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Optimizing the chemical composition of the steel of arrow translations to increase the level of physical characteristics of metal products

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Оптимізація хімічного складу сталі стрілочних перекладів для підвищення рівня металофізичних характеристик металопродукції

Abstract. *The analysis of regulatory documents on the chemical composition and level of mechanical properties of austenitic high-manganese steel 110G13L for turnouts is performed. Using mathematical methods of statistics, correlation dependencies of the influence of impact toughness values on the strength characteristics of the metal are obtained. It is established that the values of tensile strength σ_b and impact toughness a_k are decisive factors for a set of strength-viscosity properties of castings made of steel 110G13L. The rational composition of the metal is substantiated, taking into account the manganese content (≈12%) and the ratio of manganese to carbon (10.56-13.60) for the production of metal castings of group I according to GOST 7370-98.*
Key words: *turnouts, steel 110G13L, chemical composition, mechanical characteristics.*

The publication is prepared based on the results of the project 2023.04/0037, "Development of a technology for remelting scrap military equipment in order to preserve valuable alloying elements in the smelting of special functional steels," funded by the National Research Foundation of Ukraine from the state budget.

Анотація. *Виконано аналіз нормативних документів до хімічного складу та рівня механічних властивостей аустенітної високомарганцевої сталі 110Г13Л для стрілочних перекладів . З використанням математичних методів статистики, отримані кореляційні залежності впливу значень ударної в'язкості на характеристики міцності металу. Встановлено , що значення межі міцності σ_b та ударної в'язкості $a_к$ є вирішальними факторами для комплексу міцнов'язкостних властивостей виливків із сталі 110Г13Л. Обґрунтовано раціональний склад металу з урахуванням вмісту марганцю (≈12%) та відношення вмісту марганцю до вуглецю (10,56-13,60) для виробництва металу виливків І групи за ГОСТ 7370-98.*
Ключові слова: *стрілочні переклади, сталь 110Г13Л, хімічний склад, механічні характеристики.*

Публікація підготовлена за результатами проєкту 2023.04/0037 "Розробка технології переплаву брухту військової техніки з метою збереження дороговартісних легуючих елементів при виплавці сталей спеціального функціонального призначення", профінансованим Національним фондом досліджень України за кошти державного бюджету.

Introduction. The main operating conditions of railway transportation, characterized by a rapid increase in load stresses, dynamic loads, and train speeds, impose high demands on the metal quality of the upper track structure elements, especially on railway turnouts. One of the methods for improving the metallophysical properties of railway turnouts is the optimization of the metal's chemical composition to enhance its mechanical strength.

Therefore, research aimed at stabilizing the metal's chemical composition by regulating the ratio of the main alloying elements has significant practical value for the production of railway metals.

Analysis of the operating conditions of the railway's upper track structure. Operation of the cross-shaped element under moving load due to its constructive features has significant differences depended upon the rail operation and other turnouts elements. The behavior of the cross-shaped element under moving loads, due to its structural characteristics, varies significantly depending on the operation of the railway tracks and other turnout components.

The rolling trajectory over the frog has a gradient of up to 30–40° or more; therefore, even at low travel speeds (40–50 km/h) and moderate axle loads, the level of dynamic impact on the frogs is several times higher than that on the rails.

In the case of high travel speeds the rolling process from the wing rail to the crossing nose usually accompanies of the wheel lifts from the crossing nose and sequent impact loads which describing of the high level of dynamic effect. At high travel speeds, the rolling process from the wing rail to the crossing nose is usually accompanied by wheel lifts from the crossing nose and the resulting impact loads, which reflect the high level of dynamic effects. As the wheels roll over the frog, complex contact conditions between these elements also arise. The width of the contact surfaces averages

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5–7 mm, which is almost 10 times smaller than on the rails. Therefore, the overall level of contact stress in the frog rolling area is extremely high. The average value of tangential stresses at different periods of frog operation reaches 1715–2254 MPa, while the maximum value ranges from 2744 to 3626 MPa.

Literature Analysis and Problem Statement. In recent years, the issue of improving the durability of railway superstructure elements, particularly railway turnouts, has attracted considerable attention from researchers in various countries. In modern studies, the main focus has been on investigating microstructural changes, wear resistance, and the influence of the chemical composition of high-manganese steels on their operational properties.

Let us consider a number of recent investigations. In study [1], the mechanisms of dynamic recrystallization in high-manganese steels of types 70Mn17 and 120Mn13 were examined, and the microstructural transformations of high-manganese steel under the influence of friction and wear were analyzed. This made it possible to determine the effect of friction and temperature on the stability of the austenitic structure.

In study [2], a numerical model of wear in turnout elements under high-speed train movement was proposed, taking into account normal and tangential contact stresses. This approach enables the modeling of wear processes in turnout zones using contact models that consider both normal and tangential interactions, as well as train dynamics and rail profile renewal. The results demonstrate that stress-based models allow more accurate prediction of wear in turnout components.

Particular attention has also been paid to the issues of detecting structural defects and residual stresses. Thus, in study [3], modern non-destructive testing methods—specifically X-ray diffraction—were applied to analyze the stress–strain state of high-manganese railway crossings after service. Important data were obtained for assessing material degradation, crack initiation mechanisms, and the influence of residual stresses on durability.

In addition, studies [4] and [5] investigated the effect of manganese content on the microstructure and plastic properties of U71Mn-type steels, as well as models of plastic deformation and wear of the nose section of crossings. Publication [4] examines the influence of manganese concentration on the microstructure and mechanical properties of welded U71Mn rail joints, with particular attention to the role of MnS inclusions in crack initiation and the long-term performance of welds. This provides a valuable analogy regarding the influence of alloying and impurities on structural and mechanical properties.

In study [5], a semi-physical model was proposed to predict deformation and wear of the turnout nose without complete finite element modeling. Such a model is useful for engineering assessment and long-term performance analysis of turnout components. Consequently, studies [4-5] confirm the importance of optimizing the ratio of basic alloying elements (Mn/C) to ensure high strength and impact toughness.

The study conducted at Sheffield Hallam University [6] analyzes the mechanisms of spalling formation on high-manganese railway crossings under cyclic wheel loading, revealing typical failure mechanisms closely related to the subject of this work.

Thus, the results of recent research are consistent with the objective of the present study — optimization of the chemical composition of 110G13L steel to improve the metallophysical characteristics of cast components used in railway turnouts.

Aim and Objectives of the Study. To determine the influence of variations in the chemical composition of turnout metal on the mechanical properties of metal products and to optimize the ratios of the main alloying elements in high-manganese steel in order to enhance the metallophysical properties of the elements of the upper track structure.

Research Methods. Analytical studies were conducted using statistical methods to process the mechanical property data of castings made from 110G13L steel, depending on variations in the chemical composition of the metal.

Scientific Significance. The influence of each mechanical property indicator on the strength and plasticity of high-manganese steel castings has been determined.

Practical Significance. Rational alloying of the metal within the grade composition of 110G13L steel ensures a high level of mechanical properties of the upper track structure metal in railway transport.

The high level of dynamic effects and the small size of the contact surfaces in the wheel rolling area over the frog lead to a relatively rapid loss of serviceability, which occurs as a result of the formation of contact-fatigue damage, unacceptable from the perspective of train operation safety. In domestic practice, monolithic railway frogs and turnout crossing noses are manufactured from austenitic high-manganese steel of grade 110G13L, the chemical composition of which, according to the requirements of the interstate standard GOST 7370-98 [7] and the regulatory documents of several countries, is presented in the table.

According to the data presented in Table 1, steel produced in foreign countries is characterized by narrower ranges of both main (Mn, C, Si) and impurity (P, S) elements. In foreign grades of steel, the manganese content varies within narrower limits — from 11.0% to 14.5%. In domestically produced high-manganese steel, silicon content ranges from 0.30% to 0.90%. Silicon displaces carbon from the solid solution and promotes the formation of large iron–manganese carbides inside the austenitic grains and, which is particularly dangerous, along their boundaries. An increased concentration of silicon in steel with average carbon and manganese content leads to the formation of a dendritic structure in the castings.

Table 1. Chemical Composition of High-Manganese Steel 110G13L [7, 8].

State/standard	Mass fraction of the chemical element				
	C	Mn	Si	S	P
GOST 7370-98	1,0-1,30	11,50-16,50	0,50-0,90	0,02	0,09
Czech Republic /CSN 422920	1,1-1,5	12,0-14,0	≤0,7	≤0,005	≤0,1
Germany/SEW 395*	1,1-1,3	11,5-13,5	≤0,5	≤0,003	≤0,06
Romania/STAS 3718	1,25-1,4	12,5-14,5	≤1,0	≤0,005	≤0,11
Poland /PN/H83160**	1,0-1,4	12,0-14,0	0,3-1,0	≤0,003	≤0,1
Finland/SFS 380	1,05-1,35	11,0	≤1,0	≤0,003	≤0,07
Japan, JLS G 5131(81)	0,9-1,3	11,0-14,0		<0,05	<0,10
Sweden/SS	1,0-1,35	11,0-14,0	≤1,0	<0,06	≤0,08
Spain/UNE 36253-71	1,0-1,4	11,5-14,0	≤1,0	≤0,06	≤0,1
Great Britain/ /BS3100(91)	1,0-1,35	11,0	≤1,0	≤0,05	≤0,06
Italy/ 3160(83)	1,0-1,4	10,0-14,0	≤1,0	≤0,05	≤0,1
China/5680-85	1,1-1,5	11,0-14,0	≤1,0	≤0,05	≤0,1
USA (ASTM A 128-64)	1,05-1,35	11,5-14,0	0,3-1,0	<0,050	<0,09

*Germany/SEW 395 Al cont. 0,055%, ** Poland/PN/H83160 cont. Cr ≤ 1,0,
*** Romania/STAS 3718 cont. Ni ≤0,88

The strength level and plastic properties, as well as their correlation - including the wear resistance—of high-manganese steel are determined by its chemical composition, the steelmaking method, heat treatment, and a number of other uncontrolled factors (such as the content of non-ferrous metal impurities, gases, etc.). The technical specifications of manufacturing plants allow fairly wide ranges in the content of basic and impurity elements in the metal (carbon, manganese, silicon, sulfur, and phosphorus), which in most cases is not entirely justified and is one of the causes of instability in the mechanical property values.

The physicomechanical characteristics of cast metal made of steel grade 110G13L, depending on the indicators of mechanical properties according to GOST 7370-98, determine its classification into one of three quality groups (Table 2).

Table 2. Mechanical Properties of 110G13L Steel [7]

Name of the Indicator	Mechanical Properties of Grouped Metals		
	I	II	III
Tensile strength, σ_b, H/mm^2 (kgf/mm^2)	more 880 (90)	From 780 (80) to 880 (90) inclusive	From 690 (70) to 780 (80) inclusive
Межа плинності, $\sigma_{0,2}$, H/mm^2 (kgf/mm^2) no less	355 (36)	355 (36)	355 (36)
Yield strength, δ,%	More 30	More 25 to 30 inclusive	From 16 to 25 inclusive
Elongation, ψ,%	More 27	More 22 to 27 inclusive	From 16 to 22 inclusive
Impact toughness, KCU , J/sm^2 (kgf·m / sm^2)	More. 2,5 (25)	More 2,0 (20) до 2,5 (25) inclusive	From 1,7(17) to 2,0(20) inclusive

Frogs with cast components made of high-manganese steel of Group 1 are used on main railway tracks in sections with the highest traffic load. To determine the influence of each mechanical property parameter on the strength and plastic characteristics of the metal, a correlation analysis of the physicomechanical properties of 110G13L steel was carried out. For this purpose, based on industrial data (200 heats), the coefficients of pairwise correlation were calculated (Table 3). The analysis of the statistical significance of the correlation coefficients showed that there are strong linear relationships between the parameters (σ_b, $\sigma_{0.2}$, δ, ψ, KCU).

Table 3. Pairwise Correlation Coefficients of the Mechanical Properties of Currently Produced 110G13L Steel.

Mechanical properties \ Pairwise correlation coefficient	σ_b	$\sigma_{0,2}$	δ	ψ	KCU	Rank of Importance
σ_b	1	0,95	0,89	0,94	0,98	2
$\sigma_{0,2}$	0,95	1	0,58	0,48	0,93	5
δ	0,89	0,58	1	0,96	0,91	3
ψ	0,24	0,48	0,96	1	0,94	4
KCU	0,98	0,93	0,91	0,94	1	1

Since impact toughness ranks first in the order of significance, the KCU indicator is a general property that makes it possible to calculate σ_b, $\sigma_{0.2}$, δ, and ψ based on the KCU value using the following expressions:

$$\sigma_b = 334{,}25\ KCU + 20{,}5 \quad (1)$$

$$\sigma_{0,2} = 201{,}60\ KCU\ 18{,}7 \quad (2)$$

$$\delta = 7{,}1\ KCU + 6{,}8 \quad (3)$$

$$\psi = 7{,}645\ KCU + 7{,}01 \quad (4)$$

In addition to the chemical composition and physicomechanical properties of 110G13L steel, one of the most important acceptance characteristics is the metallophysical structure of the metal — a homogeneous austenitic structure without the formation of iron–manganese carbides $[Mn, Fe]_3C$ and carbophosphides. The presence of residual carbides (carbophosphides) in the structure of 110G13L steel leads to casting failures due to chipping. The metallophysical structure of austenitic manganese steel is determined by the temperature–time conditions of the steel's structural transformations (Fig. 1).

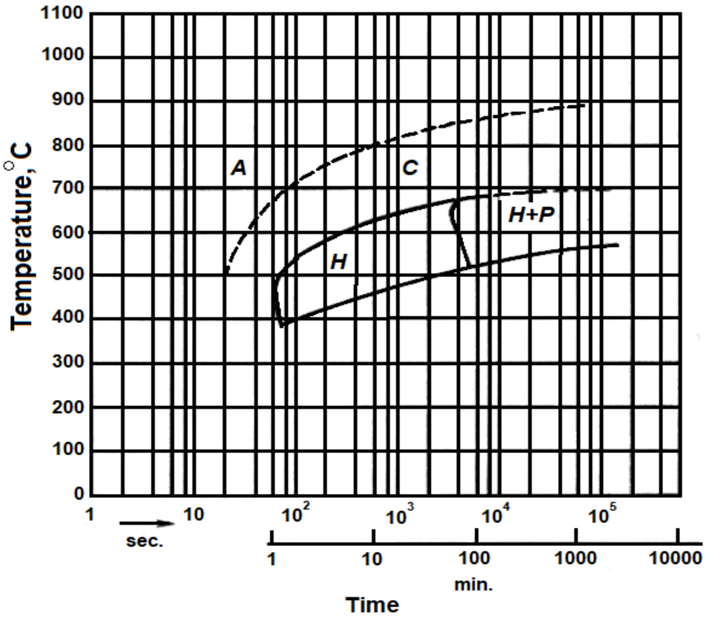

Fig. 1. Thermokinetic diagram of austenitic manganese steel (C – 1.29%, Mn – 13.3%). Austenitization at 1050°C for 15 minutes [9]: C – grain boundary carbide; H – needle-shaped carbide; P – pearlite

Reducing the carbon and manganese content to their minimum values within the grade chemical composition leads to an increase in the critical points Ac_3, A_3, and Ar_3 by 10–30°C. Conversely, increasing the C and Mn concentrations up to the grade limits lowers these temperatures by 10-30°C.

At PJSC Dniprovskyi Switch Plant [10], heat treatment is carried out according to the following regime: heating and prolonged isothermal holding at 1050–1100°C for 4–6 hours, depending on the weight of the product, followed by water quenching to obtain a homogeneous austenitic structure. During very slow cooling of the steel, precipitates of $[Mn, Fe]_3C$ carbide are formed.

Since manganese and carbon are the primary elements in the grade composition of the steel, determining the phase structure of the metal and its associated mechanical properties, the primary objective of the steelmaking process for frogs is to maintain a controlled content and ratio of these elements to produce castings with enhanced mechanical properties of Group 1 according to GOST 737.

A statistical analysis was performed on a dataset of the chemical composition and mechanical properties of industrial steel melts, with a sample size of 300 heats. It was determined that steel with a manganese content of 15.5% could belong to the third quality group based on mechanical property indicators, while steel with a manganese content of 12.1% corresponds to the first group. As a result of the statistical processing, frequency distribution characteristics of manganese content and the Mn/C ratio were constructed. The results are presented in Table 3, from which it follows that the frequency distributions of Mn and the Mn/C ratio are close to a normal distribution of a random variable.

The data presented in Table 4 show that the largest number of melts (42.12%) in the studied dataset have manganese content limits of 13–14%.

Statistical processing of the data showed that the majority of melts in the sample (≈89%) have a [%Mn]/[%C] ratio within the range of 10–13, with 45.99% of melts falling within the ratio 11.0 < [%Mn]/[%C] ≤ 12.0. The least common ratios are 9.0 < [%Mn]/[%C] ≤ 10.0, accounting for only 4.33%, and 13.0 < [%Mn]/[%C] ≤ 14.0, accounting for 5.99% (Table 4). It should be noted that the [%Mn]/[%C] ratio for the first quality group lies within 10.56–13.50; for the second group, within 9.74–14.63; and for melts of the third quality group, it ranges from 9.30 to 13.45.

Table 4. Specific Fraction of Steel 110G13L Melt Groups Depending on [Mn] Content, % and the Mn/C Indicator.

Grouping of Melts by Manganese Content, wt.%	Number of Melts, pcs	Specific Fraction of the Melt Group of the Total Number of Melts, %	Grouping of Melts with Respect to [%Mn]/[%C]	Number of Melts, pcs	Specific Fraction of the Melt Group of the Total Number of Melts, %
11,0 <X≤12,0	18	5,99	9,0<X≤10,0	13	4.33
12,0 <X≤13,0	86	29,67	10,0<X≤10,0	61	20,33
13,0 <X≤14,0	134	42,12	11,0 <X≤12,0	138	45,99
14,0 <X≤15,0	50	16,67	12,0 <X≤13,0	68	22,66
15,0 <X≤16,0	8	2,67	13,0 <X≤14,0	18	5,99
16,0 <X≤17,0	4	1,33	14,0 <X≤15,0	2	0,7
Total	300	100	Total	300	100

When selecting the chemical composition of 110G13L steel for specific groups of castings, it is necessary to take into account the influence of carbon and manganese content within the grade composition on the mechanical property indicators. With a rational alloying regime, a significant reduction in manganese consumption is possible while maintaining or even improving the mechanical properties of the steel.

Conclusions. An analysis of regulatory documents concerning the chemical composition and mechanical property levels of austenitic high-manganese steel 110G13L for railway turnouts has been performed.

Using mathematical methods of statistics, correlation dependencies describing the influence of impact toughness values on the strength characteristics of the metal were obtained. It was established that the tensile strength (σ_b) and impact toughness (a_k) values are the determining factors for the complex of strength and toughness properties of castings made of 110G13L steel.

A rational metal composition has been substantiated, taking into account the manganese content (≈12%) and the manganese-to-carbon ratio (10.56–13.60), for the production of cast steel components of Group I according to GOST 7370-98.

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НАЦІОНАЛЬНИЙ ФОНД ДОСЛІДЖЕНЬ УКРАЇНИ

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