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Moscow, USSR, 19 September - 9 October 1968

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LATEST PROGRESS IN CONTINUOUS STEEL CASTING PRACTICE [1]

by

A.I. Manokhin
Head of Laboratory
Central Scientific Research Institute
for the Iron and Steel Industry
Moscow, USSR

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The Soviet Union has been occupying a leading place in the field of continuous steel casting since the very beginning of the development of this process in regard to the number and capacities of the plants in operation, their technical performances, practice in casting billets of different cross-sections and theoretical investigations of the processes in continuous steel casting.

The Central Research Institute of Ferrous Metallurgy - TSNIICHERMET has carried out a great deal of research work at the pilot and industrial plants in the field of continuous casting of carbon and alloy steels into round bars, square blooms and rectangular billets, which has made it possible to develop the basic theoretical fundamentals and production technology and to work out the most efficient designs of machines which provide for stable operation of the steelmaking shops and production of cast billets of a required quality.

At the early stage there were encountered some difficulties in developing the technique of continuous steel casting of billets.

These were connected with formation of hot surface cracks (both traverse and longitudinal) on the wide faces of the cast billets , indentation with internal defects and central porosity.

The study of the nature of the above defects has shown that they, as a rule, depend upon the analysis of the metal to be cast, casting practice, geometrical dimensions and design of the mould and its surface conditions as well as upon the conditions of casting and cooling of continuous castings. During the shrinkage process the wide faces of the solidifying skin of a billet are influenced by ferrostatic pressure against the narrow ones and by friction forces. Under delayed solidification conditions the total stress in the solidifying surface of the billet may grow up to such an extent that breakouts occur in the skin. The total stress is a combination of thermal stresses, bending stresses in the corners of the solidifying skin of the slab which stretch the internal layers and rupturing stresses created by ferrostatic pressures against the narrow faces of the billet.

The investigations of the tensile-stressed skin on the wide faces of a billet with smooth surfaces have shown that it is of use to divide the side face into a number of curved portions with slightly concaved ribs or waves in order to reduce surface tentions. Such a shape makes it possible to disperse the shrinkage deformation on the wide faces of a billet and provides for the latter's higher longitudinal rigidity which makes the billet surface more resistant to bending in the vertical plane and consequently to developing traverse defects on the surface.

The optimum shape and parameters of the waved surface chosen with a certain ratio between the wavelength and depth have made it possible to considerably reduce the number of defects in wide cast slabs such as longitudinal surface cracks and traverse indentation and practically completely eliminate slab scrap on account of surface defects.

The development of the optimum rates of spray cooling has made it possible to produce castings of a required density in the central zone and with an optimum ratio between the structure zones as well as without any internal defects.

The casting of high-alloy steels containing easily oxidizing elements such as chromium, titanium, aluminium and others is accompanied by formation of rough non-ductile crust on the metal meniscus and its folding into the cast body considerably decreases the quality of the slab surface.

One of the methods which have been developed to prevent the metal surface from secondary oxidization lies in the application of protective gaseous media. It is found out that a propane-butane mixture may be an optimum protection in casting such easily oxidizing steels as the electrical steel.

However, the intensive development of secondary oxidization cannot be avoided when a number of steel grades are cast under similar protection. For these particular cases a combined method has been worked out to protect metal surface which is based on pouring the metal under its surface level, i.e. the metal stream is directed to below the metal surface through an extended nozzle, the surface being protected with a slag layer.

The main difficulties in solving the problem of producing high-quality rolled products were encountered in eliminating such defects as distortion of shape in cast blooms, internal cracks and central porosity.

The application of section-shaped and open-corner moulds as well as exothermic slag mixtures has made it possible to produce cast billets of correct geometrical shape and to eliminate internal corner cracks.

The optimum rates of pouring and cooling of castings have ensured production of sections with a developed zone of equiaxed crystals in the centre. The presence of equiaxed structure makes it possible to disperse central porosity and, if corresponding reduction applied, the rolled steel quality meets the requirements of any consumer.

During solidification of round castings transcrystallization develops nearly up to the axis of the casting. The defects connected with metal shrinkage and segregation are, therefore concentrated in the axial zone. In addition, the round shape ingots have a tendency to a distortion (ellipticity) of their shape during casting operation and this results in forming a gap between the casting skin and the mould walls and consequently leads to longitudinal surface cracking.

The causes of longitudinal surface cracking have been studied in the course of the process development. It has been found out that only moulds with a reverse taper should be used in order to eliminate this defect. The walls of the round mould must be of a waved shape. The application of a waved shape on the working surface of the mould has made it possible not only to eliminate the surface cracking but also to avoid any distortion of the casting cross section.

In rimming-steel production a satisfactory quality and reliable pouring capability of the heats depend upon oxidization and temperature of the molten metal. Oxygen concentration in steel determines, to a considerable extent, the position, quality and distribution of honeycomb blowholes along the height of the casting.

It is established that when the metal is insufficiently oxidized it rims very poorly in the mould. As a result of it the continuously cast billets are obtained with a thin and insufficiently dense outer skin. The rimming of extremely oxidized metal is characterized by non - uniform gas evolution by boiling and even ejections when it is difficult to maintain the required level of metal in the mould and carry out casting operation.

The worked out process of melting and continuous casting of rimming steel with 0.08 per cent carbon content have made it possible to produce a cold-rolled steel of fine surface. All the specifications of the cold-rolled sheets meet the requirements. When a number of parts were produced by drop forging the study of deep and extremely deep drawing of sheets had shown that the plasticity of metal produced from continuously-cast slabs was to some extent higher than that of ordinary metal.

To further improve the quality of continuously cast billets we conduct further theoretical investigations in the following directions:

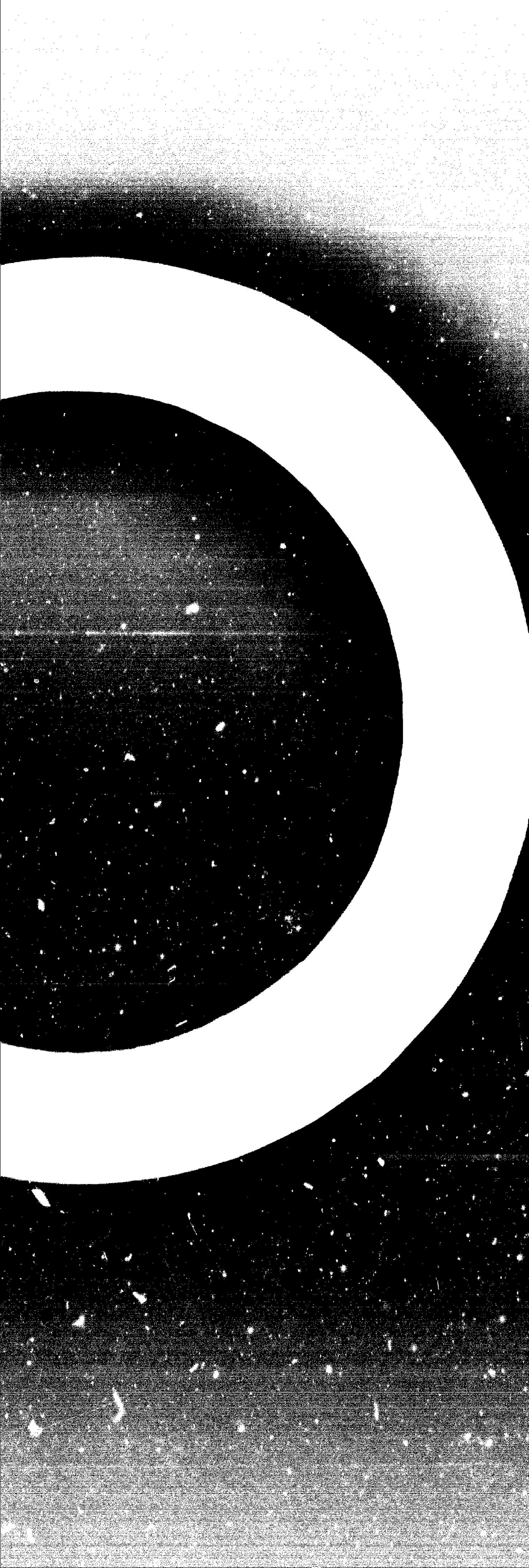
1. Development of thermo -,chemically - and erosion-resistant refractory materials for lining the steel-pouring ladles and tundishes as well as nozzles and nonswirl nozzles. The latter must ensure long-time pouring when submerged under the metal level in the mould.

2. Further study of waved mould application (wave parameters, wall thickness) which makes it possible to cast wide slabs without longitudinal surface cracking.

3. Extension of work on application of free-of-pressure pouring in combination with metal surface protection in the mould with exothermal mixtures, graphite or reducing gas (first of all for steels possessing higher tendency to secondary oxidization).

4. Study of the two-phase zone and its extension at certain chemical analysis in relation to the heat exchange condition between the casting and its environment.

5. Development of methods for active interference into the solidification processes by influencing the solidifying metal with magnetic field, vibration, ultra-sounds and by introduction of additional crystallization centres in solid, liquid and powder state.



LATEST PROGRESS IN CONTINUOUS STEEL CASTING PRACTICE

The Soviet Union has been occupying a leading place in the field of continuous steel casting since the very beginning of the development of this process in regard to the number and capacities of the plants in operation, their technical performances, practice in casting billets of different cross-sections and theoretical investigations of the processes in continuous steel casting.

About 3,000,000 tons of billets and slabs have been cast on the plants of the USSR in 1967.

The total quantity of continuously cast billets produced since the early stages of developing this process till now amounts to more than 9,000,000 tons.

Constructing 25 plants is envisaged for the period of 1968-1970, the total capacity of the continuous casting plants of the USSR reaching 8,000,000 tons per year by 1970.

The Central Research Institute for Ferrous Metallurgy - TSNIICHERMET - has carried out a great deal of research work at the pilot and industrial plants in the field of continuous casting of carbon and alloy steels into round bars, square blooms and rectangular billets which has made it possible to develop the basic theoretical fundamentals and production technology and to work out the most efficient designs of machines which provide for stable operation of the steelmaking shops and production of cast billets of a required quality.

The results of these investigations made it possible to find out the principal conditions to provide for a reliable process of continuous steel casting.

They are as follows:

1. A reasonable distribution of metal as it goes through the tundish into moulds.
2. Casting of steel within the optimum temperature limits.
3. Providing symmetrical crystallization during the formation of billets.
4. Creating the conditions to reduce shrinkage strains in a solidifying billet.
5. The withdrawal of billets at the assigned and as constant as possible speed.
6. Protecting the molten metal from oxidation during the casting process.
7. Maintaining the optimum rate of oxidation of the whole heat of rimming steel in the course of casting.
8. A complete solidifying of billets in the secondary cooling zone under assigned conditions.
9. Providing automation and mechanisation of the plants.

Continuous casting of rectangular billets

At the early stage some difficulties were encountered in developing the technique of continuous casting of steel rectangular billets. These were connected with formation of hot surface cracks (both longitudinal and transverse) on the wide faces of the cast billets, indentations with internal defects and central porosity. Studies of the nature of the above defects have shown that, as a rule, they depend on the analysis of the metal to be cast, on casting practice, on the geometrical dimensions and the design of the mould and its surface conditions as well as on the conditions of casting and cooling of continuous castings.

As it has been shown by investigations the skin of a billet separates from the mould walls already in the meniscus zone. Depending upon the cross-section of a casting the area of contact in the meniscus zone is 40-60 per cent. However, to simplify the scheme of calculations it can be assumed with a reasonable level of approximation that at an early stage of solidifying the skin of a billet closely adjoins the mould walls along the whole length of the perimeter. It is also assumed that three different stages of mutual location between the skin and the mould exist:

- the skin closely adjoins the mould walls along the whole length of the perimeter,
- the skin separates from the narrow faces of the mould and adjoins the wide faces only,
- the skin separates from the mould walls along the whole length of the perimeter.

Prior to the initiation of a gap some strains are developing in the skin of a casting for two reason given below

- a linear shrinkage being developed by the forces of the ferrostatic pressure as well as by the friction against the walls of the mould and by other reasons,
- a temperature gradient in the skin (thermal stresses).

During the shrinkage process the wide faces of the skin have to overcome the effect of the ferrostatic pressure P_{fp} on the narrow faces as well as the friction force P_{fr}. Considering the band of the skin at a distance of 1 cm from the metal meniscus level we find out that the force of the ferrostatic pressure against both the narrow faces may be defined as:

$P_{fp} = 2a\gamma h_b \cdot 1$ (kg)

The friction force of the wide faces against the walls is:

$P_{fr} = 2\varphi N F_{fr}$ (kg)

Where φ - friction coefficient

$N = \gamma h$ - standard pressure

$F_{fr} = b \cdot 1$ - surface of friction against the wide faces, sq.m

The total force rupturing the skin on the wide face in a horizontal direction can be expressed as:

$P_f = P_{fp} + P_{fr} = 2\gamma h_b(a + \varphi B)$ (kg)

The stress developed by this force is:

$\sigma_{br} = \frac{P_f}{2\xi_m \cdot 1} = \frac{\gamma h_b(a + \varphi B)}{\xi_m}$ (kg/sq.cm)

Where ξ - mean thickness of an elementary band of the skin, m (cm).

When a quick decreasing of the surface temperature occurs, the tensile thermal stresses of the first kind will develop in the external layers of the skin. They can be represented in the form:

$\sigma_{th} = \frac{2}{3}(t_{or} - t_o)\frac{\alpha_1 E}{1-\mu}$ (kg/sq.cm)

Where α_1 - coefficient of linear shrinkage $(0.3 \cdot 10^{-4}\ 1)^{\circ}C$

E - modulus of elasticity, n/sq.m (kg/sq.cm)

μ - Poisson's number.

The calculations indicate that $\sigma_{th} \leq 20$ kg/sq.cm and the sum of tension stresses equals about 23 kg/sq.cm.

It is necessary to note that the coefficient of friction may increase up to 10 if the walls of the mould are warped or a casting is welded to them.

In that case stresses may increase up to such an extent that a breakout occurs in the skin, i.e. " a breakthrough" of molten steel into the secondary cooling zone takes place.

Under the conditions of a completely delayed shrinkage:

$\sigma_{shr} = \alpha E(t_{or} - t_o)$.

This equation leaves out of account the dimensions of the face, the thickness and the uniformity of the solidified skin. As the thickness of the skin is non-uniform then:

$$\sigma_{shr} = \frac{\alpha E(t_{cr} - t_{surf})\Sigma l_n}{F_n \Sigma \frac{l_n}{F_n}}$$

where l_n and F_n are respectively the length and the thickness of the skin in the elementary horizontal area of the wide face.

It follows from this equation that if the thin areas are present in the skin, the stresses concentrate in them and consequently deformations occur in those areas. The possibility of forming cracks at these places increases.

After the narrow faces of the skin have separated from the mould walls and the contact has been kept only at the centres of the faces, some bending moments develop in the corners of the skin which can be represented by the equation:

$$M_b = \frac{\gamma Z}{12} \cdot \frac{b+2a^2\beta}{1+2\beta} \quad (\text{kg-cm})$$

where $\beta = \frac{k_b^2}{k_a^2} \cdot \frac{a}{b}$ and

b and a - dimensions of the wide and narrow faces, a (cm)

k_b and k_a are friction coefficients of solidifying the metal on the wide and narrow faces respectively

Z - distance from the meniscus of the metal to the particular section of the billet, cm.

The angular momentum produces bending stresses:

$$\sigma_{fb} = \frac{6M_b}{k_b^2\tau}$$

The rupturing action of the ferrostatic pressure on an elementary band of the wide face at this period may be defined as:

$$P_{br} = \frac{\gamma Za}{2}$$

It produces the stress in the skin having the thickness ξ_b and the height of 1 cm that can be expressed by the equation:

$$\sigma_{fbr} = \frac{P_{br}}{\xi_b \cdot 1} = \frac{\gamma Za}{2k_b\sqrt{\tau}}$$

When the wide faces have completely separated from the walls of the mould the total stress of the ferrostatic pressure on the wide face areas adjoining the corners can be expressed by the following equation:

$$\sigma_f = \sigma_{fb} + \sigma_{fbr} = \frac{\gamma Z}{2k_b\sqrt{\tau}}\left[\frac{b^2 + 2a^2\beta}{3(1 + 2\beta)k_b\sqrt{\tau}} + a\right]$$

After the skin has separated from the walls of the mould the temperature of its surface is increased being affected by heating, which results in delaying the shrinkage of the inner layers (thermal stresses - σ_{th}). These stresses will be added to the bending stresses (σ_{fb}) leading to the tension of the inner layers as well as to the breaking stresses of the ferrostatic pressure (σ_{fbr}) on the narrow faces.

The total stress can be expressed as:

$$\Sigma\sigma = \sigma_{th} + \sigma_{fb} + \sigma_{fbr}$$

The investigations of the tensile-stressed skin of the billet with smooth surfaces of the wide faces have showthat it is possible to decrease the stresses by shortening the linear dimensions of those areas of the skin of the wide faces that have separated from the walls of the mould. It is achieved when casting the billet with a corrugated surface. Such a shape makes it possible to disperse the shrinkage deformation on the wide faces of a billet and provides for the latter's higher longitudinal rigidity which makes the billet surface more resistant to bending in the vertical plane and consequently to developing transverse defects on the surface. The shape of the waved surface must provide for the greatest heat removal from the skin at the top of the wave in order to obtain the sufficient thickness of the skin before its separation from the wall.

Calculations have shown that the greatest heat removing ability is characteristic of the waves formed by two parabulas. In this case the size of the interstice between the skin and the wall of the mould at the top of a wave diminishes with shortening the distance between the waves and with decreasing the height of the wave. The primary skin of the waved casting represents a shell injected to uniformly distributed load. The stress of the ferrostatic pressure in the skin defined from the conditions of the equilibrium of forces acting upon the skin can be calculated by the equation.

$$\sigma_t = \frac{\sqrt{\left(\frac{2z\delta^2\gamma h}{r_1}\right)^2 + \delta^2\gamma^2 z^2}}{1+\delta h}$$

where δ, h – the pitch and the height of the wave respectively, m (cm)

Z – distance from the meniscus of metal to the section being examined

The stresses decrease with the increase of the height and with the decrease of the wave spacing.

The choice of the optimum shape and parameters of the corrugated surface with a certain ratio between the spacing and the depth of wave has made it possible not only to considerably reduce the number of defects in wide cast slabs such as longitudinal surface cracks and transverse indentations but also to practically completely eliminate slab scrap on account of surface defects.

The investigations have shown that appearing the inner cracks is stipulated by the occurence of mechanical and thermal stresses as well as of the stresses caused by the phase transformations in the metal.

The cracks are mainly appeared when the critical value of tension or compression stresses at the boundary between liquid and solid phases has been surpassed. Almost all inner cracks appear in the temperature range of the so called "hot brittleness" i.e. immediately below the temperature of solidus. As it has been shown by tests the sensitivity of steel to cracking is increased in the presence of alloying components mainly chromium and when increasing the content of sulphur and phosphorus. The chief factor which determines the formation of cracking is the relation between the strength and ductility of steel at high temperatures.

At the first moment the surface layers of the solidified skin of the casting are subjected to the shrinkage proportional to the change of temperature and they squeese the internal layers. The soundness of metal at high temperatures is not violated by the compression strain as all stresses are relieved due to plastic deformations. In spite of their transitions into the region of elastic deformations noticeable stresses are not formed in the external layers as their shrinkage is not resisted by the internal layers which are in the temperature range of plastic deformations.

It is obvious that as the thickness of the skin is increased, the rate of temperature decrease in the internal layers and consequently the size of shrinkage will be greater than in the external ones. The cooled external layers being in the temperature region of elastic deformations will prevent the shrinkage of internal layers as a result of which tension stresses will develop in the latter and internal cracks may appear under suitable conditions.

With high intensity cooling internal cracks have been observed in the rectangular billets (slabs) cast of carbon steel.

Warming up the surface of the billet after its going out of the secondary cooling zone exerts a great influence upon the initiation of internal cracks. In this case the warming up external layers expand and carry along the internal layers. Tension stresses develop in the latter and as a result of that internal cracks are initiated.

Internal cracks are absent in the billets cast without the secondary cooling. However, it is only billets with a small cross-section that is acceptable to cast without the secondary cooling. In casting billets of medium and large dimensions without the secondary cooling it is necessary to considerably decrease the withdrawal rate of strand i.e. the output of the plant due to the danger of the breakthrough of the molten metal below the mould.

Peculiarities of casting alloy and high-alloy steels

The casting of high-alloy steels containing easily oxidising elements such as chromium, titanium, aluminium and others is accompanied by formation of surface laps, pits, belts and other defects on the surface of the billets which cause sharp deterioration of the quality of finished metal.

For example, the casting of stainless steel is accompanied by formation of a rough non-ductile crust on the metal meniscus and its folding into the cast body considerably decreases the quality of the slab surface and increases the consumption of metal when scarfing it.

Increasing the temperature of metal and the rate of casting which may be resorted to in order to reduce the dimensions of the skin is restricted because of the danger of the breakthrough of the molten metal into the secondary cooling zone.

One of the methods which have been developed to prevent the metal surface from secondary oxidation lies in the application of protective gaseous media. An inert gas (argon), the natural gas and artificial gas mixtures have been tested for this purpose. The results of casting with these methods of metal protection are given below.

	Results of use
Argon	A dense crust is formed on the metal surface just as at the casting in air. The combustion of lubricant is not complete and is accompanied by smoking flame. The surface of metal is considerably cooled as well as it is oxidised by the residual oxygen.
Natural gas	This atmosphere prevents the metal from oxidation, but the evolution of a considerable quantity of soot products makes the observations extremely difficult. The surface of a billet is carburised from 0.05 up to 0,1 per cent of carbon.
Propane-butane gas mixture	A protective atmosphere is created over the surface of metal. Propane-butane gas mixture clarifies the flame from the burning lubricant. This atmosphere contains less than 1 per cent of oxygen. There is practically no rejection of metal on

account for the oxidised skin. Carburisation is negligible. The increase of hydrogen content is restricted and is not accompanied by the formation of defects.

As a result of performed experiments it has been found out that a propane-butane gas mixture under the surplus pressure of 0.5-0.8 kg per sq. cm and with the averaged amount of 0.8 kg per ton of steel may be an optimal protection in casting such easily oxidising steel as the electrical one.

The combustion of this mixture results in the following percentage analysis of the protective atmosphere over the surface of metal in the mould: CO_2 1.8-4.0; CO 9-15; H_2 8-20; the total of hydrocarbons 6-18; O_2 1-2, bal. nitrogen. The humidity is about 2.5 per cent of H_2O, the dew point being + 20°C.

It ensures the conditions for yielding quality slabs of electric steel without defects due to the presence of oxidized film in the course of casting.

However, an intensive development of secondary oxidation cannot be avoided when a number of steel grades containing such easily oxidizing impurities as aluminium, titanium and others, for instance, stainless steels, are cast under similar protection. This is confirmed by thermodynamic calculations. For these practical cases a combined method has been developed to protect the metal surface. It is based on pouring metal under its surface level, i.e. the metal stream is directed to below the metal surface through an extended nozzle, the surface being simultaneously protected with a slag layer.

Feeding the metal is carried out through a fireclay or graphite-fireclay funnel and a graphite-fireclay nozzle having two side openings. This method provides for feeding hotter portions of metal to the surface, which contributes to warming the metal up and keeping it in a fluidised state.

Tests have shown that the nozzle is mainly eroded at the place of its contact with the interface plane between metal and slag. The erosion of discharge openings also occurs.

In casting tool and alloy steels good results have been obtained not only when feeding the metal under its surface level but also when protecting the metal surface with an exothermic mixture containing aluminium, silicocalcium, sodium nitrate and other components.

The mixture consumption of 0.4-0.8 kg per ton provides for the thickness of the slag layer of about 5-7 mm on the metal meniscus.

Developing the technique of continuous casting of alloy and high-alloy steels created the possibility to change the temperature of casting without increasing the cast steel secondary oxidising.

As a result the conditions of refractory have been improved, the consumption of alloys has been decreased, and one of the most difficult problems, viz. to produce quality castings from the steels of such type, has been solved, the latter being the most important.

At present the technique of continuous casting of alloy and high-alloy steels has been thoroughly developed and the production of quality cast billets has been ensured.

The vacuum degassing treatment of steel before casting is also used in the USSR in order to improve the quality of continuously cast alloy steels.

The casting of vacuum degassed steel is started at the temperature by 20-25°C lower than normal but the process of casting is run without forming skulls, the metal forming a good stream. Defects due to blisters are completely absent.

Continuous casting of rimming steel for the production of slabs for cold-rolled sheet and automobile sheet

The investigations and development of the technique of continuous casting of low car-

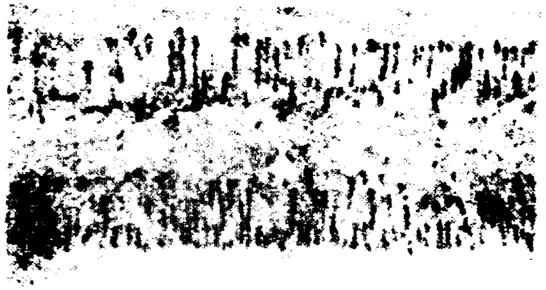


Fig. 1. Macrostructure of a continuous casting of low carbon rimming steel (0.07% C; 0.35% Mn) with the intensity of metal boiling in the mould being normal

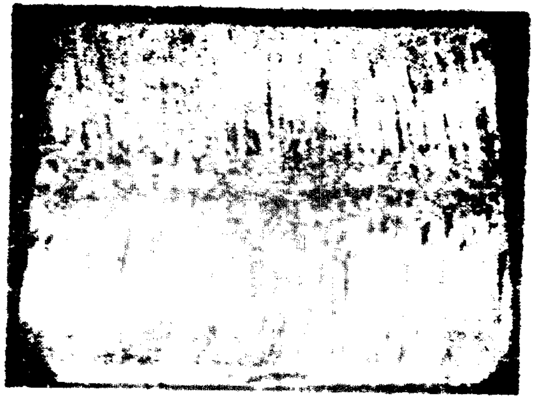


Fig. 2. Macrostructure of a continuous casting of low carbon rimming steel (0.07% C; 0.40% Mn; 0.016% O_2) with the metal boiling in the mould being sluggish

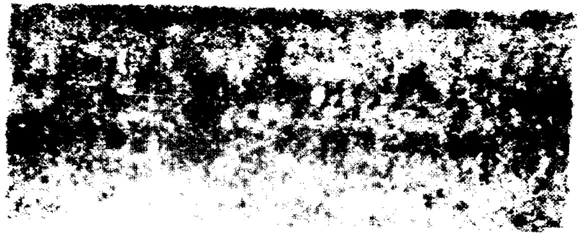


Fig. 3. Macrostructure of a continuous casting of low carbon rimming steel (0.[illegible]% C; 0.30% Mn; 0.04[illegible]% O_2) with the metal boiling being violent and periodic metal boilings-up occuring in the mould

bon rimming steel for the production of cold rolled sheets were started by TSNIICHERMET at a number of iron and steel works in 1959.

As a result of the investigations carried out in 1959-1965 the basic technological principles have been developed for melting and continuous casting of low carbon rimming steel for the production of cold rolled sheets. Reliable methods to control the quality of continuously cast slabs have also been worked out. This made it possible to introduce and to develop on an industrial scale the technique of continuous casting slabs of low carbon rimming steel at the basic oxygen shop of the Novo-Lipetsk Iron and Steel Works.

It was established that the following factors exert the decisive influence on the quality of continuous casting of rimming steel: the degree of oxidation of metal, the design of the mould, the properties of lubricant as well as its uniform supply to the mould walls, the method of pouring metal into the mould.

The location, quantity and distribution of blowholes along the height of slabs are determined to a great extent by the oxygen content of steel.

Pouring the metal into the mould under the conditions of continuous casting leads to a steady rise of the ferrostatic pressure as well to a steady action of the stream on the uprising flows in the mould. Therefore during the continuous casting of rimming steel the influence of the metal oxidation rate on the strand building up is increased considerably. The amount of surplus oxygen relative to its content balanced with carbon has the same effect.

The limits of the optimum content of oxygen in the rimming steel have been determined so that they provide for a uniform boiling of the metal in the mould and a definite intensity of gasification and gas evolution during the process of casting and solidification of the continuous casting. In this case provided that other optimum conditions were kept, the slab with a dense external skin having a thickness of 10-30 mm was formed (see Fig.1).

When the oxygen concentration was lower than that required, the boiling of the metal in the mould was inert and some turbulence was observed in the zone of the stream. The casting had a thin external skin (see Fig.2).

When the oxygen content was higher than that permissible, a violent boiling of the metal was occured together with steady level variations and periodic boilings-up. In this case it was dificult to control the metal boiling intensity since the addition of large quantities of aluminium into the tundish resulted in decreasing the fluidity of metal which deteriorated the conditions of gas evolution. The external skin of a slab had a great thickness but its density was insufficient (see Fig.3). The blisters in the skin were observed in quantity.

It should be noted that when pouring the metal into a watercooled mould with copper working walls, the rate of solidification comes up to more greater values than when pouring it into cast iron moulds. As a consequence the escaped gas bubbles are fixed in the external skin of the continuous casting. Therefore the mould design must provide for decreased heat removal in the upper zone and at the corners of the mould so that the rate of solidification were not greater than that of the gas evolution.

Some observations of the pouring process and visual examinations of the castings surface have shown that if the stream of the metal running from the tundish into the mould is unsatisfactorily organized, it leads to spilling the metal on the surface of the slab. A good organised metal stream was obtained when pouring the metal through high-aluminious noseles having corundum inserts.

As it was shown by the results of the performed investigations a great influence on the quality of the continuously casting surfaces of rimming steel was exerted by the lubricant on the mould walls. An irregular feeding and distribution of the lubricant along the perimeter of the working cavity and insufficient viscosity lead to its quick burning up and to the metal sticking to the walls. It has been found out that the tears of the skin initiated when raising the mould are flooded by molten metal as the mould is lowered.

Due to the interaction of the metal and the oxidised skin gas bubbles are formed. In the consequence of the high rate of solidifying they have no time to come to the surface and are fixed in the external skin of the casting. Simultaneously a rough folding and spillings are developed on the surface of the slab if the mould walls are insufficiently lubricated.

In the course of investigations it was also found out that the metal boiling in the mould occured due to the oxidation of the carbon both by the oxygen contained in the metal and by that absorbed by the stream and the surface of the molten metal from the surrounding atmosphere.

Special measures have been taken to limit the amount of oxygen absorbed from the atmosphere.

As a result of theoretical investigations and practical research carried out at the Novo-Lipetsk and Cherepovets Iron and Steel Works the principal process parameters of oxygen-converter operation, continuous casting and rolling the low-carbon rimming steel to produce cold-rolled sheets for use in automobiles have been determined.

Casting an experimental commercial batch of the low-carbon rimming steel at the Novo-Lipetsk Iron and Steel Works, rolling it at the Cherepovets Iron and Steel Works and using at the motor-car works of the Soviet Union have shown that the quality of sheet steel for use in automobiles fully meets the high specifications of the motor-car industry.

Continuous casting of aluminium-stabilised steel to produce the non-ageing automobile sheet

Industrial technique of continuous casting of aluminium-stabilized steel to produce the non-ageing automobile sheet has been developed by the TSNIIChM in collaboration with the Novo-Lipetsk Iron and Steel Works for the first time in the world practice.

At the early stages of the development of this technique the principal difficulties in casting this steel continuously were connected with the non-uniform aluminium distribution in the ladle, the secondary oxidation of the steel being cast and the absence of refractories providing for a stable casting of steel at a steady rate.

As a result of research the following methods have been developed: methods to feed the aluminium additions in the course of deoxidation providing for their maximum effectiveness and uniform distribution along the height of the pouring ladle; methods to feed the metal into the mould without bringing the molten steel into a contact with the atmosphere. Optimal measures to protect the metal from the secondary oxidation in the mould have also been developed.

The developed technique of continuous casting of the aluminium-stabilized steel (2.5 kg per ton) that has been worked out allowed the slabs to be produced providing for a high quality of the cold-rolled automobile sheet. A surface quality of sheets rolled from continuously cast non-ageing steel slabs was suitable for manufacturing facial parts of automobiles.

High plastic properties of sheets and good pressability of automobile parts have been predetermined by the high chemical homogeneity of the continuous casting.

The mechanical properties of sheets exceed the specifications of the respective standards.

On the basis of a licence agreement between the V/O "Licencintorg" and Cobe Steel Ltd. of Japan the technique of continuous casting of aluminium-stabilized steel developed by the TSNIIChM and the Novo-Lipetsk Iron and Steel Works was introduced at the Nissin Steel Works, Cure, Japan.

On the reference of Japanese experts the cold-rolled sheet produced according to the Soviet technique on the continuous casting plant of the Soviet design well meets the high requirements of the Japanese motor-car makers.

Peculiarities of the continuous casting of square blooms

Square blooms account for an important portion of the total production of continuously cast steel. Thus 77 per cent of all the plants in the world, except the USSR, are intended to produce blooms for bars; 12.5 per cent, for a mixed range of sections and only 10.5 per cent of the plants produce slabs exclusively.

In spite of the fact that in the nearest future (by 1971) the relative portion of plants producing slabs will be increased and account for 37.5 per cent mainly as a result of their construction at the works and shops of high output, the portion of plants to produce blooms for bars will remain rather large.

A large amount of investigations to produce the continuously cast square steel blooms has been carried out by the TSNIIChM in collaboration with a number of iron and steel works.

The principal regularities of shaping the bloom and the influence of the continuous cast process factors on the production of the quality blooms have been established.

In the course of developing the technique of producing the continuously cast blooms some difficulties were met due to the distortion of the bloom shape and the appearance of cracks and axial porosity.

The initial stage of the bloom shape distortion is brought about by the emergence of an irregular gas gap that sharply decreases the heat removal and leads to an uneven cooling along the perimeter of the bloom by different values of the friction forces between the solidifying skin and the walls of the mould along its perimeter as well as by the non-uniform deformation of the bloom skin at the upper part of the mould as a result of its insufficient strength.

It was found out that rounding the corners of the mould contributed to decreasing the bloom shape distortion (its rhomboidity). Some decrease of rhomboidity was gained due to the use of waved surface and a projection in the centers of the mould walls.

The use of shaped moulds, exothermic slag mixtures, holding devices in the secondary cooling zone made it possibly to considerably decrease the dimensions of shape distortion. However, this distortion continued to remain appreciable.

Having investigated the peculiarities of the crystallization of the continuously cast square blooms, the moulds of special design were developed, which allowed identical conditions to cool the corners of a continuously cast bloom to be provided for. The use of the moulds of such a type made it possible to produce cast blooms of correct geometrical shape as well as to eliminate the internal corner cracks.

A most important problem encountered in producing quality finished bars was the axial porosity present in the blooms.

It was established by the TSNIIChM's investigations that dimensions, shape and location of non-solidity in the axial zone depended on the structure of the bloom.

Research on the principal regularities of solidifying and building up the structure of a cast bloom especially in the axial zone and the application of the knowledge to get the optimum structure of the bloom have made it possible to produce quality finished bars.

It has been found out that two characteristic types of structure develop in the cast bloom.

The first type of structure is characterized by the presence of two zones, viz. an external zone of little crystals and a zone of the columnar crystallization spreading to the central axis of a billet. Such a type of structure appears under the conditions of intensive heat removal. The irregularity of the solidifying front leads to the concentration of shrinkage looseness in the content zone of columnar crystals growing out of the faces of the bloom along the thermic central line.

The second type of bloom structure is characterized by the presence of three zones, viz. a peripheral zone of little crystals, a zone of columnar crystals having a limited growth and randomly oriented crystals in the axial zone. In solidifying the areas of axial porosity is fixed in the central zone consisting of randomly oriented crystals. As a result of that the axial porosity is distributed throughout the whole volume of the central zone.

A substantial influence on the spreading of the columnar crystal zone as well as on the relations between the zones of the continuously cast bloom is exerted by the analysis of steel and its properties determined by the range of temperature between the crystallization start and finish, by the conditions of the heat exchange between the bloom and the ambient medium, by the movement of the metal at the time of solidification, and by the content of gases, impurities and inclusions.

Proceeding from the hypothesis of a volume-sequential crystallization, the following scheme of solidification of the continuous casting can be suggested.

As the molten metal comes into contact with the mould walls a thin layer of randomly oriented crystals is developed. The origination of this layer may be caused by the supercooling occuring at the moment of contact of the metal with the walls of the mould. In the consequence of it a large number of nucleation centers appear and little equiaxial crystals producing the skin layer intensively grow around them. The thickness of the peripheral zone of the randomly oriented little crystals is 3-10 mm. Investigations carried out by us on the castings produced of the steel of different chemical analysis (for instance, St.10, St.5, St.3, St.45, 65Г, 40X, 30XГC, 20X, 30X, 15X, 20XH, 30XM, 40XH, 20XM, 12XH3A, etc) allowed us to establish that the thickness of this zone does not depend upon the chemical composition of steel (within the investigated limits). Apparently this is accounted for by the identity of the heat-dependent physical properties of the different steels at the temperature close to the crystallization temperature. Variations of this zone thickness are dictated by changing the heat removal intensity through developing gas gaps along the perimeter and length of the mould as well as through lubricant and slag penetration into the interstice between the solidifying metal and the mould wall.

In the course of further solidification the skin of the casting separates from the walls of the mould due to its shrinkage and the dimensions the gas gap increase whereby the heat removal is slightly decreased. It should be noted that it was repeatedly pointed out in the technical literature that for an extent of 300-400 mm from the metal level there existed a so-called zone of tight contact between the bloom and the mould walls. However, the recent experiments carried out by modern and reliable methods have shown that the contact is disturbed immediately after the molten metal touches the wall of the mould and that this contact is of a broken nature along the whole length of the mould.

However, the skin of the billet is very thin at this moment and the heat is removed

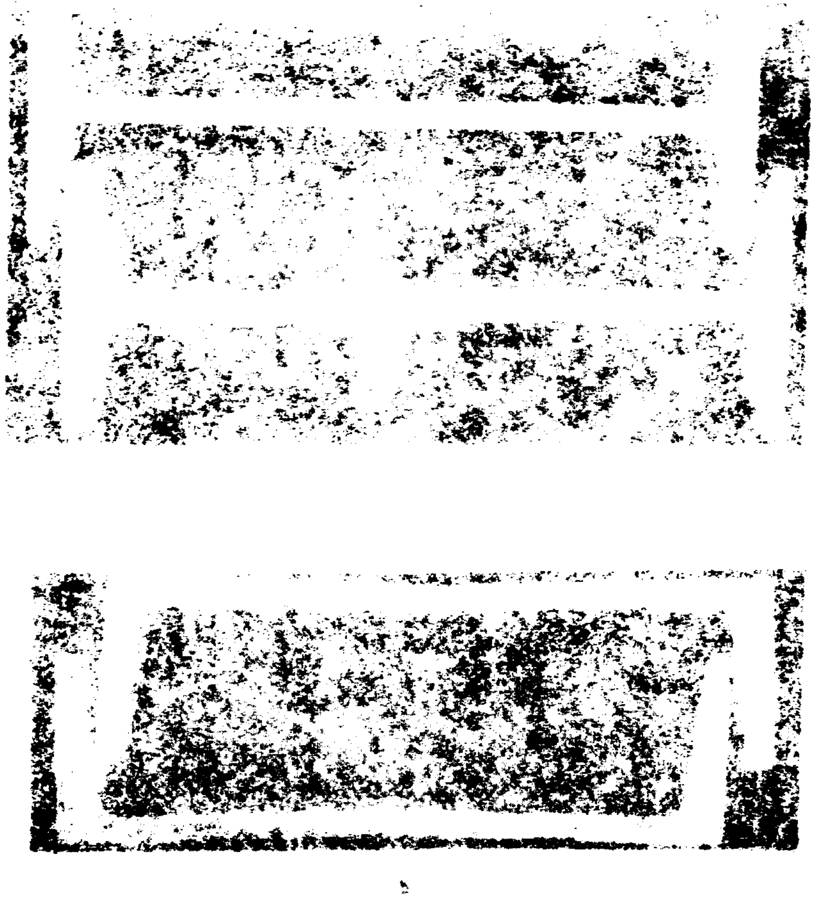


Fig. 4. Macrostructure of profiles produced of the continuously cast 280 by 320 mm billet:

a - beam N 36; b - channel N 30

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in a definite direction, viz. out of the molten metal to the copper water-cooled walls, i.e. in the radial direction. Under these conditions it is those crystals the axes of which coincide with the direction of heat removal that grow very intensively. Thus, a co- lumnar crystal zone is formed. The growing of this zone occurs under the conditions of absence of an appreciable supercooling and the rate of solidification is sufficiently well described by the principal law of the sequential crystallization theory.

While the casting passes through the mould and the secondary cooling zone, the intensity of directed heat removal remains appreciable as a result of the fact that the value of the temperature gradient remains high and the solidified skin is of little thick- ness. Hence the conditions for growing the columnar crystal zone remain preserved; the thickness of the latter may become substantial depending on the chemical composition of the metal and on a number of technological factors.

The thickness of the solidified metal skin gradually increases, its thermal resis- tance to the heat removal intensifies, the temperature gradient at the cross section of a crystallizing bloom decreases and the rate of the growth of the columnar crystals dece- lerates. As the temperature gradient at the interface of solid and liquid phases becomes minimal, the growth of the columnar crystals eliminates. In addition the growth of crys- tals is also decelerated by the particles of impurities that are present in the molten me- tal. Some of these particles grow into the crystals, others remain between the latter (mostly at the boundaries of the columnar crystals) and still others are pressed by the growing crystals to the centre of the bloom. As a result the temperature along the cross -section of a bloom is equalized and the temperature gradient decreases. By this time a certain number of the centers of crystallization in the form of fragments of dendrites, some non-metallic inclusions and impurities are present in the non-crystallized core of the bloom the temperature of which is close to that of metal crystallisation. As a result of that in this zone of the casting volume crystallization may take place simultaneously with sequential or frontal crystallization.

The basic technological parameters of casting (the temperature of casting, the withdrawal speed and the intensity of secondary cooling) have been determined, which allows an equiaxial structure and a dispersed axial porosity to be provided for in case of casting different grades of steel into square section moulds.

The results of performed investigations show that dense rolled metal can be pro- duced at a suitable reduction if castings have an equiaxial structure with dispersed axial porosity.

It was found out for instance that when rolling 200 x 200 mm blooms of low-or me- dium carbon steel the axial porosity was compacted at the reduction equal to 4, and when rolling these of tool steel at the reduction equal to 8. Investigations have also shown that to compact the axial porosity when rolling 280 by 320 mm billets of the low alloy steel the reduction of not less than 5 is required and those of high alloy steel, at le- ast of 13.

It is of interest to produce large sections and rails from 280 by 320 mm cast billets.

A comparative analysis of mechanical test data of metal cast by conventional and continuous methods shows that the quality of structural sections produced from cast bil- lets is not worse that the properties of sections manufactured from rolled blooms.

The study of sulphur prints and macrostructures showed that the structure of bil- let was dense, the distribution of sulphur along its cross-section was regular (see Fig. 4, 5).

The microheterogeneity of continuously cast square blooms of alloy steel grades has been investigated. It has been found that the dendritic segregation in the continuously cast bloom is by 30-40 per cent lower than in the ordinary one. This may be explained by the increased mean rate of crystallization and the decreased (against the ordinary) cross-section of the billet. The results of this investigation are of great importance for production of high-quality pressings from continuously cast blooms. The homogeneity of these products provides for manufacturing parts of great serviceability and with a high value of fatique strength.

Continuous casting of round sections

Round castings have the lowest surface of cooling relative to the area of cross-section and the longest time of solidification in comparison with the other shapes of billets having the same area of cross-section.

Solidification of the round castings prone to transcrystallization finishes in a small volume along the axis of the section where, as a rule, defects due to the shrinkage of metal and the segregation are concentrated.

The thickness of the round casting skin solidifying in the mould is very irregular. This irregularity decreases as fast as the round casting solidifies but the developing bridges cause the process of metal shrinkage in the axial part of the billet to take place under the conditions of their hindered feeding by the molten metal.

Axial looseness develops in consequence of these processes. The extent of the development of axial looseness depends in large part on the amount of shrinkage when converting the metal from a liquid into a solid state as well as on the degree of irregularity of the crystallization front. The amount of shrinkage of rounds from the Cr-Ni stainless steel is appreciable and the axial non-solidity of this castings is greatly pronounced.

To compact the axial part of a round castings the liquid core of it is affected by a magnetic field at the time of solidification. To remove a possibility of developing annular segregation stripe the magnetic field actions has to be mantained from the start of solidification to its finish.

The causes of longitudinal surface cracks in the continuously cast billets of a number of grades have been studied in the course of process development. It has found out that only moulds with a reverse taper should be used in order to eliminate this defect. The walls of this mould must be of a corrugated shape. The application of a corrugated shape on the working surface of the mould has made it possible not only to eliminate the surface cracking but also to avoid any distortion (ellipcity) of the casting cross-section.

A mould of round cross-section has been designed with a differential heat transfer along its height, which allows a regular heat transfer to be provided for at the places of variable contact of the billet and the mould to produce rounds of ideal geometrical shape.

The conditions of secondary cooling are of particular concern in casting round sections. It is shown by investigations that internal cracks initiate in the billets of carbon, low carbon and low alloy steels (exept the austenitic grades) if the water consumption is more than 0.5 litre per kg. "Dry" cooling of small diameter round billets is recommended, i.e. cooling the rounds in the air without feeding water.

In casting round sections from the steels containing light-oxidizing elements (Ce, Al, Ti) it is essential to protect the stream and the surface of metal in the tundish and in the mould with liquid slag. The compositions of slag and the methods of feeding the metal when casting round sections have been developed.

The technique of manufacturing consumable electrodes from continuously cast round sections of high alloy steels and different alloys for vacuum arc remelting (VAR) and electroslag refining (ESR) processes has been developed and introduced by the TSNIICHM in collaboration with a number of steel works.

The quality of rolled metal produced by the ESR or VAR processes from the continuously cast electrodes is at the level of the quality of metal manufactured from wrought electrodes.

The yield of consumable electrodes manufactured as described above is by 8-10 per cent higher than that of the electrodes produced by other methods used earlier.

The results of the work carried out allowed the conclusion to be made that it is expedient to extensively develop this new commercial method of manufacturing consumable electrodes for the VAR and ESR processes from continuously cast billets of high alloy stainless, heat resistant and hot resistant steels and different alloys.

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x

To further improve the quality of continuously cast billets through theoretical investigations are carried out by the TSNIICHM as in the following directions:

1. Development of thermo-, chemically- and erosion-resistant refractory materials for lining the steel pouring ladles and tundishes as well making nozzles and nonswirl nozzles. The latter must ensure long time pouring when submerged under the metal level in the mould.

2. Further study of waved mould application (wave parameters, wall thickness) which makes it possible to cast wide slabs without longitudinal surface cracking.

3. Extension of work on application of free-of-pressure pouring in combination with metal surface protection in the mould with exothermal mixtures, graphite or reducing gas (first at all for steels possessing a higher tendency to secondary oxidation).

4. Study of the two-phase zone and its extension at certain chemical analysis in relation to the heat exchange conditions between the billet and the environment.

5. Development of express-methods of controlling the oxygen content in the molten steel.

6. Development of methods for active interference into the solidification process by influencing the solidifying metal with a magnetic field, vibration, ultra-sounds and by introduction of additional crystallisation centers in solid, liquid and powder states.

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