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Research of the Influence of Chemical Composition on the Mechanical Characteristics of Cast Parts for Freight Car Bogies

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Abstract. This article presents the main factors influencing the mechanical properties of steel. The influence of the main chemical elements in the composition of steel on mechanical properties is shown and their role in obtaining a high complex of operational characteristics is explained. Laboratory data on chemical composition and mechanical properties of steel were analyzed. The possible effects of chemical elements on the formation of the non-metallic inclusions and microstructure are considered. Steel grade 20GL must possess high strength, plasticity, and impact toughness, which are crucial for cast parts of freight cars. In railway transport, the side frame and overhead beam are considered critical components are cast from 20GL grade steel. Improving the mechanical properties of this steel is the main task.

Key words: strength limit, relative elongation, impact toughness, chemical composition, non-metallic inclusions, microstructure.

Introduction

The mechanical properties of a material characterize its resistance to destruction, deformation, or behavior during the destruction process. These include hardness, plasticity, strength, elasticity, impact toughness, fatigue resistance (endurance), and others.

Strength is the ability of a material to resist destruction and deformation when compressed, stretched, twisted, and bent. Two strength characteristics are used: fluidity limit σ_T and strength limit σ_S [1].

Plasticity is the ability of metals and alloys to deform irreversibly (plastically) under external load without breaking down. The characteristics of plasticity are relative elongation and relative narrowing [1].

Impact toughness is the ability of metals and alloys to resist impact loads. For testing, samples of standard size according to GOST 9454-78 with a concentrator are used, the role of which is performed by a V-shaped incision [1].

High impact toughness (from 20 to 80 J/cm^2 for different groups of alloys) is characteristic of highly plastic single-phase metals and alloys, pure in impurities or heterogeneous in structure alloys with a small number of non-metallic inclusions or their optimal sizes and distribution. Alloying leads to a decrease in impact toughness. Impact toughness is increased by removing impurities that lead to the formation of fragile excess phases [2].

The impact toughness test is the main one due to the instability of this parameter, as impact toughness depends on many factors: chemical composition, heat treatment, microstructure, casting defects, etc. [3].

One of the main criteria for the quality of metal is its cold resistance, i.e., high plasticity and low-temperature viscosity. The quality level of the metal, i.e., its high mechanical properties and cold resistance, is determined by the degree of contamination with harmful impurities such as sulfur, phosphorus, oxygen, nitrogen, hydrogen, etc. At the same time, sulfur and phosphorus have the most negative effects - through non-metallic inclusions and through the enrichment of metal boundary volumes, which leads to the weakening of bonds at grain boundaries [4].

The main objectives of this work are analyzing the effect of key chemical elements on strength, plasticity, and impact toughness and determining methods for improving the mechanical performance of steel grade 20GL for freight car cast components. To achieve these objectives, the following tasks are performed: analyze the influence of key chemical elements on the strength, plasticity, and impact toughness of steel grade 20GL; investigate the relationship between chemical composition, microstructure, and non-metallic inclusions, and their effect on mechanical properties; develop practical recommendations for improving the mechanical properties of 20GL steel used in critical freight car components (side frame and overhead beam).

As expected results, the research will establish the dependence of the mechanical properties of 20GL grade steel, used for manufacturing critical components of freight car bogies, on its chemical composition and the level of harmful impurities.

It will also study the influence of sulfur and phosphorus on the steel's plasticity, impact toughness, and low-temperature resistance, which is caused by the formation of non-metallic inclusions and the development of intergranular brittleness.

1. Research method

The smelting processes were carried out in a six-ton induction crucible furnace of the Otto-Junker company (Fig. 1). Table 1 presents the technical characteristics of the ICF-6 induction crucible furnace [5], which is used at JSC "Foundry and Mechanical Plant" (Tashkent, Uzbekistan).

Fig. 1. – Induction crucible furnace

Table 1. Technical characteristics of ICF [5].

Parameter name	Norm
Capacity	6 t
Nominal power	4.8 MB•A
Current frequency	500 Hz
Internal diameter of the crucible	920 mm
Lining thickness	125 mm
Specific electricity consumption	505 kWh/t
Lining	Based on Al_2O_3

Metallographic studies were conducted on cast metal cross-sections (trifle-shaped samples) and after etching with a 3% HNO_3 solution in spirit (alcohol). The "Olympus BX 41M LED" modular microscope was used to determine the microstructure of the metal (Figure 2) in scientific-research laboratory of the Materials Science and Mechanical Engineering Department, Tashkent State Transport University.

Fig. 2. – Modular microscope "BX 41M LED"

Figure 3 shows the MSA optical emission spectrometer of the scientific-research laboratory of the Materials Science and Mechanical Engineering Department (Tashkent State Transport University), which was used to determine the chemical composition of steel.

Fig. 3. – Optical-emission spectrometer for chemical composition analysis

The chemical composition and mechanical properties of 20GL steel according to GOST 32400 2013 are presented in tables 2 and 3 [6].

Table 2. Chemical composition of 20GL steel, (% by mass.)

C	Si	Mn	Al	P	S	Cr	Ni	Cu	Fe
				no more than					
From 0.17 to 0.25 (-0.020)	From 0.30 to 0.50 (±0.10)	From 1.10 to 1.40 (±0.10)	From 0.020 to 0.060 (+0.005)	0.020 (+0.005)	0.020 (+0.005)	0.30 (+0.20)	0.30 (+0.30)	0.60	rest

Note! In brackets, the permissible deviations from the chemical composition of steel are indicated.

Table 3. Mechanical properties of 20GL steel

Fluidity limit, MPa	Strength limit, MPa	Relative elongation, %	Relative narrowing, %	Impact toughness, KCV^{-60}, kJ/m^2
no less than				
343	510	18	30	200

2. Results and discussion

The results of the analysis of samples for the chemical composition and mechanical characteristics of some 20GL steel alloys are considered. Figure 4 shows the dependence of mechanical characteristics on the carbon content in the steel.

From Figure 4, it can be seen that with an increase in the carbon content in cast steels, their strength increases, while plasticity and impact toughness decrease. With an increase in carbon from 0,19% to 0,25%, the relative elongation of steel significantly decreases from 30% to 24%, and the value of the strength limit slightly increases. An increase in carbon content in steel, accompanied by an increase in the proportion of perlite in the structure, leads to an increase in fluidity limit and strength limit and a decrease in plasticity.

The impact toughness level is decreasing imperceptibly. Perhaps this is due to the increase in the pearlite fraction in the steel.

Silicon is also introduced into steel to reduce its oxidation. Silicon enters the solid solution in ferrite, increasing the strength properties of steel.

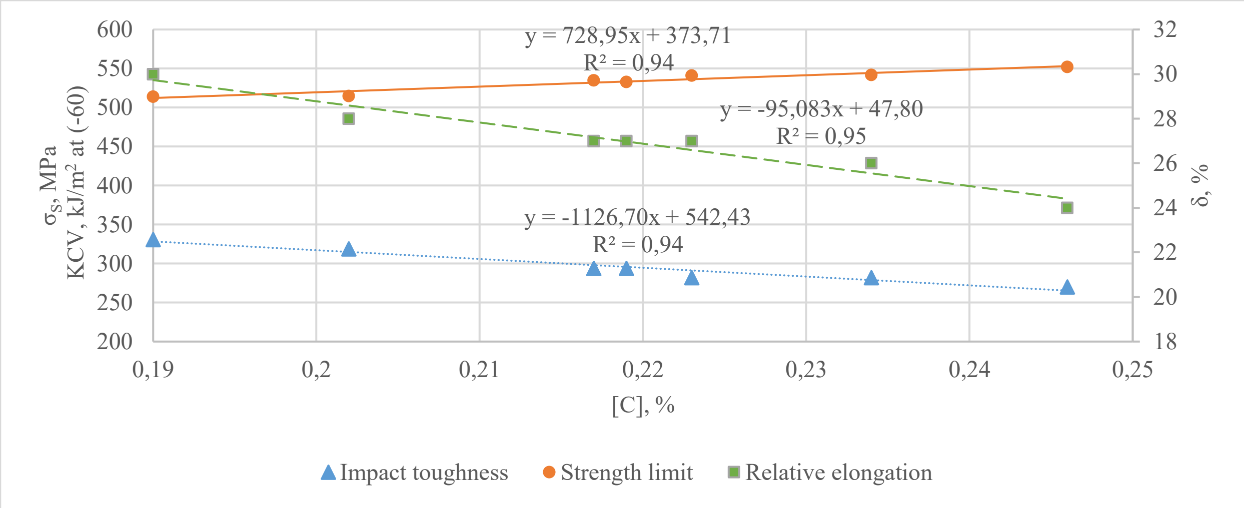

Fig. 4. - Dependence of mechanical properties on the carbon content

Figure 5 shows the dependence of mechanical characteristics on the silicon content in the steel.

From Figure 5, it can be seen that with an increase in the silicon content within the range of 0,33-0,46%, the value of relative elongation and impact toughness decreases insignificantly, while the strength limit increases.

Manganese is a technological additive that is introduced into steel for deoxidation and desulfurization - to eliminate the harmful effects of sulfur. Manganese is partially dissolved in ferrite and partially in cementite, where it replaces iron atoms. Manganese impurity slightly increases the strength of the steel.

Manganese and silicon can partially be part of non-metallic inclusions - complex oxides of the spinel type FeO·MnO, silicates $2FeO \cdot SiO_2$, $2MnO \cdot SiO_2$, etc. [7].

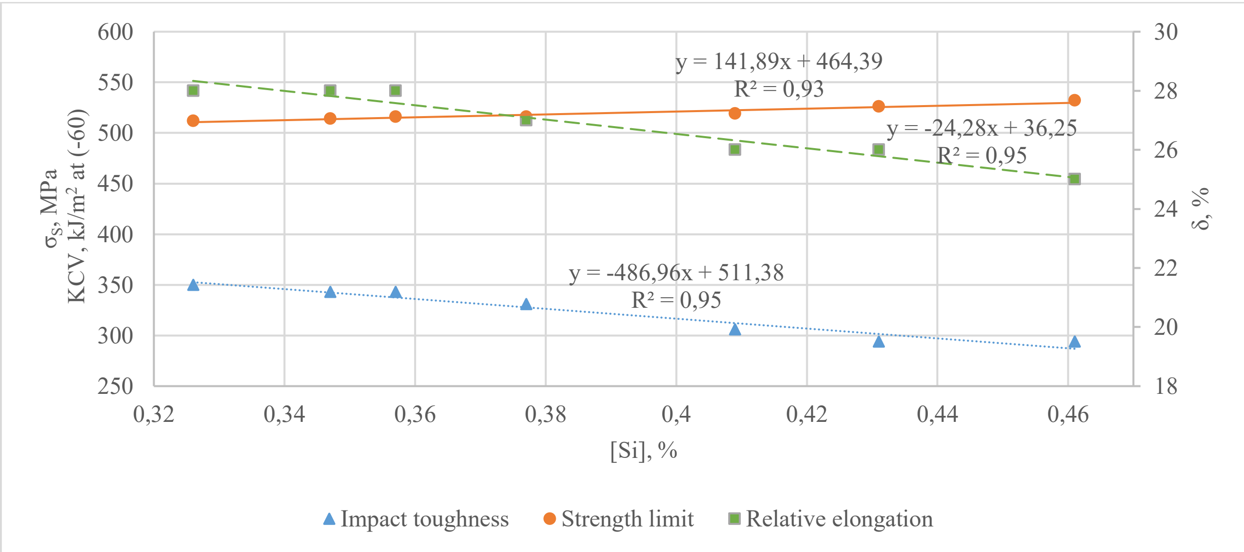

Fig. 5. – Dependence of mechanical properties on the silicon content

Figure 6 shows the dependence of mechanical properties on manganese content.

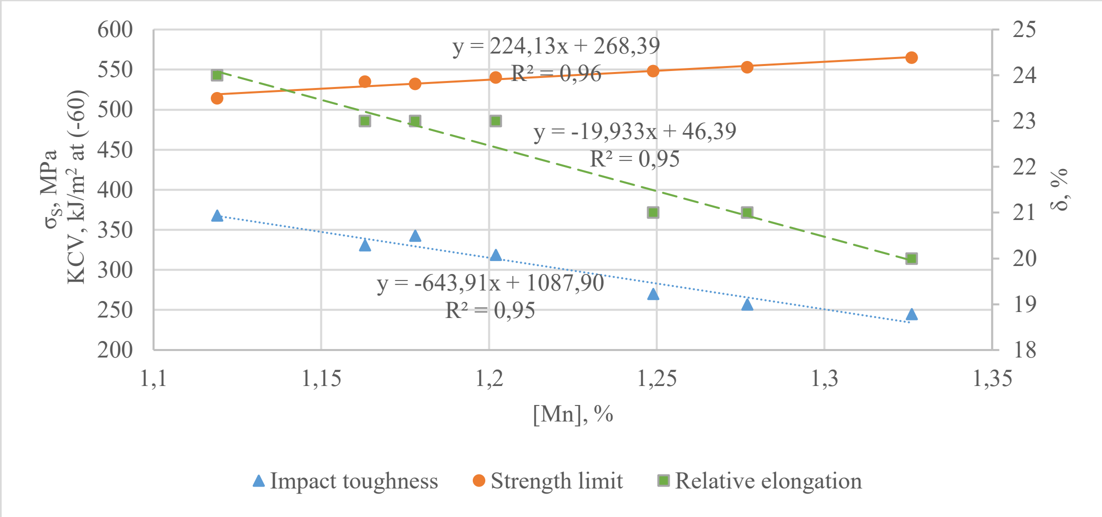

Fig. 6. – Dependence of mechanical properties on manganese content

From Figure 6, it can be seen that with an increase in manganese content from 1.1% to 1.35%, the relative elongation decreases. Manganese also leads to a decrease in impact toughness. However, it increases the strength limit of the steel.

Aluminum is the best deoxidizer, plays the role of deoxidizing and grinding grains, which increases the impact toughness and plasticity of steel. Additionally, nitrogen can be bound to nitrides (e.g., AlN), aluminum (approximately 0,05%) is introduced into the ladle before pouring to obtain hereditary fine-grained steel - dispersed particles of aluminum oxide and nitride inhibit the growth of austenite grains [7].

Figure 7 shows the dependence of aluminum's influence on the mechanical properties of steel.

From Figure 7, it can be seen that with high aluminum content, the level of mechanical characteristics of steel reaches high values. When oxidized with aluminum, the aluminum content should be at the highest level according to GOST 0,04-0,06%. Aluminum has no apparent harmful effect on the mechanical properties of steel.

Phosphorus, being a harmful impurity, significantly reduces the properties of steel. With an increase in the phosphorus content, the strength, brittleness, and cold-breaking threshold increase, while simultaneously reducing the plasticity and viscosity of the steel [8].

Phosphorus influences the properties of the metal matrix, while sulfur influences the properties of the metal matrix through sulfides. The brittleness of phosphorus is enhanced by the action of the third element. Carbon and manganese displace phosphorus from the solution to the grain boundaries, significantly weakening the intergranular bonds and leading to a decrease in plasticity and viscosity [4].

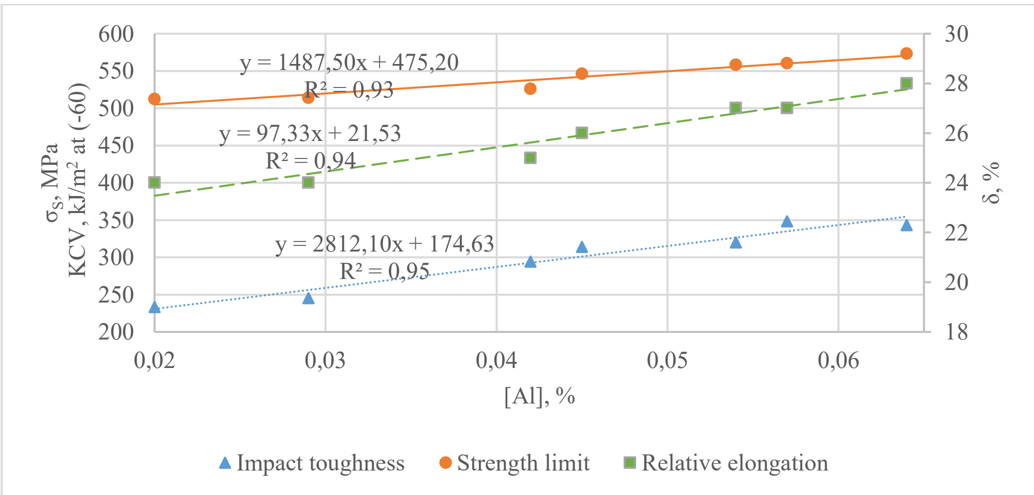

Fig. 7. – Dependence of mechanical properties on the aluminum content

The harmful effects of phosphorus are related to the peculiarities of the iron-phosphorus phase diagram. Phosphorus dissolves in austenite up to 0,2%, and in ferrite even more, and significantly strengthens the solid solution. The plastic properties of steel, especially at low temperatures, significantly decrease due to the release of very fine phosphide segregations along the grain boundaries. The damage from phosphorus is always observed in grain boundary brittleness, which reduces impact toughness [9].

Sulfur dissolved in steel acts similarly to phosphorus, and non-metallic inclusions are released at the boundaries of primary grains (when oxidized by aluminum), weakening the metallic bond and reducing viscosity and plasticity indicators [4].

The large radius of the sulfur atom (0,104 nm) compared to the iron atom leads to an increase in strength and loss of plasticity due to the stressed state in the iron lattice [4].

Figure 8 shows the influence of the total sulfur and phosphorus content on the mechanical properties of steel.

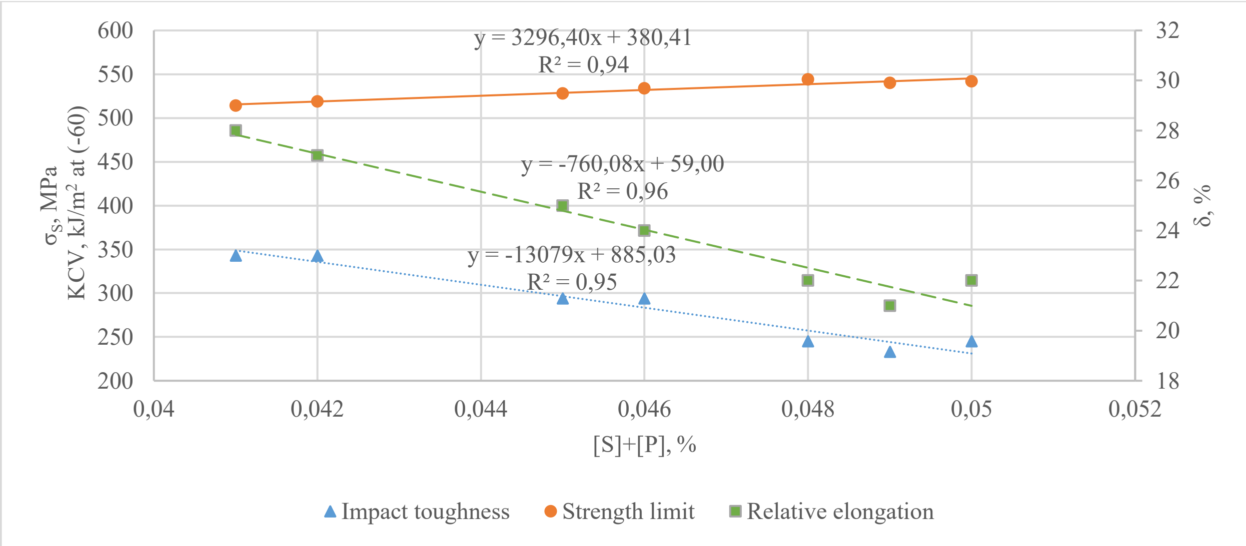

Fig. 8. – Influence of sulfur and phosphorus on the mechanical properties of steel

As can be seen from Figure 8, sulfur and phosphorus are harmful impurities, significantly reducing impact toughness and relative elongation. Especially, the impact toughness decreases from 350 KJ/m^2 to 230 KJ/m^2 with an increase in the total sulfur and phosphorus content from 0,040% to 0,050%.

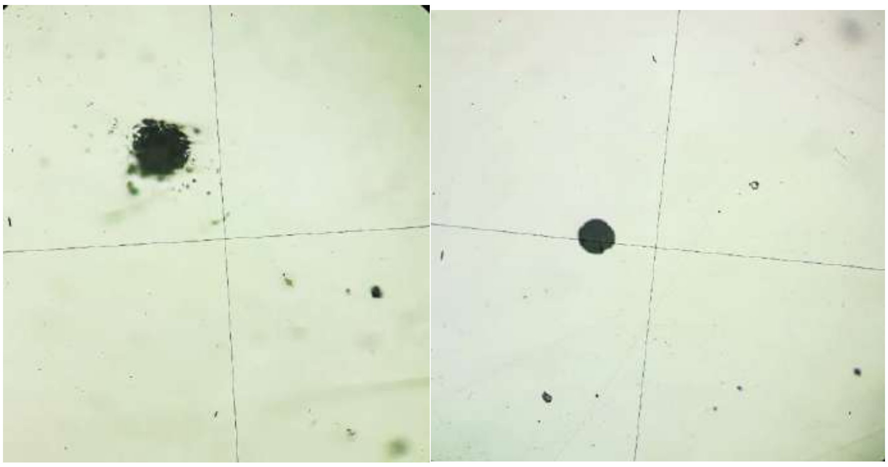

Fig. 9. – Non-metallic inclusions in 20GL steel

Figure 9 shows non-metallic inclusions in 20GL steel. The main part of oxide inclusions (endogenous inclusions) is formed as a result of oxidation during the addition of reducing agents and cooling of liquid steel (pre-crystallization) and during its crystallization (crystallization) [10].

Stress concentration causes a volumetric stress state, inclusions worsen the plasticity (relative elongation and relative narrowing) and impact toughness. The strongest inclusions affect the impact toughness, which is especially sensitive to stress concentrators and metal cuts [10].

Increased sulfur content leads to steel contamination with non-metallic inclusions, mainly sulfides. For this reason, the decrease in plasticity and impact toughness with increasing sulfur content is explained not only by metal contamination with non-metallic inclusions but also by changes in the solubility of sulfur present in the solution, which will enrich the boundary areas of austenite and ferrite grains during steel cooling, leading to metal brittleness at positive and low temperatures [4].

Sulfides are the main type of inclusions. The type or form of sulfide inclusions separation is determined by the degree of deoxidation (content of residual aluminum and oxygen) of the steel [11].

When the amount of [O] in the metal is 0,02%, only globular sulfides (type 1) are formed, at 0,01-0,02% - sulfides of type 1 and 2, and when [O] is less than 0,01%, only sulfides of type 2 are formed [11].

Type 1 - small globular sulfides and oxysulfides that are separated in steels in the branches of austenite dendrites as droplets of a high-sulfur liquid during separate or cooperative monothetic transformation. These droplets, upon further cooling, solidify as manganese sulfide or oxysulfide inclusions. This type of inclusion is characteristic of steels containing low aluminum concentrations.

Type 2 is characteristic of well-deoxidized steels, but containing low concentrations of excess aluminum. Such sulfides lead to a sharp weakening of intergranular bonds and a significant decrease in the plastic and viscous properties of steel, which plays the role of films located along the grain boundaries.

Type 3 - edged, anchor-shaped, and dendritic sulfides formed under conditions of separate eutectic crystallization with a further increase in aluminum content. They reduce the quality of steel to a lesser degree than type 2 inclusions, but still deteriorate the properties of the metal to a greater extent than type 1 inclusions.

To obtain type 1 sulfides, it is necessary to have a critical amount of aluminum in the steel. However, this is not enough to obtain a dense metal with a fine-grained structure. Therefore, to make a high-quality metal, it is necessary to introduce a supercritical amount of aluminum into the steel.

Elongated inclusions are dangerous because, under the influence of external loads, stress concentration occurs around these sulfides, resulting in microcracks. Inclusions with a size of 5-10 μm are especially dangerous [11].

Deoxidation solely by aluminum does not ensure the favorable forms and topography of non-metallic inclusions, and consequently, the physical and mechanical properties of steel. Therefore, complex modification is used, where elements are introduced along with aluminum for globulation and more disoriented distribution of oxidesulfide formations. The most promising in this direction are alkaline-earth and rare-earth metals (AEM and REM). These elements have a beneficial effect on the mechanical and operational properties of steel due to their high deoxidizing ability, refining effect, and globularization of non-metallic inclusions. However, the application of these elements is effective after preliminary oxidation with aluminum [12].

Figure 10 shows the microstructure of 20GL steel after heat treatment.

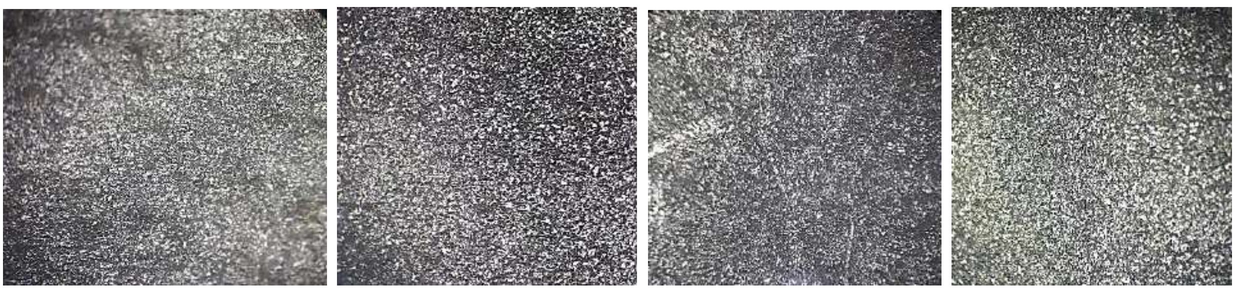

Fig. 10. – Microstructure of 20GL steel after normalization and tempering (x100)

The microstructure is homogeneous, ferrite-pearlite, fine-grained, with a uniform distribution of structural components. The grain score according to GOST 5639-82 is 8-9, which is permissible according to GOST 32400-2013 (not lower than 8) [13].

Ferrite is a soft, plastic component of the structure. The properties of ferrite primarily depend on its carbon content, alloying elements, and grain size. Carbon and nitrogen, which form solid solutions with iron, provide the most significant effect of ferrite hardening, which is mainly due to their strong interaction with dislocations and hardening of the latter [14-16].

Alloying elements, which form solid substitution solutions with iron, strengthen ferrite less than carbon and nitrogen.

Substitution elements and, to a greater extent, embedding elements increase the temperature of the viscous-fragile transition T_{cr}, which characterizes the steel's tendency to fragile destruction.

The strength of ferrite is greatly influenced by the size of its grain. With the grinding of ferrite granules simultaneously with additional hardening, the viscous-fragile transition temperature decreases [17-19].

Thus, grinding ferrite granules is an effective strengthening method, as it simultaneously reduces the tendency for brittle destruction.

The viscosity of steels with a ferrite-carbide structure increases when pearlite colonies and ferrite grains are ground. These structural parameters significantly depend on the size of the austenitic grain. Therefore, to obtain a high degree of mechanical properties during heat treatment, a fine austenitic grain is sought [20-22].

Conclusions

This research was conducted as part of the scientific and innovative projects of Tashkent State Transport University, commissioned by JSC "Foundry and Mechanical Plant" (Tashkent, Uzbekistan).

As a result of the conducted research, it was established that the mechanical properties of 20GL grade steel used for critical parts of freight car bogies significantly depend on its chemical composition and the level of contamination with harmful impurities. Particularly significant influence is exerted by sulfur and phosphorus, which deteriorate the plasticity, impact toughness, and cold resistance of steel due to the formation of non-metallic inclusions and inter-crystallite brittleness. Increasing the carbon and silicon content contributes to an increase in strength characteristics, but is accompanied by a decrease in plasticity and viscosity indicators. The addition of aluminum positively affects the dispersion strengthening, deoxidation, and grinding of grain, thereby increasing the complex of mechanical properties. The most critical indicator characterizing steel reliability is impact toughness, as it is most sensitive to the presence of casting defects, microstructural changes, and stress concentrators. Tests show that a steel structure with minimal harmful impurities and an optimal alloying system provides a high level of strength and operational reliability. Thus, effective management of the chemical composition and modification technology of steel allows for obtaining optimal mechanical characteristics necessary for reliable and safe operation of rolling stock parts.

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