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Development and Implementation of Electric Steelmaking Technologies for Manufacture of Railway Transport Parts and Main Steel Routes

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Described innovative competitive practice of electric steelmaking in arc furnaces for obtaining bearing rolled section ШХ15СГ-В (analogue 1.3520, EN) of freight wagon forged axes (35G, EAN1), castings of truck elements was developed and implemented by Electrometallurgy Department of National Metallurgical Academy of Ukraine in collaboration with JSC "Dneprospetsstal", JSC "Nizhnedneprovsk Tube Rolling Plant" and others. The results are generalized and analyzed. The new method of steel bath carburization - CSiC-briquettes and results of its application when steelmaking in arc and open-hearth furnaces are presented.

Keywords: ELECTRIC STEEL, ARC FURNACE, SMELTING PRACTICE, REDUCERS, ALLOYING, OUT-OF-FURNACE TREATMENT, ROLLED SECTION, CASTINGS, QUALITY, NONMETALLIC INCLUSIONS, MECHANICAL PROPERTIES

Introduction

Total length of the whole railway in the world is 1.12 million km including 228.5 thousand km in the USA (20.4 %), 87.2 thousand km in Russia (7.8 %), 70.1 thousand km in the People`s Republic of China (6.3 %), 46 thousand km in Germany (4.1 %).

Ukraine is the 13th in the world (22.5 thousand km, 3.9 %) and the 5th in Europe (after Russia, France, Germany and Poland). At the same time, the network of railway lines is the densest in Ukraine among CIS countries. Almost 50 % of all Ukrainian weights are transported by rail.

Mining and smelting industry as well as the whole industrial sector of Ukraine is characterized by developed transport infrastructure. 75 % are accounted for railway transport in total amount of cargo and passenger transportation. Joining of Ukrainian railways to the West European transport networks in many respects would predetermine integration of our country into the European community.

Creation and development of railway transport lines has a great geopolitical and economic importance. Export expansion of metal products produced by mining and smelting industry of Ukraine for railway transport also could become a real additional source of currency proceeds for strengthening export-import currency balance of the country.

According to the project of the International Transport Corridor ("New Silk Route"), three railway corridors (Berlin - Lviv - Kyiv; Trieste - Lviv; Helsinki - Kyiv - Odessa) from nine transport corridors can cross the territory of Ukraine.

Therefore, mining and smelting industry of Ukraine takes one of the most leading positions in solving the problems related to development of transport corridors. Also, improvement of metal products quality for railway vehicles and trunk lines should promote safe and cost-effective passenger and cargo transportation by rail.

Results and Discussion

Electric bearing steelmaking practice

According to previous technology at JSC "Dneprospetsstal", steel ШХ15СГ-В (analogue

1.3520, EN) was made in EAF-60 with the use of high-carbon ferromanganese FMn78 (State Standard of Ukraine 3547-97) and ferrosilicon FSi65 (State Standard of Ukraine 4127:2002) as alloying elements [1]. Sulfur was removed on ladle furnace by solid slag mixtures SaO-SaF_2, steel was deoxidated by silicon (ferrosilicon) and aluminum. At the finishing stage, metal was subjected to vacuum treatment in a ladle vacuum vessel with ultimate deoxidation by aluminum.

Despite constant improvement of steelmaking practice, rolled section yield from the first quality inspection did not exceed 70-75 % [2].

Requirements to both dimensions of bearing elements and quality of rolled section in relation to nonmetallic inclusions according to GOST 801-78 (with changes) and ASTM E-45 (A method) become more severe.

Moreover, supply of tubular billet for manufacture of bearing rings for railway transport has increased. Demand of ball bearing plants in rolled section has essentially raised recently due to increase in deliveries of large batches of bearings in the near and far abroad countries.

JSC "Kharkiv Bearing Plant" is one of the main suppliers of bearings to CIS countries, Baltic, Western Europe and South America. A number of car assembly plants of leading companies are being constructed in Russia. In this conjunction, equipment for manufacture of high precision class bearings meeting rigid requirements of mechanic engineers was overhauled. JSC "Kharkiv Bearing Plant" is implementing also an investment project providing manufacture of driving motor bearings, which will allow the plant to take a leading position in the market of bearings for railway transport.

Arc-furnace shop No. 3 of "Dneprospetsstal" specialized on bearing steelmaking is equipped with arc furnaces EAF-60, ladle furnace and ladle vacuum vessel. Steel bottom pouring is applied, and 3.6 t castings are obtained [3]. Equipment of the plant provides producing billets and rolled section of five dimensional groups of round and square profiles.

Conducted physic-chemical analysis of process cycle [4, 5] allowed determining that one of the major causes of increased amount of rejected samples with a high level of nonmetallic inclusions (first of all, globular hard-to-deform calcium aluminates) was application of ferrosilicon FSi65 with high calcium concentration (up to 0.6 %) not regulated by standard [7]. The features of steel deoxidation reaction products formation at single addition of manganese (ferromanganese) and silicon (ferrosilicon) also affect the rolled section yield from the first control.

ШХ15СГ-В steelmaking practice was developed and adopted by means of scientifically based diversification of applied ferroalloys and conditions of deoxidation and metal alloying. It was determined that at addition of ferrosilicomanganese instead of ferrosilicon FSi65 (0.4-0.6 % Ca) [5], metal deoxidation reaction products appeared in the form of low-melting manganese silicates, which are completely assimilated by slag during steel treatment by slag-forming mixtures on ladle furnace [6, 7]. Together with aluminum deoxidation condition, the rolled section yield increased up to 90-92 % from the first nonmetallic inclusions control [5].

In the process of adoption, steel ШХ15СГ-В was made in arc furnaces EAF-60 by two methods differing in addition of ferrosilicomanganese MnS17 into ladle (method 1) and steelmaking bath (method 2). Other manufacturing operations were carried out in complete conformity with developed technological instruction. 12 smelting operations were carried out by method 1 and 24 smelting operations by method 2 (with addition of MnS17 in the furnace) according to ШХ15СГ-В steelmaking practice.

803 kg of ferrosilicomanganese MnS17was added into steel bath per melting at FS65 ferrosilicon consumption 453 kg by method 1; by method 2 - 847 kg of MnS17 and 450 kg of ferrosilicon FS65.

Specific consumption of ferrosilicomanganese MnS17 in case of its addition into furnace (method 2) was 13.82 kg/t of melted steel, which was by 0.54 kg/t more than in case of ladle addition (method 1). So, smelting by 1st method was characterized by small consumption of ferrosilicomanganese FS65 (7.49 kg/t by method 1 instead of 7.34 kg/t by method 2). Thus, steelmaking by method 1 (addition of all ferroalloys into ladle) is featured by a little smaller total consumption of ferroalloys in relation to smelting by method 2 though this difference is not so significant (taking into account estimation of ferroalloys cost) as compared to technological advantage of ferrosilicomanganese MnS17 addition into furnace bath.

Efficiency of ferrosilicomanganese MnS17 application is confirmed by results of quality control of steel ШХ15СГ-В rolled section in relation to nonmetallic inclusions. 165 samples of steel rolled section from 20 batches and 12 smelting operations by method 1 and 374 samples from 52 batches and 24 steelmaking operations by method 2 were controlled. In case of method 2, yield from the first quality control of rolled section was 98 %. Lower yield by method 1 was caused primarily by increased amount of rejected samples of III group by oxides (13.8 %) at yield 100 % for 1, 2, 4 and 5 groups. Quality indexes of 1 and 5 groups were selected to determine characteristics of metal by mathematical statistics methods. Results of statistical processing are given in **Table 1** [5].

Table 1. Generalized results of quality of ШХ15СГ-В (analogue 1.3520, EN) steel smelted experimentally

Method	Groups according to GOST 801-78	Number of samples	Inclusions, point		
			oxides O	sulfides S	globules G
1 (MnS17 into ladle)	1	57	1.90±0.03	1.70±0.03	1.92±0.04
	У	149	2.20±0.04	2.21±0.03	2.14±0.03
2 (MnS17 into furnace)	I	60	1.97±0.06	1.96±0.06	1.88±0.07
	У	153	2.36±0.04	2.32±0.03	2.13±0.03

Statistical selection of quality indexes with the use of Fisher's ratio test allows drawing conclusion about the absence of statistical differences in two technological methods. Both methods completely ensure yield for 1 and 5 groups according to GOST 801-78. Metal of 2nd group is characterized by stably low point of globular inclusions regulated by the standard.

Addition of ferrosilicomanganese MnS17 into furnace creates premises for further improvement of steelmaking and refining practice according to ASTM E-45 (A method). As a whole, metal smelted with application of MnS17 corresponds to norms ASTM E-45 (A method). Quality of rolled section in relation to concentration and composition of nonmetallic inclusions expands export possibilities of ШХ15СГ-В manufacturer for countries focused on application of metal products under American standards.

Thus, large-scale adoption of steel ШХ15СГ-В smelting and refining showed high efficiency of practice with diversification of applied ferroalloys, deoxidation conditions, alloying with MnS17 (State Standard of Ukraine 3548-97) instead of ferrosilicon FS65 and high-carbon ferromanganese FMn78 (State Standard of Ukraine 3547-97) as complex reducer and alloying element. Yield of steel ШХ15СГ-В rolled section from the first control in case of addition of ferrosilicomanganese MnS17 into ladle was 90 % and into furnace - 98 %.

Implementation of innovative ШХ15СГ-В steelmaking practice with diversification of applied ferroalloys and conditions of deoxidation and metal alloying with ferrosilicomanganese, with partial utilization of FS65 instead of high-carbon ferromanganese and great amount of ferrosilicon ensures decrease of specific consumption of ferroalloys from 25.3 to 21.5 kg/t, i.e. by 15 % along with improvement of rolled section quality [2, 7].

Thus, developed and scientifically-based bearing steelmaking practice ensures rolled section manufacture with quality meeting requirements of GOST 801-78 and norms ASTM E-45 (A method). And yield from the first inspection of ШХ15СГ-В steel rolled products is 98 %.

Electric steelmaking practice for manufacture of forged blank of car axles

The mobile freight train is operated at car axle loading 228 kN (23.25 t). It is necessary to increase axle loading up to 245 kN (24.99 t) by upgrading quality of forged axes and seamless-rolled wheels. Increasing unit loads in reliance on mounted wheels and increase in train speed cause more severe requirements to mechanical properties of steel for seamless-rolled wheels and axes of freight wagons.

Manufacture of forged blanks for electric steel axes is a complicated multistage process including steelmaking in arc furnaces with basic lining, refining of steel half-finished material in the electric furnace-ladle, steel degassing in the ladle vacuum vessel, steel bottom casting, rolling of ingots with subsequent forging, forging and heat treatment of axes which should meet quality requirements of domestic and foreign standards. The processes were theoretically grounded, innovative flow diagram of electric steel EA1N axes manufacture was developed in [8]. According to standard UIC 811-1 OR, temporary agglomeration of axe metal should be within the limits 550-650 N/mm^2, ultimate strength should be not less than 320 N/mm^2, contraction ratio not less than 22 %, impact work at longitudinal cutting of sample 25 J, at cross cutting -10 J. According to norms EN 13261, impact energy for longitudinal cut sample is 30 J and for cross cut sample is 25 J.

According to standard UIC 811-1 OR, all types of nonmetallic inclusions should not exceed 2.5-3.0 (for thin) and 2.0 (for thick) points under control by ISO 4967 A method. According to standard EN 13261, metal impurity with these inclusions should not exceed 2.0 and 1.5 points respectively.

The principles of new EA1N steelmaking practice

Steel was made in the arc furnace EAF-60 with oxygen application. Slag was removed after oxidation of phosphorus and carbon, and metal-semiproduct was deoxidated by ferrosilicon FSi65, aluminum and processed by solid slag mixtures in the ladle. Further, metal was treated on furnace ladle and in vacuum vessel. Steel was deoxidized with aluminum, titanium and ferrosilicon. Sulfur content was lowered in the process of steel treatment on furnace ladle to reduce steel impurity. Also residual concentrations of Al, Ca and addition of Ti were strictly regulated.

Thus, the innovative technology of forged blanks manufacture for freight cars of railway transport was developed and adopted.

Electric steel 110Г13Л (analogue 1.3401, DIN) smelting practice for frogs and diamonds

Pointworks of express tracks at iron & steel works are complicated and critical components of railways and are operated under conditions of considerable dynamic loads and abrasive-corrosion wear. It leads to premature wear and necessity to put frogs out of operation after 2-3 years.

The urgency of problem related to improvement of frog quality is confirmed by immensity of their use on railways of Ukraine [9]. As known, the length of main railways in Ukraine is 22.5 thousand km. 2-3 pointworks fall on 1 km of railway, so the total amount of frogs in the pointworks of Ukrainian railways reaches 45-60 thousand.

Frogs and diamonds are made of carbonaceous high-manganese austenite steel. Chemical composition is, %: 11.5-16.5 Mn; 1.0-1.3 C; 0.3-0.9 Si and ≤0.09). Mechanical properties are regulated by standard of GOST 7370-98 (**Table 2**).

There were no quality groups of casting metal, and indexes of mechanical properties for 110Г13Л steel were much lower (σ_{TS} 720 MN/m^2, $\sigma_{0.2}$ 353 MN/m^2, ψ 20 %, δ 20 %, KCU 1.8 MJ/m^2) in the previous GOST 7370-86. Therefore, 110Г13Л steelmaking practice did not provide frogs and diamonds of the first quality group.

One of the most important factors affecting quality of mechanical properties of castings is scientifically-based regime of steel deoxidation ensuring low residual concentration of oxygen, certain types and amount of nonmetallic inclusions [10].

Physic-chemical investigation of products of steel deoxidation by aluminum was conducted in present work with the use of micro X-ray spectrum analysis on electron microscope JEOL and fractional gas analysis (FGA) [11]. Thermodynamic analysis of processes of molten steel deoxidation with C, Mn, Si and Al preceded the experiments. Mathematical models were developed and change of mechanical properties of casting metal depending on chemical composition of steel taking into account wide intervals of each element content in accordance with GOST 7073-98 was forecasted on the basis of these data. Rational element concentrations were defined by developed

Table 2. Mechanical properties of 11013Л steel for frogs and diamonds in accordance with GOST 7370-98 [9]

Mechanical properties	Limits of mechanical properties by quality groups		
	I group	II group	III group
Tensile strength, σ_{TS}, MPa (kgs/mm^2)	≥ 883 (90.1)	785 – 882 80.1 – 90.0	686 – 784 (70.0 – 80.0)
Conventional yield strength, $\sigma_{0.2}$, MPa (kgs/mm^2)	≥ 353 (≥ 36.0)	≥ 353 (≥ 36.0)	≥ 353 (≥ 36.0)
Elongation, δ, %	≥ 30.1	25.1–30.0	16.6–25.0
Contraction, ψ, %	≥ 27.1	22.1–27.0	16.0–22.0
Impact strength, MJ/m^2	(≥ 25.1)	(20.1–25.0)	(17.0–20.0)

statistical models. Physic-chemical simulation of casting properties was carried out according to E. V. Prihodko's theory. Indexes of required mechanical properties of metal for a specified group of casting quality were forecasted with application of this model [12].

Process conditions of 110Г13Л steelmaking were scientifically-based and recommended for practical application on the basis of data of theoretical and experimental investigations accomplished with the use of current equipment and methods. Process conditions of steelmaking providing increase in manufacture of frogs and diamonds of the highest group quality and reduction of specific consumption of aluminum for steel deoxidation are implemented.

20ГЛ (analogue A352 Gr LCC, ASTM A352) steelmaking practice for freight-car trucks with the use of new recarburizing agent of steel bath instead of iron

When steelmaking in arc and open-hearth furnaces and synthetic iron smelting in induction furnaces using scrap, selection of effective recarburizing agents of steel bath is an urgent problem [13]. Traditionally applied recarburizing agents (iron, crushed electrodes, coke breeze, anthracitic coal) are high cost or scarce. Disadvantages of these recarburizing agents were revealed in the process of bath decarburization by oxygen, which is known to carry out for the purpose of liquid metal degasification (reduction of hydrogen content). The mechanism of metal degasification during metal boiling is researched enough. At the same time, when analyzing the process of steel bath decarburization less attention is paid to growth of oxygen concentration in metal and content of iron oxides in slag as carbon content in metal decreases.

When working out a new recarburizing agent, we proceeded from necessity to create a such recarburizing agent which from one hand would act as a recarburizing agent and from another - would reveal ability of decarburized metal to deoxidation. It is clear that such recarburizing agent should be a material composed of carbon and deoxidant components [14, 15].

Expedience of obtaining composite recarburizing agent with the use of secondary carbon materials of manufacture of graphitized carbon products and abrasive (metallurgical) silicium carbide is confirmed on the basis of investigation data. Basic materials are subjected to briquetting on a cement bond for the purpose of effective utilization of new recarburizing agent [14, 15]. Composite recarburizing agent of new type was called CSiC-briquettes. Briquettes CSiC contain 10-15 % of SiC and 55-65 % of carbon. Briquettes are not dried but soaked under usual conditions until hydration of cement is finished. Mechanical strength of briquettes is 50 kg/cm^2 per briquette.

The processes of CSiC-briquette and melt interaction have a number of distinctive features as compared to bath carburization with crashed electrodes, coke or anthracitic coal.

Carbon component of briquette is dissolved in iron according to endothermic reaction

$$C_{gr} + Fe \rightarrow [C]_{(1\%\text{solution in Fe})} \quad \text{(Eq. 1)}$$

$$\Delta G^0_T = 22600 - 42.3\ \text{J/mole}. \quad \text{(Eq. 2)}$$

Silicic carbide interacts with iron melt with silicium and carbon entry into steel bath:

$$SiC_{sol} + Fe \rightarrow [Si]_{(1\%\text{solution in Fe})} + [C]]_{(1\%\text{ solution in Fe})} \quad \text{(Eq. 3)}$$

$$\Delta G^0_T = 4070 - 102.66\,T,\ \text{J/mole}. \quad \text{(Eq. 4)}$$

Endothermicity of this reaction is caused by high thermodynamic strength of silicon carbide:

$$Si_l + C_{gr} + SiC_{sol} \quad \text{(Eq. 5)}$$

$$\Delta G^0_T = -100600 + 34.9\,T,\ \text{J/mole} \quad \text{(Eq. 6)}$$

So, the higher temperature, the more SiC dissolution rate in the liquid iron. Mathematical model of SiC and iron melt interaction process was developed.

$$\tau = 183.6 \cdot r_0^2,\ \text{s}. \quad \text{(Eq. 7)}$$

Results of calculations show that if SiC particle size with radius *r* exceeds the "critical", duration of its "dissolution" in iron is longer than duration of scrap melting. Not dissolved part of SiC particle can float and be assimilated by slag.

Cement high-melting bond of high basicity in CSiC-briquettes ensures slow dissolution of silicon carbide grains and carbon material in the course of scrap melting also at its full melting down.

20ГЛ steelmaking practice with the use of CSiC-briquettes without iron application

Experimental smelting of steel 20ГЛ was carried out in arc furnaces EAF-25 using fresh charge with carburization of steel bath by CSiC-briquettes and carbon oxidation by gaseous oxygen. The charge consisted of steel scrap (25 t) and CSiC- briquettes (0.4-0.6 t). All steelmaking operations were accomplished according to current technological instruction. Metal in the furnace and ladle was deoxidated by aluminum and poured into sandy-argillaceous molds. Further, the castings were heat treated (normalized). After heat treatment, ferrite-perlite microstructure of castings corresponded to quality indexes of standard-technological documentation.

We examined nonmetallic inclusions using electron microscope JEOL with energy-dispersive add-on device RSMA 101A. Microanalysis was carried out on polished microsections and fresh fractures of samples with recording energy-dispersive spectra. Oxygen concentration in samples of 20ГЛ steel was defined by fraction gas analysis method developed by Corresponding Member of the Russian Academy of Sciences K. V. Grogorovich.

Fraction gas analysis method allowed defining total concentration of oxygen in steel sample, amount of oxygen bounded with sample surface, estimating amount of oxygen bounded in various types of oxygen-containing inclusions: silicates (36-55 %), aluminates (40-57 %) and aluminosilicates (1,2-5,8 %) [16]. The use of CSiC-briquettes instead of iron during experimental melting allowed reducing metal cost price by 15 %.

Tube steelmaking practice in open-hearth furnace with the use of CSiC-briquettes

Tube steelmaking practice in open-hearth furnace with partial substitution of iron by CSiC-briquettes was developed and adopted [17]. Preliminary experiments determined that one ton of CSiC- briquettes is equivalent to 10 t of iron in relation to carbon content. 42 smelting operations were carried out in 250 open-hearth furnaces with the use of CSiC-briquettes. Statistical processing of data allowed determining analytical interdependence between iron consumption per melting operation ($Q_{\text{iron per melting operation}}$) on amount of added CSiC- briquettes ($q_{\text{briq. per melting operation}}$)

$$Q_{pig-iron} = 1.247 q_{briq}^2 - 15.774 q_{briq} + 8.585. \quad \text{(Eq. 8)}$$

Data processing of rolling 330 ingots (weighing 1.74 – 2.6 t) in tubes with diameter from 168 up to 219 mm showed that amount of rejected tubes was 0.95 % against 1.42 % under current steelmaking practice.

Developed steelmaking practices with the use of CSiC-briquettes are recommended for steelmaking at other plants.

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Разработка и внедрение электрометаллургческих технологий выплавки электростали для производства элементов подвижного состава и стальных магистралей железнодорожного транспорта

Гасик М. И.

Обобщены и проанализированы результаты разработанных и внедренных в производство кафедрой электрометаллургии НМетАУ совместно с ОАО «Днепроспецсталь», ОАО «ДСЗ», РАО «КСЗ», ОАО «НТЗ» инновационных конкурентоспособных технологий выплавки электростали в дуговых электропечах для получения сортового проката подшипникового (ШГ15СГ-В) кованых осей грузовых вагонов (35Г, EAN1) отливок элементов вагонных тележек (20ГЛ, 20ГФА), приведены данные о разработанном новом виде науглероживателя стальной ванны – CSiC-брикетов и результатов их применения при выплавке стали в дуговых и мартеновских печах.