RESEARCH INTO THE EFFECT OF CERTAIN CHEMICAL ELEMENTS IN MICROALLOYED STEEL GRADES ON CONCAST SLAB AND ROLLED PLATE SURFACE QUALITY

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Abstract: *Investigators has developed a complex technology of manufacture of high quality skelp and shipbuilding grades and nickel-, chromium-, molybdenum-, niobium- and vanadium- microalloyed steels with carbon mass fraction within 0.06% to 0.22% and manganese mass fraction within 1.0% to 1.7%. Over the course of the research, relative occurrence of surface cracks of various morphology – transverse, longitudinal, spider, net-like – on the concast slab surface has been determined. The above research resulted in the development of a number of technological innovations both in preparation of liquid steel for casting and in continuous casting itself, preventing initiation or reducing by 30% – 40% the amount of surface defects on the rolled plates.*
KEY WORDS*: PERITECTICAL STEEL GRADES, CHEMICAL COMPOSITION, CASTING TECHNOLOGY*

Introduction

The experience of prime steel production made it possible to find out that the surface of a concast slab and consequently that of plate steel under certain conditions has a number of defects like cracks of different morphology – cross, longitudinal, net-like and star cracks.

Experimental

A complex procedure of plate steel production of prime steels for large diameter gas line pipes, shipbuilding and steel structures of critical application microalloyed with niobium wherein carbon weight fraction. is in the range of 0.06 to 0.22% and manganese weight fraction – 1.0 to 1.7% was developed and implemented at the Iron and Steel Works. Steel was made in 350 t converters and put to ladle treatment at the metal-refining plants with introduction of silicocalcium wire. Continuous casting was done at curvilinear slab concasters into 220…300 x 1550…2100 mm section slabs as to a worked-out procedure.

Chemical composition of the steel grades studied is shown in Table 1.

Table 1. *Steel chemical composition*

Steel grade	Application	Elements weight fraction, %							
		C	Mn	Si	S	P	Al	Nb	V
08MnNb	Skelp	0.06–0.09	1.00–1.35	0.15–0.35	max 0.006	max 0.020	0.020–0.050	0.020–0.040	0.015–0.035 Ti
09Mn2VNb	Skelp	0.08–0.11	1.50–1.70	0.15–0.35	max 0.006	max 0.020	0.020–0.050	0.020–0.040	0.050–0.070
13Mn1SiNb	Skelp	0.12–0.15	1.30–1.60	0.40–0.60	max 0.007	max 0.025	0.020–0.050	0.020–0.040	0.015–0.035 Ti
ASTMA572	Structure	0.12–0.16	0.80–1.00	0.15–0.35	max 0.015	max 0.020	0.020–0.060	0.005–0.020	–
S355J2G3	Structure	0.16–0.19	1.40–1.60	0.15–0.40	max 0.015	max 0.020	0.020–0.050	0.020–0.040	–

* - other elements are in the range specified by standards for residual content

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For a more serious study of concast slabs affected with surface defects, determination of factors conducive to crack formation process and elaboration of practices aimed at reducing defect occurrence, surface templates were cut from middle slabs of 5 to 10 heats of the above-mentioned BOF shop current production steel grades. To reveal surface defects the said templates were put to hot etching with 50% aqueous solution of hydrochloric acid. The evaluation of surface quality was done as per the current scales and procedure of researches institutes. Evaluated were the slab wide face surfaces corresponding to the smaller and larger concaster radii (in percentage) and the extent of defect development (severity evaluation system).

In the course of the study relative affection of the concast slab with surface cracks was determined. Each typical concast slab defect, unless revealed and rectified, gets transformed into plate steel surface defects. Slabs with revealed and identified defects were selected for rolling to study concast slab surface defects transformation into plate steel surface defects. Slab rolling was done at 3600 mm Plate Mill as per conventional procedure of slab preheating and rolling.

Results and Discussion

Based on the results of rolling slabs having surface defects transverse cracks 0.5 to 3.0 mm deep as per the folds of the mould oscillation were found to get transformed depending on the gauge of plates, into rolling skin of specific appearance – so called “μ -defects” having the depth of penetration of up to 0.03 mm (vide fig.1). Longitudinal cracks having the depth of 0.5 to 3.5 mm get transformed into skin spread along rolling direction to a considerable length resembling so-called “streaks”. Check cracks 0.5 to 3.0 mm deep and star cracks, 3.0 to 10.0 mm deep after rolling plates look like randomly oriented skins and cracks with different depth of penetration (vide fig.2).

Metallographic studies revealed certain regularity between steel product quality indexes and steel chemical composition and, accordingly, between polymorphous transformations of iron-carbon alloy with a number of alloying elements being used.

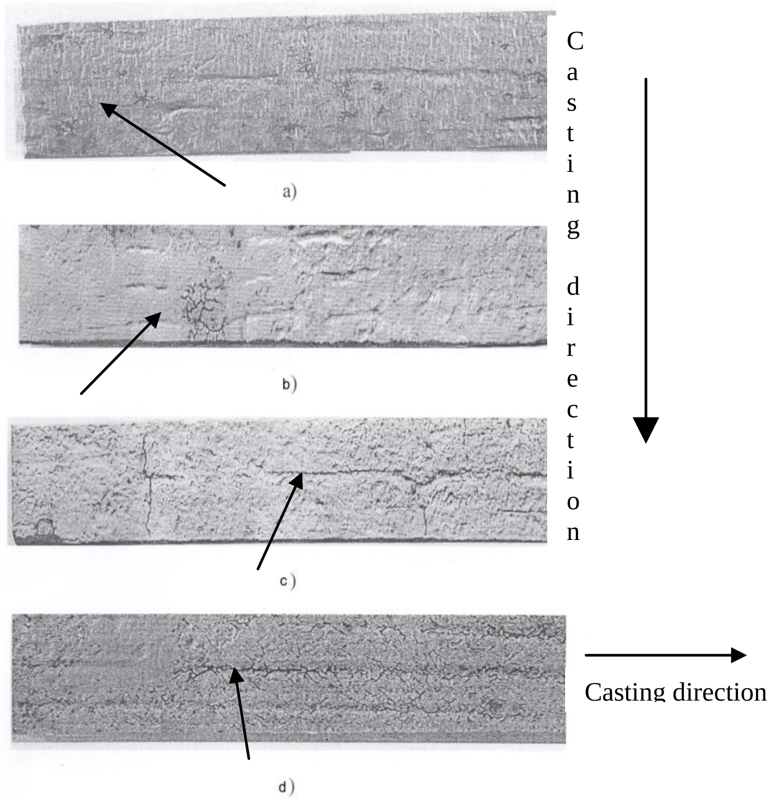

Fig. 1. *Typical slab surface defects.*
a – "star" cracks; ; b – netlike cracks; c – transversal cracks; d – longitudinal cracks

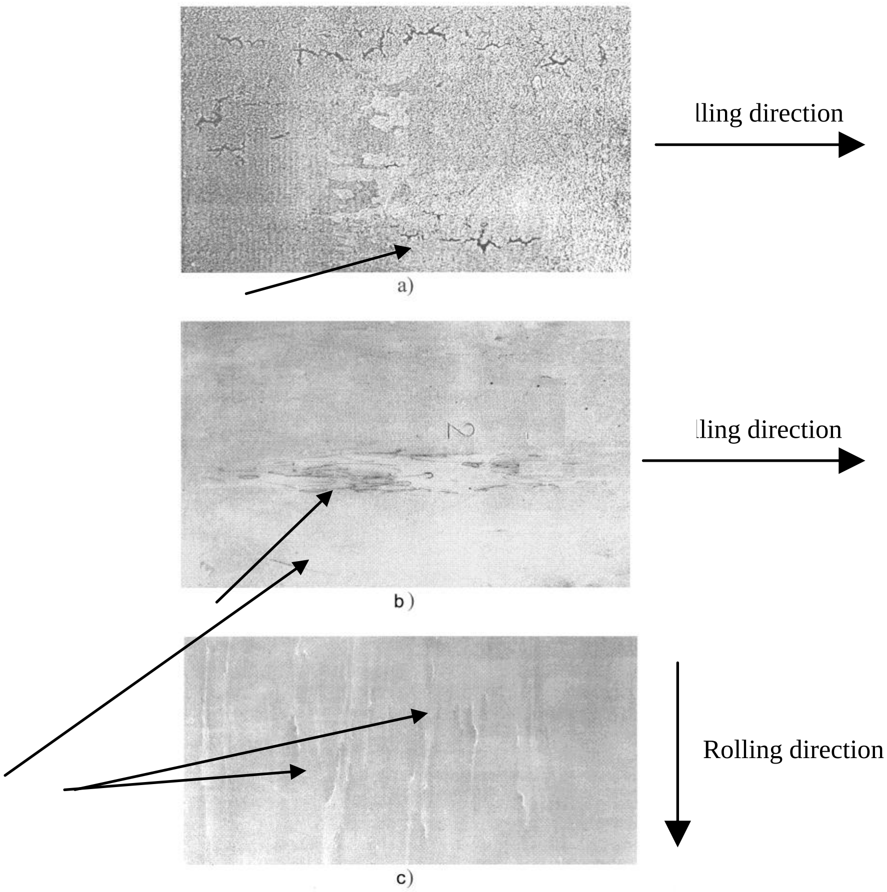

Fig. 2. *Transformation of slab defects to rolling plates.*
a – netlike cracks; b – rough scab; c – shallow scab ("μ"-defect).

Carbon content impact

In the course of study observed was an obvious tendency of crack number increase per unit of area and the degree of their development with an increase of carbon content in the examined range of carbon content changes – from 0.07% to 0.21%. The integral value of the defect-stricken surface of slab of steel grade 08MnNb with carbon content being 0.06 ÷ 0.09% was taken for a unit of crack formation conventional index. The crack formation conventional index takes into account both the value of the slab surface affection with cracks and the crack depth penetration.

Simultaneously it was observed that along with carbon concentration change from 0.09% to 0.21% surface crack morphology undergoes certain changes – at carbon weight fraction being in the range of 0.10 ÷ 0.14% check cracks are prevalent, while at carbon content being 0.15–0.21% there was a considerable amount of transverse and star cracks observed along with check cracks.

Analysis of the Fe-C diagram at carbon weight fraction in steel being within 0.08 to 0.45% shows presence of 3 principally different areas of the melt solidification. Comparing the data of the table and the Fe-C diagram it was noted that steel grades 08MnNb and 09Mn2VNb solidification takes place in the area where there's a transition from δ-iron to γ-iron in the completely solidified metal.

For steel grades 13Mn1SiNb and ASTMA572 having δ-γ transition in accordance with the standard interval of carbon content there's a provision both for a variant of transition into a completely solidified metal and for a variant of peritectic transformation from "δ+liquid" to "δ+γ" at constant temperature. For steel grades S355J2G3 or St52.3 the following variants of solidification are possible: "δ+liquid" into "δ+γ" or "δ+liquid" into "γ+liquid". Under such conditions the factors, which usually play unimportant role, have significant influence on quality indexes of the surface of metal. To these factors should be referred minor fluctuations of hot metal level in the mould while casting steel at a concaster, inessential moisture deviations and deviations of granulometric slag-forming composition (within the limits stated by normative documents), technological deviations of casting rate related to changes of submerged nozzles, tundishes etc.

Based on the results of the study, considering that carbon weight fraction in steel affects consumer qualities of finished metal product to a large extend, the Works' specialists focused their special attention to such steel grades, that were most susceptible to defect formation processes. As a result, a whole series of engineering measures and corrective actions both in the field of preparation of liquid steel for casting and directly at concasting of steel were worked out to avoid or to reduce essentially defect formation processes essentially.

Manganese content impact

It was established that, fraction of surface defects had steady tendency to increase with growth of manganese weight fraction in steel, which was confirmed with essentially greater number of defects on the surface of steel 13Mn1SiNb and 13Mn1Si (manganese content up to 1.6%) in comparison with steel grade ASTM A572 (manganese content up to 1.0%). It was found, that with increase of manganese weight fraction in steel in 0.05% in the range of 1.2% to 1.8% of manganese content defect-stricken surface of the concast billet increased approximately in the same value according to linear dependence. In addition, it was found that most unfavorable conditions of billet skin formation in the mould at casting steel are observed for the grades, whose solidification was possible under various variants so-called peritectic steel grades – 13Mn1SiNb and S355J2G3.

Aluminum and nitrogen content impact

The impact of such elements as aluminum and nitrogen was put to the study too. As a result of these elements emission at grain boundaries in the form of aluminum nitride ALN metal ductility in the temperature interval of embrittlement while casting steel of peritectic type decreased. It promotes the formation of small-sized longitudinal cracks at the temperature of slab surface of 700–900°C, that corresponds to the area of a billet unbending at the concaster secondary cooling zone (curvilinear area), where slab crust is put to considerable fluctuating load. As a result of transformation of this type of defects at rolling, shallow skins were formed, which are situated mostly at side area at a distance of up to 300 mm from the plate edge. Based on the results of the study it was stated, that minimal propagation of longitudinal cracks was formed at nitride content less than 0.006% and aluminum weight fraction in the range of 0.029–0.032%.

Impact of impurities of nonferrous metal

Taking into account, that peritectic steels are susceptible to crack formation initially rather topical question is the issue of rating of impact of impurities of nonferrous metals on quality of concast slab and plate products. It is generally known that residual impurities of nonferrous metals have a harmful effect on the quality of cast and rolled metal. At the analysis of effect of impurities of nonferrous metals on quality indices an essential influence of the increased concentrations of nonferrous metals was marked on: 1) formation of the rough cross cracks in some cases resulting in destruction of slabs; 2) formation of cracks perpendicular to a wide side or narrow and face sides of a slab; 3) increase of a rejecting of plate steel regarding surface defects of steelmaking and the defects revealed with the ultrasonic control (presence of internal cracks in the center line area of a sheet).

A thorough investigation and analysis of the manufacturing method of the slabs, undergone to destruction was carried out: 1) in the slab yard of the BOF shop; 2) during transportation or transfer; 3) at reheating in the furnace before rolling; 4) during rolling.

It is necessary to note, that the fact of slabs destruction at a rough cross crack occurs rather seldom. So, a number of the destroyed slabs at all stages (conversions) in the last years came to 5.5 cases / 100 thousand of slabs. It was noted, that exclusively manganese steel microalloyed with niobium or steel fully alloyed with niobium and vanadium, first of all steel grades: St52.3 under DIN 17100 or S355J2G3 under EN 10025 (about 90%) were susceptible to destruction.

The formed crack in overwhelming number of cases passes all over the dendritic-web areas. In the area of a break small-sized stress cracks depart from the basic crack. Microfractographic study was carried out on a focused-beam electronic microscope REMMA-202M and to show, that destruction of samples basically was characterized by fragile destruction of grain boundaries. It confirmed the statement about embrittlement at grains boundaries due to nonferrous impurities.

According to the carried out studies determined were the maximum permissible impurities concentrations: for lead – 0.0003–0.0004%, for antimony – 0.0003%, for tin – 0.0005–0.0006%, for zinc – 0.0020–0.0030%. It was established, that the degree of effect on increase of crack sensibility decreases in the following order «antimony-lead- tin-zinc». Based on this, the empirical formula determining the given total limiting concentration of impurity of nonferrous metals, not rendering visible deterioration of properties of cast and rolled metal of manganese steels with carbon content 0.17–0.22% is offered: C_M = %Sb + 0,75%Pb + 0,5%Sn + 0,1%Zn ≤ 0,0012, where C is the given total concentration of nonferrous metals in finished steel.

At excess of the given "threshold" value expansive growth of deterioration continuous cast slabs – occurrence of rough transverse cracks on the surface of narrow and wide sides of an billet, face cracks perpendicular to wide sides is observed. In most critical cases (for steels with carbon content in the range of 0.18–0.21% of 78 and manganese more than 0.01%) destruction of slabs or presence of a main cross through-the-thickness transverse crack of plate steel is observed.

"Threshold" value C_M increases with simultaneous decrease of the carbon and manganese content. During studies it is marked, that for steel with the carbon content in the range of 0.17–0.21% at increase by carbon in 0.01% "threshold" value of the given factor

C_M should be decreased by 0.0004%. At excess of “threshold “values” C_M for steels with carbon content in the range of 0.10–0.11% and manganese more than 1.6% or with carbon content 0.14–0.16% and manganese in the range of 1.0–1.2% face cracks perpendicular to wide sides at the worst are observed.

Hydrogen impact

Not less essential effect on quality of a surface of concast slab is rendered by availability of the dissolved hydrogen in steel. Change of a heat sink from a mold wall to a solidified billet skin is the factor resulting in formation of the above-mentioned net-like check and star cracks. This assumption is confirmed by calculation of the amount of hydrogen releasing at steel solidification and its getting into the hit in a liquid layer of slag at the copper wall of a mould.

It’s from the known published sources that the data for the equilibrium value of hydrogen solubility in liquid steel was taken to be within the limits of 26 ppm near the liquid point and within 8 ppm near the solidus in solid δ-iron. The thickness and length of a liquid slag interlayer was taken for calculations to be respectively 2–3 mm and 600–700 mm, a reference value of hydrogen concentration in solid steel over equilibrium concentration to be 4 ppm. For case of short periods of time it’s possible to assume that up to 2 ppm of hydrogen are released from the solid shell of an billet into the liquid interlayer of slag. Taking into account low sorption ability of slag on the basis of and the initial moisture content in the mix to be within 0.4 – 0.5% it is pertinent to make the assumption that hydrogen released from steel forms bubbles floating up to the surface of slag. The greatest possible amount of the released hydrogen in the way of bubbles is comparable to the volume of the whole liquid interlayer of slag. Simultaneously nonuniform hydrogen allocation along the perimeter of billet can be the additional factor that breaks a uniformity of a heat-conducting path and accordingly results in initiation of concast billet surface defects both on wide and narrow sides of billet.

Development of corrective actions

Taking into consideration that a fracture of total mass of a number of elements contained in steel is defining the consumer properties of finished steel products, particular attention was paid to those steel grades that are to the utmost susceptible to the defect forming process. In the course of work several technological innovations were generated both in the field of liquid steel preparation for casting and directly in the process of continuous casting thus allowing to avoid or essentially minimize negative affect of the unstable processes of crystallization and solidification.

A number of measures were worked out at several Works to significantly improve slab surface quality. In case of possible change in steel chemical analysis, not contradicting the regulatory documents, the content of carbon was changed towards minimization.

Several technological measures were suggested for steels with strict specification of chemical composition (in particular, by carbon content): 1) use of recycled low sulphur scrap only in steel melting and primary aluminum for steel deoxidation; 2) optimization of the granulometric composition of slag-forming mixtures for concasting of steel and in a number of cases use slag-forming mixtures of the molten base for the purpose of improving the slag-forming process on the surface of melt in the mould and conditions of heat abstraction between the mould wall and the slab crust; 3) application of special “mild” secondary cooling mode to melt slab steel grades 13Mn1Si and 13Mn1SiNb to decrease thermal stress in the solidifying rim of the slab; 4) slow cooling slabs of steel grade S355Nb slabs including cooling in boxes to reduce internal macro stresses in cast steel.

Found that changing of the heat sink conditions under unsteady casting conditions has negative effect on solidification of steel undergoing peritectic transformation. In that case unsteady solidification process facilitates extension of lap depth and crack initiation of different morphology – transverse, netlike and spider cracks – on the billet surface. Increasing of mixture viscosity due to mixture temperature reduction at metal mirror and billet surface results in slag pulling into billet subsurface layer. Reduction or full stoppage of metal feeding to the mold during transient process leads to almost complete liquidation of compelled upflows in steel and facilitates nonmetallic inclusions entanglement among growing dendrite axis from the direction of CCP minor radius. Reduction of slag layer temperature and billet temperature is a reason of saturation of liquid slag layer with the bubbles of hydrogen escaping from billet and heat sink abrupt change at local points. Reduction of billet surface temperature in unbending zone towards brittleness temperature interval is a reason of initiation or propagation of surface cracks originated in the crystallization zone both on the narrow and broad billet edges.

Essential increasing of concast slabs rejection due to surface defects and downgrading of rolled plates manufactured from the slabs cast under irregular condition is a confirmation of the above mentioned negative factors effect. Rejection of the slabs cast under transient condition due to surface defects is 1.5 – 2 times more than that during casting under stabilized condition. For example, “pipe” defect is detected only under transient condition. At the same time plate downgrading due to the defects discovered with the help of ultrasonic testing, according to 2^{nd} – 3^{rd} class of SEL 072 standard and similar to it, increases 3 – 5 times more. Rolled metal downgrading due to the skins and slag impurities is increasing 2 – 3 times more.

Casting process under irregular condition increases essentially hazard of off-optimum and emergency situations at the CCP. As example of such negative influence is increasing of billet skin sticking index and bleeding index under the mould. Sticking and bleeding index while casting of the first slab’s meter after nozzle exchange is 20 – 30 times more, while casting of the second – third meter is 15 – 20 times more than while casting under stabilized condition. Each case of casting under irregular condition leads to a great amount of technological crops such as teeming arrests, both top and ground scraps, scrap in the form of metal remains in tundish while tundish exchange or the termination of the casting process.

One of the possible solutions of the question of casting speed and temperature stabilization is decreasing of transient conditions quantity. It permits to increase the average casting speed to obtain the reduction of crop and metal quality improvement.

Most of the transient conditions, such as submerged nozzles replacement and tundish replacement, finishing of the casting process are related with limited life time of the casting refractory materials such as stopper rod, no swirl nozzle and submerged nozzle. Increasing of refractory components resistance and, hence, the number of heats a series is one of the important conditions of concast billet quality improvement.

With the purpose to reduce the rate of defects in a concast slab, the usage of rational by chemical composition refractory materials, with more than 1.2% manganese mass fraction, for steel casting was introduced at some Iron and Steel Works. Mullite-graphite submerged nozzles were selected as having higher mechanical wear resistance and low sensitivity to manganese interaction. The usage of stopper rod monoblock units and argon blowing of the no swirl nozzle at the rate 0.1 – 0.2 m^3/hr, which prevents inclusion deposition on work surfaces was suggested for the purpose of steel castability improvement and decrease of non-regular conditions during casting.

More difficult question was a selection of optimal casting refractory materials for casting of ordinary peritectic steels, such as carbon and manganese steel with up to 1.2% Mn content. While casting steel of this type, it is possible to use both quartz submerged nozzles less sensitive to the process of alumina particles deposition on refractory work surfaces and high strength mullite-graphitic submerged nozzles. Three different types of casting refractory complete sets were used for comparative experiments: 1) option 1 – jointed stopper rod, biceramic no swirl nozzle and quartz submerged nozzle with steel silicocalcium treatment of the most important steel grades at argon stirring plant; 2) option 2 – jointed stopper rod rod, periclase-graphite nonswirl nozzle and quartz submerged nozzle with steel silicocalcium treatment of all grades at argon stirring plant; 3) option 3 – stopper rod monoblock unit, periclase-graphite or corundum-graphite no swirl nozzle and mullite-graphite submerged nozzle with steel silicocalcium treatment for all grades at argon stirring plant;

200–300 heats of ordinary carbon grades or low alloy steel grades with manganese content up to 1.2% were made for each option. The process waste quantity during casting (scrap, crop), casting process stability (stopper rod "no closing", metal penetration into the gap between the no swirl nozzle and the stopper rod, choking of submerged nozzle channel, concast billet and rolled plate quality were evaluated. The main parameters of steel casting process and technological waste quantity are given in Table 2.

Table 2. *Casting technological parameters*

Position	Parameters, conventional index	Production option		
		1	2	3
1	Tundish, heat life time	1	1.06	1.56
2	Nozzles life time	1	1.87	6.40
3	Casts in unstable conditions	1	0.63	0.16
4	Stopper rod pair faults	1	0.70	0.06
5	Crops	1	0.85	0.65
6	Scrap	1	0.76	0.72
7	Slab rejection due "gas blister" defect	1	0.56	0.44

The usage of high strength casting refractories together with steel silicocalcium treatment of all grades is fully reasonable.

As the result of the testing, we recommended to abandon the usage of biceramic no swirl nozzles and to use periclase-graphite or corundum-graphite nonswirl nozzles, which have mechanical erosion resistance and are insensitive to alumina deposition on working surfaces. Additionally, with the purpose of abatement of alumina particles deposition, it is recommended to treat all low-carbon steels with silicocalcium core wire. In this process, complex fusible combinations of calcium and aluminum oxides that do not deposit on refractory surface are formed.

All the measures developed and represented in this paper allowed to reduce essentially the quantity of transient casting conditions and off-optimum situations in slab casting.

Introduction of the above research results in casting of carbon and manganese steels of peritectic grades with manganese content up to 1.2% allowed: 1) to increase tundish life time 1.4 – 1.5 times; 2) to increase submerged nozzle life time 3.5 – 6; 3) to decrease 10 – 15 times the number of stopper rod pairs and submerged nozzle faults; 4) to decrease the technological waste quantity 13 – 15 times; 5) to decrease 1.3 – 2.3 times slab downgrading due to "gas blister" defect; 6) to decrease 2.1 times plates downgrading due to steelmaking defects.

Research results of unsteady steel casting conditions influence

The unsteady casting condition impact on concast billets and rolled plates internal and surface defects initiation and propagation are studied. It is demonstrated that concast slabs rejection due to surface defects and rolled plates downgrading due to steelmaking defects and defects indicated by ultrasonic testing essentially increase under unsteady conditions, the probability of non-regular and emergency situations (specifically, concast billet sticking) occurrence increases substantially.

Technological actions that facilitate stabilization of casting speed and temperature by reduction of solidification transient conditions are recommended: reduction of submerged nozzles replacements and increasing of tundish and number of heats in a series.

Usage of optimal refractories with the aim to reduce the possibility of transient conditions occurrence in continuous casting is suggested. This method implies the usage of mullite-graphite stopper rod monoblock units with stopper rod channel argon blowing, periclase-graphite or corundum-graphite no swirl nozzles and mullite-graphite submerged nozzles. The usage of refractories proposed allows to reduce occurrence of unsteady conditions and their negative impact on the complex indicators of concast slab and rolled plates quality.

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