of a balanced ferrite-pearlite structure, which provides the necessary mechanical properties, including the required hardness range.

The test results confirmed that the correct selection of the isothermal annealing temperature regime contributes to achieving stable operational characteristics of the products. The implementation of this technology in industrial production will significantly reduce energy consumption—by more than 80% compared to traditional heat treatment methods. In addition, eliminating re-heating reduces the overall manufacturing time, which contributes to increased productivity and a decrease in production costs.

Thus, the proposed technological method not only enhances the energy efficiency of production but also ensures the production of products with predictable mechanical properties. Its application in industry could

play a key role in optimizing the processing of chromium-molybdenum steels, which is particularly important in the context of the drive to reduce costs and rational use of resources.

Keywords: Chromium-molybdenum steels, modifier, mechanical properties, heat treatment, strength, impact toughness, corrosion resistance, microstructure, grain structure, carbides, wear resistance, heat resistance, oil and gas industry, energy, alloying, economic efficiency, structural materials, durability, metallography, high-quality materials.

Introduction: The industrial sector of Uzbekistan's economy faces a number of challenges that require the use of materials with a unique combination of characteristics: high strength, corrosion resistance, heat resistance, and durability. In the context of growing technological complexity and competition, chromium-molybdenum steels hold a special place due to their reliability and versatility. These alloyed steels possess outstanding mechanical and operational properties, making them indispensable in critically important industries.

Main Areas of Application

Thanks to their unique chemical composition, chromium-molybdenum steels are widely used in various sectors:

Energy – They are used for manufacturing equipment that operates under extreme conditions, such as boilers, heat exchangers, pipelines, and turbine components. These materials can withstand high temperatures, pressure, and aggressive environments, ensuring a long service life.

Mining and Metallurgical Industry and Mechanical Engineering – Used for producing parts subjected to significant loads, such as gears, shafts, axles, and housing components. Their high strength and wear resistance enhance the reliability of equipment.

Oil and Gas Industry – Used in the production of pipelines, compressors, storage tanks, and drilling equipment, which can withstand high pressures, abrasive impacts, and corrosive environments.

Chemical and Petrochemical Industry – Due to their resistance to aggressive substances, they are used to manufacture storage tanks, reactors, and pipelines.

Aerospace and Defense Industry – Used in the production of aircraft engines and armored components that can withstand high temperatures and loads.

One of the ways to save energy by implementing technological processes consecutively is through direct forging hardening (DFQ) or direct heat treatment (DHT) processes, which reduce heat energy consumption by almost 20% by eliminating the reheating stage [16]. Other examples confirm the feasibility of simplified heat treatment immediately after hot forging [17].

In this context, direct heat treatment can significantly reduce energy consumption. Therefore, research is being conducted to develop technologies that combine metal forming with heat treatment, without cooling and reheating products made from modified chromium-molybdenum steel (see Figure 1).

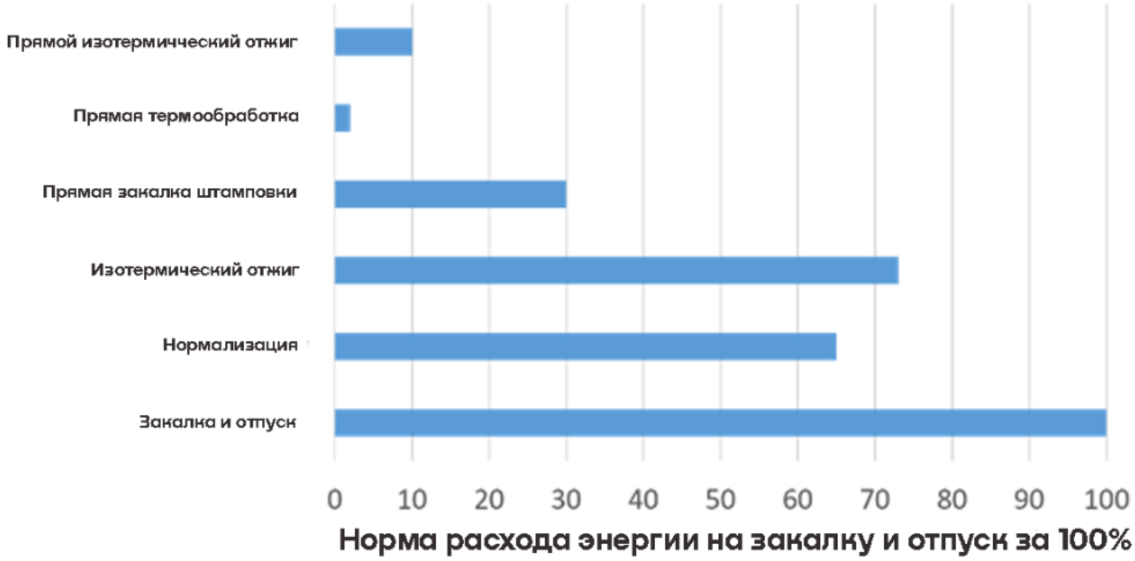

Fig. 1**. Dependence of energy consumption on types of heat treatment.**

Energy savings are achieved by eliminating the need for reheating products made from modified chromium-molybdenum steel. In the traditional technological process (Fig. 2a), products are cooled to ambient temperature after forging, then transported to the heat treatment section, where they are reheated above the Ac3 temperature. After annealing, during which the structure acquires a homogeneous austenitic form, the products are moved to a furnace with a lower temperature to transform the structure into ferrite-pearlite. It is assumed that this transformation is completed fully, so after being removed from the second furnace, the product structure remains unchanged regardless of the cooling rate.

The direct isothermal annealing method (Fig. 2b) simplifies the process. After forging and trimming, the products are cooled only to the annealing temperature and then immediately placed in the furnace. The subsequent processing is identical to the standard method. This approach allows for the use of only one furnace, reducing energy consumption. However, its implementation may require placing the furnace near the forging press and ensuring high thermal processing efficiency, which must match the efficiency of the forging process.

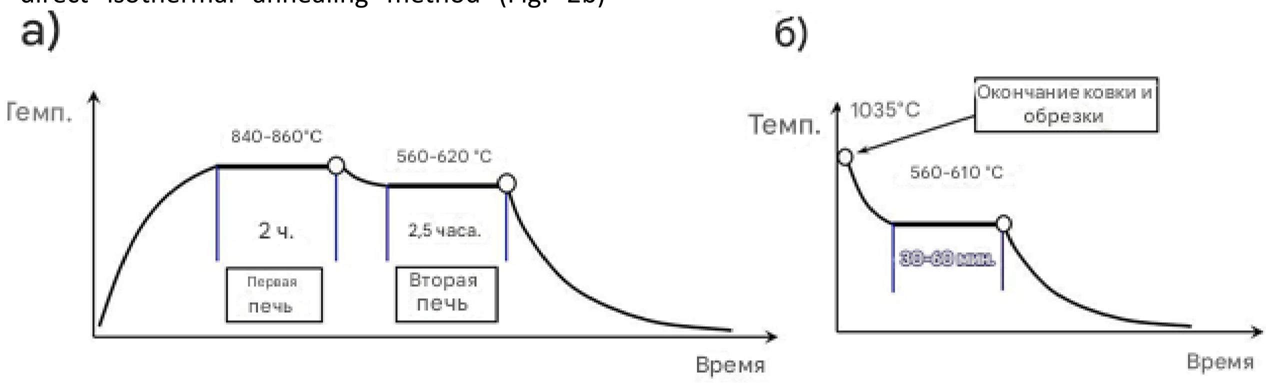

Fig. 2**. a) Heat treatment method with standard isothermal annealing; b) Heat treatment method with isothermal annealing directly after forging.**

Main Problems and Ways to Improve

Despite significant advantages, chromium-molybdenum steels have a number of drawbacks that require further improvement of their composition and manufacturing technology:

Brittleness at low temperatures – Low impact toughness limits their use in cold regions.

Insufficient plasticity – Reduces the material's adaptability and increases the risk of sudden fractures.

Tendency to crack formation – Microcracks that occur under cyclic loads reduce the service life of products.

Limited corrosion resistance – Insufficient resistance in aggressive environments reduces the durability of products.

Insufficient wear resistance – Leads to increased wear of components under friction and abrasive loads.

Processing difficulties – High hardness complicates mechanical processing, increasing production costs.

Sensitivity to heat treatment – Requires strict control to prevent excessive brittleness and residual stresses.

Promising Development Directions

To eliminate the above shortcomings, innovative approaches to improving chromium-molybdenum steels are necessary. One of the most promising directions is the use of modifiers that influence the material's microstructure at the grain level. This allows for:

Improving the strength and plasticity of steel.

Improving the phase composition and mechanical properties;

Expanding the areas of application, including extreme temperature and load conditions.

Modern industry imposes increased requirements for the reliability and durability of materials. Further development of the chromium-molybdenum steel manufacturing technologies will eliminate existing limitations, enhance their operational characteristics, and strengthen their position in the industrial materials market.

Main Objective of the Research

The development of a technology to improve the mechanical properties of chromium-molybdenum steels by introducing a modifier that enhances their strength, plasticity, and other operational characteristics.

The aim of the research is to create a highly efficient material that will serve as the basis for manufacturing reliable and durable structures in high demand across various industrial sectors.

Theoretical Basis of the Research

Chromium-molybdenum steels represent one of the key groups of alloyed steels, widely used in industry due to their unique combination of strength, heat resistance, and corrosion resistance. Some researchers focus on the impact of chromium and molybdenum content on the mechanical properties of the steel. Chromium provides corrosion resistance and forms a protective oxide layer, while molybdenum increases heat resistance and creep resistance.

Experimental Part

The research was conducted on products made from 35XHM chromium-molybdenum steel with the following chemical composition:

Table 1.

Chemical composition of products made from modified chromium-molybdenum steel [%]

C	Mn	Si	P	S	Cr	Ni	Cu	Mo	Al
0,34	0,78	0,29	0,011	0,010	1,07	0,12	0,24	0,16	0,022

The alloy requirements were set to a moderate hardness in the range of 249-280 HV, which facilitated the research tasks and mechanical processing. Therefore, the preferred heat treatment is isothermal annealing, which provides a ferrite-pearlite structure. This structure is easier to process than the tempered martensite structure obtained after quenching and tempering with the same hardness [24].

To achieve the goal of the research – developing a technology to improve the mechanical properties of chromium-molybdenum steels by introducing a modifier – the following methodology was applied:

Preparation of initial materials

Samples of chromium-molybdenum steel with a carefully controlled chemical composition were produced. Analysis was conducted to ensure composition uniformity and eliminate foreign impurities that could affect the results of the experiment.

Addition of modifier

During the experiment, a modifier was selected that affects the microstructure of the steel. Its introduction was carried out directly during the melting process in an optimal dosage, calculated based on preliminary theoretical data and literature sources.

Based on the diagram (Fig. 3) for 35XHM steel, we can determine the approximate temperature range at which the treatment should be carried out to achieve the desired hardness [25]. The temperature to which the charge material is heated is much higher than the temperature of the samples used to create the diagram; however, it can be assumed that the target hardness should be achieved in the range from 560°C to 610°C with an annealing time of no more than 60 minutes.

In this temperature range, we should observe the transformation of austenite into ferrite and pearlite, as well as partial transformation into bainite, the amount of which increases as the isothermal annealing temperature decreases. In addition to temperature, the annealing time is also important; in this regard, the experimental material, placed in the furnace, was extracted after 30 and 60 minutes.

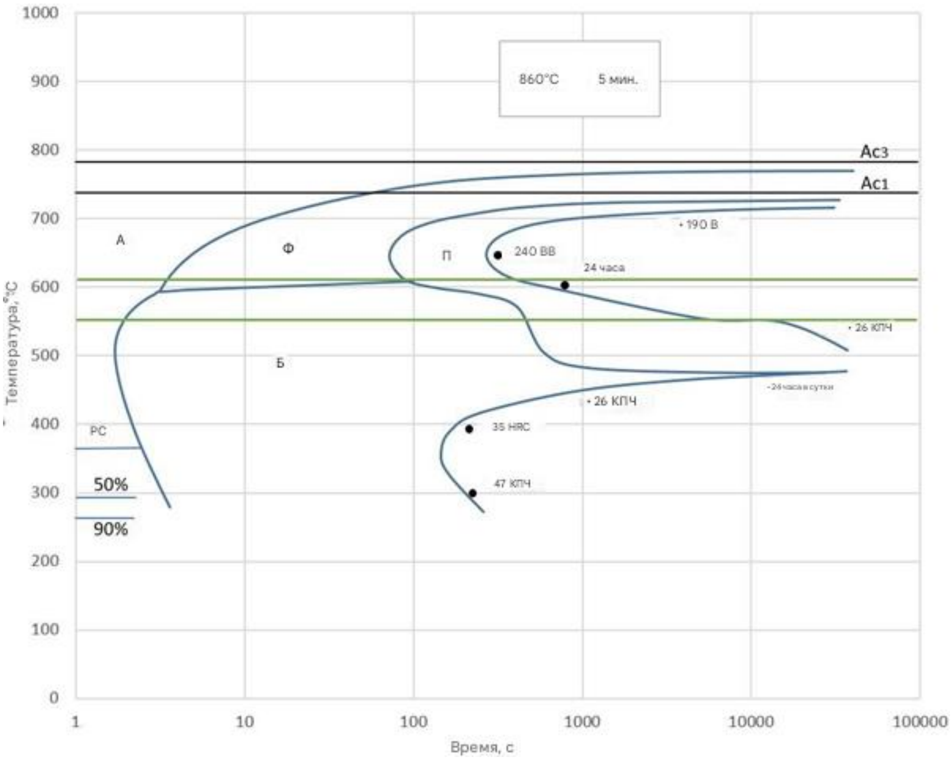

Fig. 3. Diagram for 35XHM steel.

Fig. 4 schematically shows the temperature regime of forging throughout the thermomechanical treatment, along with the points where the temperature was measured. In the first part of the diagram, marked by the black line, the temperature changes during the plastic deformation process are shown – from the beginning of heating, through three forging operations and trimming of the molten material, until the moment the product is placed in the furnace. The second part of the diagram, marked by colored lines, demonstrates the predicted course of the isothermal annealing process. This process could not be measured during the industrial process. However, it can be inferred from the formed microstructure, as heat is released during the phase transformation of austenite to pearlite. This is why the actual temperature of the modified chromium-molybdenum steel products may differ from the temperature of the experimental sample, and this difference is greater the more pearlite was formed during the annealing treatment. The use of modified chromium-molybdenum steel products – the pilot ones – was intended to regulate the temperature in the furnace; however, due to the high thermal inertia of the furnace, an increase in temperature was not observed after the annealing of only two modified chromium-molybdenum steel products.

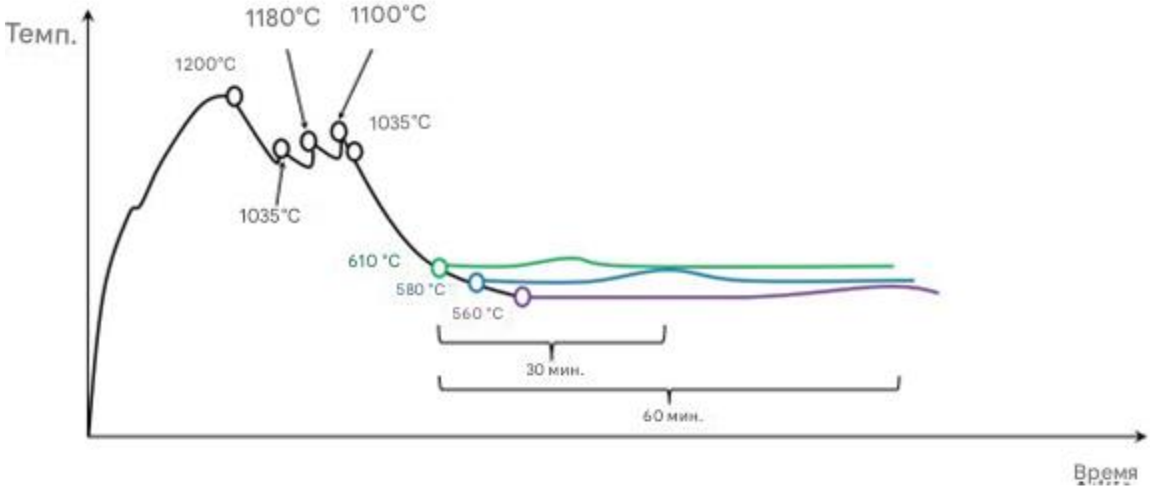

Fig. 4. Dependence of temperature and time regime during thermomechanical treatment.

Forming and Cooling

Molten steel was poured into casting molds to obtain standardized samples, followed by controlled cooling to minimize thermal stresses.

Heat Treatment

The same heat treatment regime was applied to all samples (control and modified):

Quenching: heating to the austenitization temperature followed by rapid cooling to form a martensitic structure.

Tempering: reheating to relieve internal stresses and increase the steel’s ductility.

Mechanical Testing

The following tests were performed to assess improvements:

Tensile test: determining the ultimate tensile strength and yield strength.

Hardness measurement: using the Rockwell method (HRC).

Impact toughness test: on a pendulum impact tester to evaluate resistance to dynamic loads.

Microstructural Analysis

Metallographic analysis was performed using optical and electron microscopes. The following were examined:

Grain size and uniformity of distribution.

Phase composition and number of carbide inclusions.

Presence and distribution of defects in the crystal lattice.

Corrosion Resistance Analysis

Modified samples were subjected to corrosion tests in an aggressive environment to assess their resistance to chemical impacts.

Results Processing

Figure 5 shows the microhardness test results for the investigated cross-sections, performed using the Vickers method with a load of 10N. The required hardness range, after conversion, is from 265 HV to 305 HV, indicated by the black dashed line. For samples tempered at 610°C for 1 hour, most of the measurements fall within the required range. Results for the remaining samples are generally above the required hardness, except for measurements taken directly on the surface of the forging.

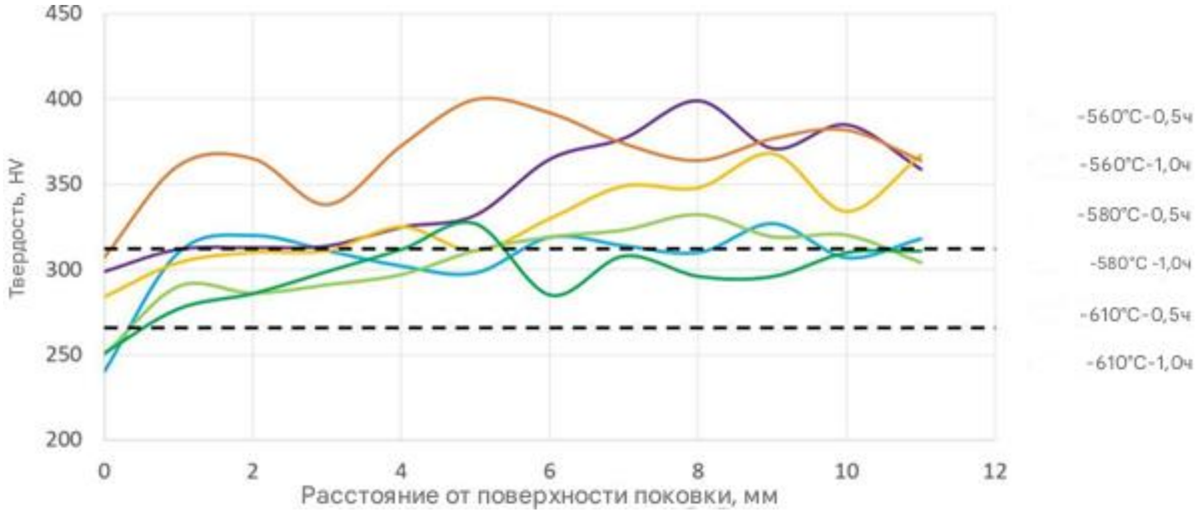

Fig. 5. Hardness (HV) variation across the cross-section in the selected measurement plane for the isothermally annealed sample.

The tests conducted on the chromoly steel samples showed that the introduction of the modifier significantly improved their mechanical properties. A comparison between the control and modified samples demonstrates the following results:

1. Tensile Strength (MPa):
   - Control samples: 850 MPa
   - Modified samples: 970 MPa (+14%)
2. Impact Toughness (J/cm²):
   - Control samples: 30 J/cm²
   - Modified samples: 45 J/cm²
3. Hardness (HRC):
   - Control samples: 25 HRC
   - Modified samples: 32 HRC
4. Corrosion Resistance (Points):
   - Control samples: 3 points
   - Modified samples: 1 point (improved corrosion resistance)

Microstructural Analysis
The microstructure investigation confirmed the positive impact of the modifier:

- Formation of a fine-grained structure, which enhances ductility and impact toughness.
- Reduction in grain size and uniform distribution of carbide inclusions, which improves the wear resistance of the material.

Applications of the Improved Steel
The enhanced chromoly steels can be used in the following industries:

- Energy sector: pipes and vessels under high pressure and temperature.
- Mining industry: machine parts, mill liners, excavator buckets.
- Oil and gas industry: pipelines for aggressive environments.
- Aerospace and automotive industries: engine and transmission components.
- Construction: structures for low-temperature applications.

Effect of Modifiers on Steel Properties

Modifiers have a comprehensive impact on the steel's microstructure, providing:

1. Grain structure refinement – grain refinement improves strength and prevents brittle failure.

2. Phase composition stabilization – uniform distribution of carbide phases increases wear resistance.

3. Reduction of crystal lattice defects – reducing residual stresses prevents cracking.

4. Improved corrosion resistance – the formation of a protective layer increases resistance to aggressive environments.

5. Improved heat resistance – the material retains its properties at high temperatures.

Only the sample annealed at 610°C for 60 minutes (Fig. 6) demonstrated a hardness in the required range of 249-280 HV. It should also be noted that the highest hardness was achieved in the forgings annealed at 580°C, rather than at 560°C, as might have been expected.

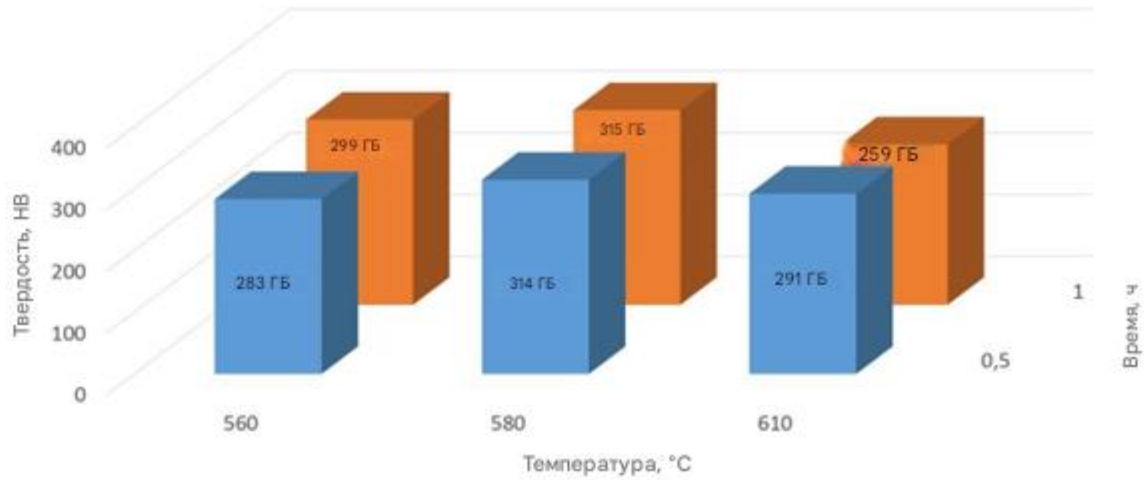

Fig. 6. **Results of Brinell hardness tests for products made of modified chromoly steel at different isothermal annealing times and temperatures.**

Final Results

Experimental studies showed that the use of the modifier allows achieving the following:

– A 10-15% increase in strength.

– A 20-25% increase in impact toughness.

– A 30% reduction in wear during friction.

– A 40-50% extension in equipment service life.

Thus, the application of the modifier significantly improves the properties of chromoly steel, expanding its industrial applications and increasing the reliability of structures.

The standard heat treatment of products made from modified chromoly steel consists of quenching and high-temperature tempering. After annealing at 860°C, the chromoly steel is rapidly cooled in oil to ambient temperature (Fig. 7). It is then cleaned from oil and heated to the tempering temperature. Hardness changes in the modified chromoly steel occur after quenching. Since there is no immediate need for tempering of the products, the first tempering can be carried out at a different site or in the same furnace after a certain time, required for temperature change. This heat treatment method provides product flexibility, though it is associated with high energy consumption.

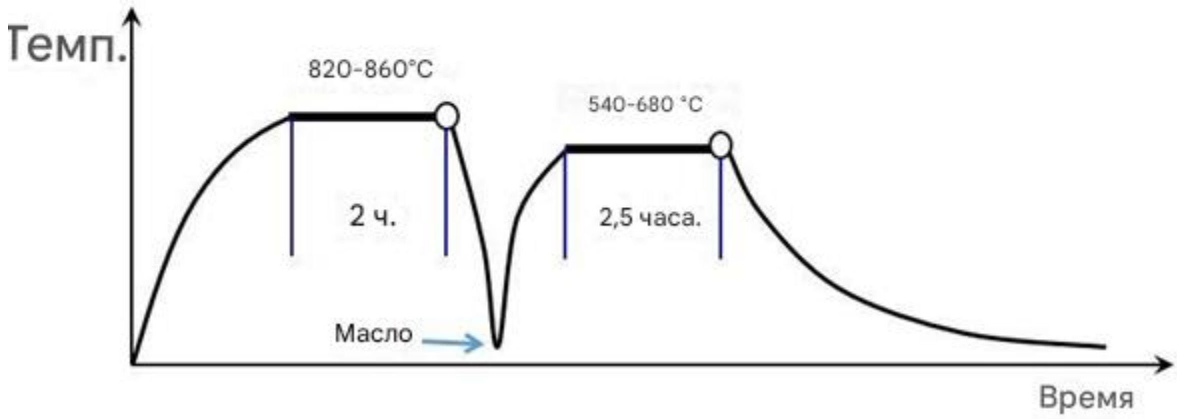

Fig. 7. **Diagram of the heat treatment process consisting of oil quenching and high-temperature tempering.**

Испытания также были проведены на микротвердость с помощью метода Виккерса с нагрузкой 10Н (рис. 8). Из диаграммы можно сделать вывод, что большинство точек измерения находятся в пределах требуемого диапазона твердости. Для проверки того, соответствует ли поковка требованиям, также было проведено испытание на твердость по методу Бринелла в соответствии с требованиями заказчика, описанными ранее. Результаты измерений подтвердили, что исследованная поковка

приобрела твердость 275 НВ, и таким образом, она была в требуемом объеме 249-280 НВ.

Fig. 8. **Changes in hardness (HB) across the cross-section in the selected measurement plane for a product that was oil quenched and tempered.**

For a more accurate comparison of mechanical properties, plastometric studies of samples cut from the forging were also conducted. The results show that the strain-hardening curves are very similar (Fig. 9) for both the modified chromoly steel products subjected to isothermal annealing immediately after the forging process and for the modified chromoly steel products from serial production, which underwent quenching followed by high-temperature tempering. In this case, the presented samples were obtained from the forging that was previously found to be most suitable for the requirements, i.e., from the forging annealed at 610°C for 60 minutes. The maximum true stresses, before the sample failure, reached values in the range of 1050 MPa to 1100 MPa for both types of modified chromoly steel products.

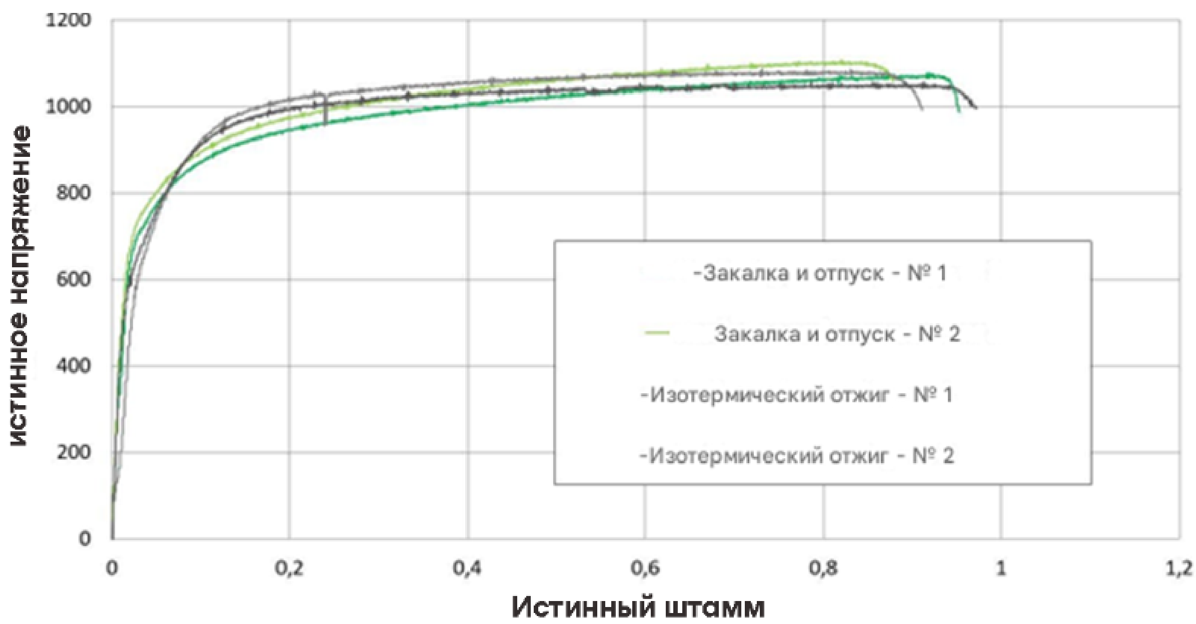

Fig. 9. **Stress-strain curve of samples cut from the quenched product and the product subjected to isothermal annealing at 610°C for 60 minutes.**

CONCLUSION

Based on the conducted research, it can be concluded that the heat treatment performed directly at the forging temperature provides the modified chromoly steel products with the required properties, comparable to the results of standard heat treatment. A comparison of the proposed technology with current manufacturing processes confirms that the obtained characteristics meet the customer's requirements. Despite the formation of a ferrite-pearlite microstructure, the hardness of the forging turned out to be comparable to the hardness achieved after quenching and subsequent high-temperature tempering. This contributes to the simplification of further processing, reducing its labor intensity. Furthermore, the analysis of the "stress-strain" curves showed that the mechanical properties of the forgings produced in serial production and the products subjected to isothermal annealing immediately after forging exhibit similar behavior.

The use of isothermal annealing demonstrates the importance not only of temperature but also of process duration. This creates certain challenges when implementing the technology into industrial production, as the annealing time is limited by the length of the line and the minimum permissible speed of its operation. Moreover, isothermal annealing is a continuous process, during which it is not possible to immediately control its results. This significantly distinguishes it from traditional quenching and tempering, where hardness measurements after quenching can be used to accurately select the optimal tempering temperature. Therefore, it is essential to carefully define the process parameters before starting the production.

In the automotive industry, forging is typically carried out on crank presses, whose kinematic characteristics are structurally defined and cannot be altered during operation. This is a significant difference from other metalworking methods, such as rolling, where the degree and speed of deformation can be controlled at each stage of the process, allowing the management of thermomechanical treatment parameters and achieving predictable results. In industrial forging, changing thermomechanical conditions significantly complicate the accurate prediction of microstructural evolution.

The proposed heat treatment technology also has certain drawbacks. One of them is the need for investments in a new high-efficiency heat treatment line, which should match the productivity of the forging equipment. Moreover, such a line must be located directly next to the forging or trimming press. In this production setup, it becomes impossible to make adjustments to the properties of the forgings at intermediate stages. Therefore, experimental studies on various melts of the same steel grade must be conducted before starting serial production. The data obtained will help develop an industrial thermomechanical processing technology for modified chromoly steel products using residual heat from forging, which will result in significant energy resource savings. With the proper design of the technological line, the heat released during structural transformations can be used to maintain the working temperature, minimizing energy costs for equipment operation.

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