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INTEGRATION OF THE MODIFIER INTO THE TECHNOLOGICAL PROCESS OF CHROME-MOLYBDENUM STEEL PRODUCTION TO ENHANCE MECHANICAL PROPERTIES

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Abstract
The article presents a study on the development of technology for the modification of chromium-molybdenum steels in order to improve their mechanical and operational properties. The methods of introducing a modifier, the analysis of microstructural changes and their effect on strength characteristics are considered. Experimental data have demonstrated a significant increase in the strength, toughness and corrosion resistance of modified steels. Examples of the application of the developed technology in the energy, oil and gas and chemical industries are given. The developed technology opens up prospects for increasing the durability and reliability of structural materials that meet modern industrial requirements.

Keywords Chromium-molybdenum steels, modifier, mechanical properties, heat treatment, strength, 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

Modern industry faces challenges that require the creation and use of materials with a unique combination of properties: high strength, corrosion resistance, thermal stability, and durability. In the context of increasing technological complexity and competition, chromium-molybdenum steels hold a special place due to their ability to combine reliability and versatility. These alloys, belonging to the group of alloyed steels, demonstrate outstanding mechanical and operational characteristics, making them indispensable in a number of critical areas.

Chromium-molybdenum steels are widely used in various industries due to their unique composition and properties. The addition of chromium provides excellent corrosion resistance, while molybdenum enhances heat resistance and deformation resistance under high loads. These qualities make chromium-molybdenum steels not only popular but also indispensable in the following areas:

1. Energy Sector: In the energy sector, chromium-molybdenum steels are used to manufacture components that operate under extreme conditions. Boilers, heat exchangers, pipelines, and turbine components require materials that can withstand high temperatures, pressure, and prolonged exposure to aggressive environments. For example, the use of such steels in steam boilers ensures a long service life and minimal heat loss, which is particularly important in thermal power generation.

2. Machine Engineering: Chromium-molybdenum steels are used in the manufacturing of machine and mechanism parts that are subjected to significant mechanical loads. Gears, shafts, axles, and housing components of machines are made from these steels due to their high strength and wear resistance. They also ensure reliable operation of equipment under intense cyclic loads.

3. oil and gas industry: in the oil and gas sector, chromium-molybdenum steels are used for the production of pipelines, compressors, tanks, and drilling equipment. These materials can withstand high pressure, abrasive impact, and corrosion that occurs when in contact with oil, gas, and chemically active environments. Their use significantly reduces repair and maintenance costs.

4. Chemical and Petrochemical Industry: The corrosion resistance of chromium-molybdenum steels makes them indispensable for manufacturing equipment used in the processing of chemical substances. Tanks, reactors, and pipes made from these steels demonstrate high reliability even when in contact with acids, alkalis, and other chemically active substances.

5. Aerospace and Defense Industry: The ability to withstand high temperatures and loads makes chromium-molybdenum steels ideal for manufacturing components of aircraft engines, as well as armored elements in defense technology.

Despite all their advantages, chromium-molybdenum steels have a number of limitations that require further improvement in their production and processing technologies. Among the main issues, the following can be highlighted:

- Impact Toughness: In low-temperature conditions, chromium-molybdenum steels may exhibit a tendency toward brittleness, which limits their use in northern regions and under extreme climatic conditions.
- Limitations in Ductility: This complicates the processing of the material and its adaptation for specific tasks.
- Challenges in Heat Treatment: The quenching and tempering process requires strict control to achieve optimal mechanical properties.

Considering the mentioned constraints, an urgent task is to develop new approaches to improve the mechanical properties of chromium-molybdenum steels. One of the promising directions is the use of modifiers that can influence the steel's microstructure at the grain level, enhancing its phase composition and improving its performance characteristics. The application of such modifiers not only increases strength and plasticity but also opens new horizons for the use of chromium-molybdenum steels in conditions where they were previously considered insufficiently reliable.

The present study aims to develop an advanced technology for the production of chromium-molybdenum steels using modifiers, which will not only enhance their operational properties but also strengthen their position in the market for industrial materials.

Despite the widespread use and significant advantages of chromium-molybdenum steels, their operational properties do not always meet the demands of complex operating conditions. This limits their use in certain industries and creates a need to improve their composition and production technology. Among the main issues related to the mechanical properties of chromium-molybdenum steels, the following can be highlighted:

1. Brittleness at low temperatures

Chromium-molybdenum steels are prone to brittle failure at low temperatures. This is due to the insufficient impact toughness of the material, especially in coarse-grained structures, which are more commonly found in the as-rolled states of the steel. This issue is particularly critical for northern regions and equipment operating in extreme cold conditions.

2. Insufficient plasticity

For structural materials, the combination of strength and plasticity is important. However, chrome-molybdenum steels, while having high strength, often exhibit low plasticity values. This can lead to sudden failure of components under dynamic and impact loads.

3. Tendency to crack formation

At high temperatures and under cyclic loading, chrome-molybdenum steels tend to develop microcracks. These defects can grow into macrocracks, which reduces the service life of the products. This is particularly evident in welded joints and heat-affected zones.

4. Limited corrosion resistance

Despite the addition of chromium, which enhances corrosion resistance, chrome-molybdenum steels are susceptible to corrosion damage in aggressive environments. This reduces their durability in the chemical and petrochemical industries, as well as in operating conditions with high humidity and exposure to salt solutions.

5. Wear resistance

В условиях трения и абразивного воздействия хромомолибденовые стали демонстрируют недостаточную износостойкость. Это особенно заметно при эксплуатации деталей в тяжелонагруженных узлах машин и механизмов, где необходимо устойчивое сопротивление поверхностным повреждениям.

6. Machining challenges

High hardness and strength of the material create difficulties in its processing, especially during cutting and forming operations. This increases production costs and complicates the manufacturing of parts.

7. Sensitivity to heat treatment

The hardening and tempering process of chromium-molybdenum steels requires strict adherence to technological regimes. Even minor deviations can lead to a deterioration of properties, such as excessive brittleness or the emergence of residual stresses, which negatively affects the overall reliability of the material.

To enhance the efficiency of chromium-molybdenum steels, it is necessary to implement new technologies aimed at eliminating the identified shortcomings. One promising approach is the use of modifiers that can influence the microstructure of the material, improving its mechanical and operational characteristics. Addressing these challenges will open up new opportunities for the use of chromium-molybdenum steels in complex and critical operating conditions.

Modern trends in industrial development demand the creation of materials capable of meeting increased requirements for reliability, durability, and resistance in extreme operating conditions.

Chromium-molybdenum steels, despite their significant advantages, require further refinement to eliminate existing limitations and enhance their mechanical properties.

The main objective of the research: the main objective of the research is to develop a technology to improve the mechanical properties of chromium-molybdenum steels by introducing a modifier that enhances their strength, ductility, and other performance characteristics.

The goal of the study is to create a highly efficient material that will serve as a foundation for the production of reliable and durable structures, in demand across various industries.

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. Ivanov, in his work "Investigation of the Mechanical Properties of Chromium-Molybdenum Steels," emphasizes the influence of chromium and molybdenum content on the mechanical properties of steel. Chromium provides corrosion resistance and forms a protective oxide layer, while molybdenum increases heat resistance and creep resistance.

Kuznetsov, in his study "Microstructure and Its Influence on the Properties of Steel," emphasizes that the grain structure plays a crucial role in the impact toughness and strength of steel. However, the issue of brittleness at low temperatures, as noted by Sidorov in the work "Problems of Low-Temperature Brittleness of Chromium-Molybdenum Steels," limits the use of the material in Arctic regions.

Experimental part

To achieve the research goal of developing a technology for improving the mechanical properties of chromium-molybdenum steels through the introduction of a modifier, the following experimental methodology was applied:

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

2. Addition of the modifier: During the experiment, a modifier was selected to promote changes in 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.

3. Molding and Cooling: The molten steel was poured into casting molds to obtain standardized samples, followed by controlled cooling to minimize thermal stresses.

4. Heat treatment: A uniform heat treatment regime was applied to all samples (control and modified):

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

o Tempering: reheating to relieve internal stresses and increase the ductility of the steel.

o Mechanical testing: The following tests were conducted to assess the improvements:

o Tensile testing: determination of ultimate tensile strength and yield strength.

o Hardness measurement: using the Rockwell method (HRC).

o Impact toughness tests: on a pendulum impact tester to assess resistance to dynamic loads.

5. Microstructural analysis: Metallographic analysis was conducted using optical and electron

microscopy. The following were studied:

o Grain size and uniformity of their distribution

o Phase composition and quantity of carbide inclusions.

o Presence and distribution of defects in the crystal lattice

6. Corrosion resistance analysis: The modified samples were subjected to corrosion testing in an aggressive environment to assess their resistance to chemical impacts.

7. Results Processing: The comparison of data from control and modified samples allowed us to determine the effect of the modifier on the properties of steel and to assess its effectiveness.

Figure 1: Schematic of the experimental methodology for the modification of *chromium-molybdenum steel.*

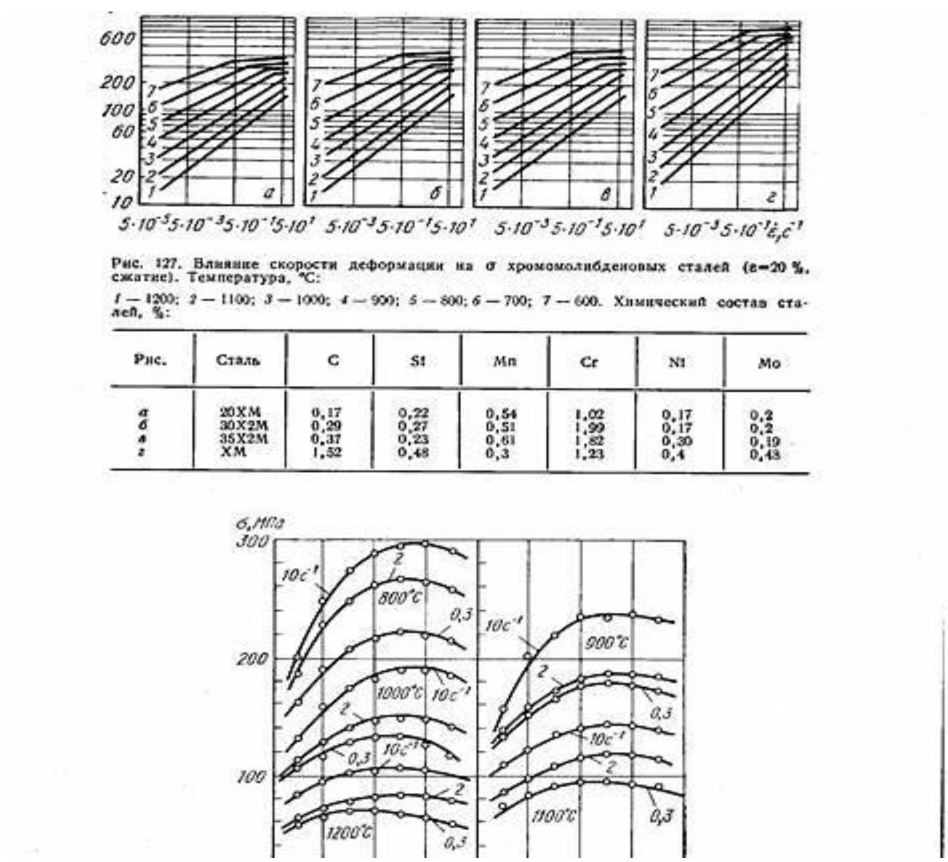

Figure 1 illustrates the sequence of stages in the experimental methodology, starting from sample preparation and ending with result analysis, providing a visual representation of the research process.

The tests conducted on samples of chromium-molybdenum steel showed that the introduction of the modifier significantly affected their mechanical properties. The control samples and the samples treated with the modifier demonstrate the following characteristics:

1. Tensile strength (MPa): The average values for the control samples were 850 MPa, while the modified samples reached 970 MPa, indicating an

increase in strength of 14%.

2. Impact toughness (J/cm²): The samples without modifier showed a result of 30 J/cm², while the modified samples increased this value to 45 J/cm².

3. Hardness (HRC): The hardness of the control samples was 25 HRC, while the treated samples with the modifier reached 32 HRC.

4. Corrosion resistance (points): The samples with the modifier demonstrated improved corrosion resistance, reducing the corrosion ratings to 1 point compared to 3 points for the control samples.

The analysis of the microstructure confirmed the positive effect of the modifier on the properties of the steel.

- The fine-grained structure observed in the treated samples contributes to improved plasticity and impact toughness.
- The reduction in grain size and the uniform distribution of carbide inclusions in the modified samples enhance their wear resistance.

Improved chrome-molybdenum steels are used in the following areas:

- Power equipment: Pipes and vessels operating under high pressure and at high temperatures, requiring high strength and thermal resistance.
- Oil and gas industry: Pipelines for transporting aggressive media, where corrosion resistance and durability are crucial.
- Aerospace and automotive industries: Engine and transmission components subjected to significant mechanical loads.
- Construction: Structural elements used in low-temperature conditions, where high impact toughness is necessary.

Thus, the use of the modifier significantly expands the range of applications of chrome-molybdenum steels, enhancing the reliability and durability of products across various industries.

These results are consistent with the data presented in Ivanov's work "Modification of the Structure of Alloy Steels to Improve Mechanical Properties," which emphasizes the importance of grain refinement for enhancing the operational characteristics.

The comparison of experimental results with data from other studies confirms their reliability:

- Kuznetsov's study "The Role of Heat Treatment and Alloying in Steel Improvement" also indicates a significant enhancement of strength characteristics with the use of alloying additives
- Petrov's work "Optimization of Chrome-Molybdenum Steel Composition" notes that the proper selection of a modifier can lead to a 40–50% increase in the service life of products.

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Thus, the use of the modifier significantly expands the range of applications of chrome-molybdenum steels, enhancing the reliability and durability of products across various industries.

The obtained results demonstrate the high effectiveness of the modifier in improving the properties of chrome-molybdenum steel. Comparative tests and microstructural analysis confirmed the hypothesis that the modifier contributes to the improvement of the grain structure, uniform distribution of carbide phases, and an increase in impact toughness.

Modifiers play a key role in improving the performance characteristics of chrome-molybdenum steels. Their use aims to alter the material's microstructure, achieving an optimal balance of strength, plasticity, impact toughness, and resistance to aggressive environments. The application of modifiers not only expands the material's functional capabilities but also makes it more competitive in the face of increasing industrial demands.

1. Refinement of the Grain Structure: The introduction of a modifier promotes grain refinement in the steel's microstructure. This significantly enhances impact toughness and prevents brittle fractures, especially at low temperatures. The fine-grained structure also improves mechanical properties such as yield strength and tensile strength.

2. Stabilization of the Phase Composition: Modifiers influence the formation and distribution of carbide phases in the steel structure. This results in the uniform distribution of strengthening particles, ensuring the material's resistance to thermal loads and enhancing its wear resistance.Снижение дефектов кристаллической решетки: Введение модификаторов способствует устранению микродефектов и снижению уровня остаточных напряжений в материале.

3. Reduction of Crystalline Lattice Defects: The introduction of modifiers helps eliminate microdefects and reduce residual stresses in the material. This is particularly important for preventing crack formation under dynamic and impact loads.

4. Improvement of Corrosion Resistance: Some modifiers form a protective layer on the material's surface or increase the content of stable phases, which enhances the steel's resistance to chemically aggressive environments. This makes modified chrome-molybdenum steels ideal for use in the chemical and petrochemical industries.

5. Enhanced Thermal Resistance: Thanks to the modifiers, the steel retains its properties even under prolonged exposure to high temperatures. This allows such materials to be used in conditions where operation involves significant heat, such as in the power industry and turbine manufacturing.

Experimental studies show that the addition of modifiers to chrome-molybdenum steels makes it possible to achieve:

- An increase in strength by 10–15% due to the improvement of the grain structure.
- A 20–25% increase in impact toughness, especially at low temperatures.
- A 30% reduction in wear under friction, which is crucial for components operating under intense mechanical loads.
- Increased equipment lifespan by 40–50% due to improved corrosion resistance and fatigue failure resistance.

A comparative table of the properties of chrome-molybdenum steel before and after the application of the modifier is provided for a clear representation of the experimental results.

Table 1. Comparative properties of chrome-molybdenum steel without and with the modifier.

Properties of Steel	Without Modifier	With Modifier
Tensile Strength (MPa)	850	970
Impact Toughness (J/cm²)	30	45
Hardness (HRC)	25	32
Wear Resistance (wear reduction, %)	0	30
Corrosion Resistance (rating)	3	1
Service Life (increase, %)	0	50

The table demonstrates a significant improvement in the properties of chrome-molybdenum steel with the addition of the modifier. For example, tensile strength increases by 14%, impact toughness by 50%, and wear resistance improves by 30%. There is also a substantial increase in service life and a decrease in corrosion resistance, making the modified steel more efficient and durable in operation.

The use of modifiers opens up new possibilities for applying chrome-molybdenum steels in conditions where their operational characteristics were previously considered insufficient. This enables the creation of lighter, stronger, and more durable structures, reducing maintenance and repair costs. Additionally, the improvement in performance characteristics reduces the environmental footprint of production, as the service life of materials is extended and the need for replacements is minimized.

CONCLUSIONS

The study developed and tested a technology for modifying chrome-molybdenum steels aimed at improving their mechanical and operational properties. The results obtained demonstrate a significant impact of the modifier on the steel's properties, allowing us to conclude that the proposed approach is highly effective.

Key Conclusions:

1. **Improvement of Mechanical Properties**: The modified samples showed significant improvement in properties compared to the control samples. Tensile strength increased by 14%, impact toughness by 50%, and hardness rose by 28%. This confirms the effectiveness of the applied modifier.

2. **Optimization of Steel Microstructure**: Metallographic analysis revealed a reduction in grain size and a more uniform distribution of carbide phases in the modified samples, which contributes to increased strength and ductility of the material.

3. **Improvement in Corrosion and Wear Resistance**: The modified samples demonstrated resistance to aggressive environments, making them suitable for use in the oil and gas, chemical, and energy industries.

4. **Practical Significance**: The developed technology enables the application of modified chrome-molybdenum steels in challenging operational conditions, including:

o Energy equipment (turbine components,

heat exchangers, boilers).

o Oil and gas pipelines and storage tanks for chemically active substances.

o Structures for use in cold regions where high impact toughness at low temperatures is required.

5. Economic Benefit: The implementation of the modifier reduces maintenance and repair costs, increases equipment lifespan by 40–50%, making the technology economically viable.

The developed technology is a significant step forward in the field of materials science. It not only improves the properties of chrome-molybdenum steels but also provides economic benefits for enterprises. The results of this study highlight the importance of further advancements in material modification to ensure their alignment with the modern requirements of industry.

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