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MAIN TRENDS IN THE DEVELOPMENT OF CONTINUOUS STEEL-CASTING IN THE USSR[1]

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Main trends in the development of continuous steel-casting in the USSR

The rapid development of continuous steel-casting in the metallurgical industry of the USSR is related to the economic efficiency of the process and the rising requirements of consumers in respect of the quality of metallurgical products. An analysis of the development of the metallurgical industry shows that the productivity of steel-smelting units is growing rapidly, and for that reason the construction of rolling mills is characterised by the constantly growing capacity of cogging plant, and of wide-strip and continuous-operation section and sheet mills.

This gives rise to a trend towards an increase in the weight of ingots cast in moulds, primarily through an increase in the cross-section.

Owing to the way in which steel hardens, the increase in ingot cross-section results in a deterioration in quality; the structural and chemical lack of uniformity is accentuated and surface quality is impaired. When the cross-section is increased, the disparity between the dimensions of the ingot and those of the finished product is also increased, in other words, the amount of unnecessary work involved in reducing the ingot constantly increases.

As the experience of the Soviet Union has shown these important drawbacks are to a large extent eliminated by the continuous casting of steel.

Accordingly, the construction of major new units with a total capacity many times larger than existing capacity is planned in the USSR during the period 1970-1975.

This development is based on a large-scale programme of work involving theoretical research into the continuous steel-casting process and the development of technology for the casting of a wide range of grade of steel as ingots of various profiles and cross-sections and on the basis of this research and experience with existing units, improvement of the technological processes and the design of basic technological units and mechanisms in order to increase productivity and raise the quality of output.

The large scale of production of steel-smelting units with short and stable melting cycles and the wide range of sizes of slab cast have posed entirely new requirements for the operating conditions of continuous steel-casting units. Large industrial units are planned in the USSR to work at accelerated rates and minimise the time lost in preparation for casting the next melt and in readjustment for the transition to another ingot profile.

Design characteristics of continuous steel-casting units

Units in the Soviet Union can cast slabs with widths of from 300 to 2,000 mm and thicknesses of from 70 to 315 mm and sections (round, square) of from 55 to 520 mm. For this purpose, universal designs for continuous-casting units have been created which make possible the casting of a wide range of types and sizes of strands with little wastage of time for readjustment.

One of the main technological installations of casting units is the mould. The quality of the ingot and the regularity of operation of the whole unit depend to a large degree on its design.

Previous research showed that, when the steel was cast, the thermal stresses in the copper walls of the mould significantly exceeded the yield strength. This resulted in deformation of the walls by warping or shear drag. Warping led to the formation of cracks on the surface of the ingot, and shear drag spoilt the tightness of the union between the copper walls and the steel base plates.

All types of deformation increased with any increase in the size of the ingots cast.

Measurements of the temperature fields and deformations in the walls of the moulds made it possible to work out a theory of heat and strength calculations for moulds and to redesign them. On the basis of theoretical and practical work, a mould has been designed and tested and is now being used in Soviet industry with which heat is removed uniformly around the perimeter of the ingot. The use of this mould has resulted in a substantial increase in the speed of steel-casting.

In order to accelerate the changing of moulds, cooling water is directed to them through two horizontal chambers placed on either side of the mould and joined together with springs which absorb the force of the water pressure. When the mould is changed, the chambers are separated with rollers.

After the new mould is put in place, the hydraulic rollers close and the chambers are again pressed against the mould. Changing the mould in this way takes no more than fifteen minutes.

Various kinds of secondary cooling systems are used in the Soviet Union. They include the screen, roller/water sprayer, bar and combined (bar and roller) types. The screen and sprayer/roller systems allow smooth removal of heat from the surface of the hardening ingots; the sprayer/bar and combined systems make it possible to shape wide slabs accurately. These systems are simple to produce and do not require large-scale operations; in the case of an accidental break-out of metal, replacement and adjustment are easy; the equipment for them is lighter, and they are more economical.

For the casting of sections of different sizes the secondary cooling system is adjusted hydraulically. The hydraulic adjustment takes two to three minutes.

In casting a large number of different profiles the number of tundishes required is reduced by using a universal tundish with changeable heads. For example, when slabs are cast, the tundish has the thickness of the thinnest one and the width of the widest one.

The changeable head used corresponds to the cross-section of the ingot being cast. Thanks to this design, one size of tundish body can be used, for example, for twenty types and sizes of slab.

The operation of continuous steel casting units is largely automated through the general use of interlocking gears, which link the operation of their many mechanisms and machines.

Systems of control-and-measuring instruments and automation ensure control of the temperature of the cast steel; automatic regulation of the level of the metal in the mould and of the temperature of the cooling water and its supply; control of the pressure and rate of flow of the cooling water for the secondary cooling and the mould, the length of the slabs cast and their cutting into regular lengths, the speed of the casting and the rolls of the drawing stand, the pressure and in-put of oxygen, fuel gas, water, etc.

Soviet-designed units are characterised by great regularity of operation, ease of maintenance and high productivity. The efficiency of the units has been demonstrated in large industrial steel-casting plants, where all the steel is cast only by machine.

Experience in the operation of units

The main difficulties in establishing continuous steel-casting units in converter shops were connected with the rapid and precise flow of melts in the converters. The high speed of operation of the converters and the continuous casting of many ladles in one machine complicated the operation of the equipment. With such a cycle, it is difficult at the outset to combine efficient converter and continuous-casting unit operation.

By finding highly refractory materials for intermediate ladles, improving the design of the basic technological components of continuous-casting units, ensuring a standard quality of steel from converters, devising new means of feeding the molten steel into the moulds, raising the speed of casting and protecting the molten metal from secondary oxidation, normal combined operation of converters and continuous-casting units was made possible and the highly productive "melt upon melt" method of casting could be brought into general use.

Calculations have shown that merely by bringing this system into general use in converter shops productivity (per continuous-casting unit) can be increased by no less than 20 per cent.

Introduction of continuous-casting using the "melt upon melt" method at the converter shop of the Novolipetsk Iron and Steelworks

The converter shop of the Novolipetsk Iron and Steelworks is equipped with three 100-tonne converters and six 2-strand continuous-casting units for pouring slabs with widths of from 900 to 1,850 mm and thicknesses of from 175 to 345 mm.

The adoption of the "melt upon melt" method in the continuous-casting unit gave the shop the following advantages:

(a) An increase in the productivity of the continuous-casting unit and the converters through an increase in machine time spent on auxiliary operations and more efficient use of the working time of maintenance personnel;

(b) Improvement of the operating conditions and quality of repairs of the continuous-casting units;

(c) Improvement of the use of intermediate ladles and reduction of the amount of refractory materials used;

(d) An increase in the usable output by reducing wastage

The successful introduction of this process was assisted by a number of measures.

The main step was the installation of lifting and rotating tables which have enabled intermediate ladles to be taken out of operation during long castings and replaced by new ones. Before the introduction of rammed linings, the maximum life of the refractory materials used for intermediate ladles in one casting amounted to five melts, and this determined the length of the series. With periodical change of the intermediate ladle, it became possible to increase the number of melts in a series substantially.

The introduction of rammed intermediate ladles made it possible to increase the life of the ladles. Subsequently, special ladles were used which significantly reduced nozzle and stopper wear, a factor limiting ladle service during casting. The number of melts poured through one intermediate ladle (without changing it) was increased to eight or twelve.

In order to increase the reliability of operation of the secondary cooling system and to improve the operating conditions of the continuous-casting unit during long castings, uniflow sprayers are used; the mechanism for driving the mould has been changed from hydraulic drive to electro-mechanical drive; a method of removing scale from the secondary cooling bunker during casting has been organized and the mode of operation in the gas cutting department has been improved.

In order to reduce the time required for changing the steel-casting ladles and, at the same time, to improve the quality of the change-over section of the ingot, a flow plan for the combined operation of converters and continuous-casting units has been worked out and applied. The tapping of melts takes place 15 to 20 minutes before completion of the casting of the previous melt, and by the completion of the casting of the first ladle, the following ladle is already on a steel car near the continuous-casting unit concerned. Under this method, the change-over cycle for steel-casting ladles has been reduced from 15 to 17 minutes to 9 to 12 minutes.

The introduction of the "melt upon melt" method of casting in continuous-casting units in a converter shop has made possible a sharp increase in the productivity of continuous-casting units and converters and has substantially improved the technical and economic indicators for the operation of the shop.

The progress made in mastering the "melt upon melt" casting process is shown by the following figures:

Melts (percentages of total melts by casting series)

Year	Single	From 2 to 5	From 6 to 10	From 11 to 15	From 16 to 20	From 21 to 25	From 26 to 30	From 31 to 35	From 36 to 40	From 41 to 45	From 46 to 50	71 melts
1967	8.3	91.7	0	0	0	0	0	0	0	0	0	
1968	7.3	72.8	2.8	3.9	5.5	4.5	3.2	0	0	0	0	
1969	5.8	41.6	15.6	12.7	8.6	5.5	4.6	2.5	1.7	1.03	0.24	1 casting

The over-all economic effect of the introduction of this process is reflected in a whole series of indices. However, from the reduction in wastage of metal in spoilage and cutting alone, the sum of 1,850,000 roubles was saved in 1969 by comparison with 1967.

Acceleration of casting in continuous-casting units

An increase in the capacity of steel-smelting units and, at the same time, in that of steel-casting ladles to 250-300 tonnes necessitated an increase in the rate of ingot drawing and a substantial decrease in ladle casting time.

Theoretical research confirmed by many years of practice has shown that the rate of ingot drawing depends primarily on the thickness of the hardened skin of the ingot leaving the mould.

The solidification face can be made uniform by regulating the heat removal in the mould around the perimeter of the billet, and also by ensuring the necessary temperature reduction pattern on the surface of the ingot.

Calculations show that with uniform growth of the skin, the rate of casting of slabs with a cross-section of 210 x 1,250 mm can be increased from 0.6 m/minute to 2.9 m/minute (more than fourfold). The thickness of the skin when the ingot leaves the mould can be 16 mm.

As was pointed out above, on the basis of theoretical research a mould has been designed which makes it possible to increase the rate of casting by increasing the uniformity of the solidification face and intensifying the removal of heat from the ingot. When the speed of ingot drawing is increased, the quality of the axial zone of the ingot is usually impaired. However, it was found possible to reduce the depth of the liquid phase by intensifying the hardening process through the introduction of metal additives into the molten metal.

The metal additive particles, which act as additional nuclei of solidification and at the same time cool the molten steel, increase the rate of solidification and reduce the depth of the liquid phase.

This alone made it possible to double the rate of casting while reducing the time of full hardening by 30 to 50 per cent.

The optimum amounts of metal additives for various grades of steel have been determined.

Experience has shown that uniformity of the solidification face and acceleration of the solidification of a continuous-cast ingot can also be achieved by the use of a vacuum, electro-magnetic fields, ultra-sound and various combinations of those means.

Calculations have been made in the Soviet Union of the maximum rates of casting in vertical continuous-casting units.

These maximum rates are determined by the following factors:

(1) Longitudinal tensile stresses in the ingot due to frictional forces in the mould;

(2) Stresses due to ferrostatic pressure;

If σ_1 is the tensile stress, and σ_2 is the stress under ferrostatic pressure, then the condition of ductility gives us:

$$|\sigma_1| + |\sigma_2| \leqq \sigma_s \qquad (1)$$

$$\sigma_1 = \frac{\mu\gamma + H\sqrt{H}}{2K}\sqrt{V} \qquad (2)$$

μ - Coefficient of friction;
γ - Specific gravity of molten steel;
H - Effective length of mould;
V - Rate of casting;
K - Coefficient of hardening;

$$\sigma_2 = 0,5\gamma \cdot H \left(\frac{a}{K\sqrt{H}} - 2 \right)^2 \qquad (3)$$

where a - is the thickness of the ingot;

σ_3 - which depends on the temperature of the skin, is determined on the basis of linear distribution of temperatures throughout the thickness of the skin (from $T_{sol} = 1,500°C$ to $T = T_{is}$, where

T_{sol} = temperature of solidification;

T_{is} = temperature of the ingot surface.

The value of σ_3 varies according to the temperature in the range 1,000°-1,500°C as follows:

$$\sigma_3 = 127,5 \left(1 - e^{-5,33t} \right) \qquad (4)$$

Having the value of σ_1, σ_2 and σ_3, we get the following equation for determining the maximum rates of casting for square ingots with varying lengths of the active zone of the moulds

$$0,5\gamma H \left[\frac{\mu\sqrt{H}}{K}\sqrt{V} + \left(\frac{a}{K\sqrt{H}} \cdot \sqrt{V} - 2 \right)^2 \right] = \qquad (5)$$
$$= 127,5 \left(1 - e^{-5,33t} \right)$$

The rates actually achieved are a half or a third of the theoretical maximum rates. This is usually due to the following reasons.

(a) The unevenness of the ingot skin, which has hollows and protuberances on the inside, creating a concentration of stresses;

(b) The necessity of having a certain safety margin in the skin in order to prevent breakouts of metal.

In the case of ingots with a large section, the main factor limiting the rate of casting is the stress due to ferrostatic pressure. In this case, a reduction in the coefficient of friction does not produce significant results, and the most promising course appeared to be to look for a way of relieving the ingot skin from the action of ferrostatic pressure, particularly when it leaves the mould. For this purpose, effective systems of secondary cooling have been worked out in the USSR which make it possible to increase the rate of casting of large-section ingots.

The maximum rate of casting also depends on the length of the active zone of the mould ("a").

When square billets are cast, there is a maximum value for the rate of casting for each value of "a", the maximum being clearly defined for billets with thickness $a \leq 300$ mm. With an increase in the section of the ingot cast, the maximum rate shifts towards larger values of the length of the active zone of the mould.

However, at values of "a" of 500 mm, the rate of casting is more or less independent of the length of the active zone of the mould.

Analysis of industrial casting rates for rectangular and square ingots

The maximum rate of continuous-casting in industrial units is determined by a number of factors, the most important of which are: the steel solidification period, the uniformity of the solidification face, the strength of the hardened skin at high temperatures, its ability to withstand sudden super-cooling, etc.

Experience in the continuous-casting of steel in profiles has shown that the values of coefficient "k" range from 0.20 to 0.30 t/hour ·cm. In this connexion, the smaller the section of the profile, the faster it can be cast, since the value of "k" is larger.

When slabs with a section of 150 - 250 x 800 - 2,000 mm are continuous-cast, the value of "k" ranges from 0.23 to 0.36.

Continuous-casting of steels and alloys as round bars

The Soviet steel industry has developed original designs for the main components of continuous-casting units (mould, secondary cooling system, drawing equipment, etc.) and a technology for the continuous-casting of steels and alloys as round bars with a diameter of up to 500 mm, at a constant rate.

The bars produced with this equipment and technology are free from distortion, have a compact structure free from external or internal fissures and a good outer surface.

Round bars of tubular steel cast by this new process have been rolled on automatic and pilger mills at a number of plants, producing seamless hot-rolled tubes of high quality.

In rolling the tubes there was no wastage due to defective metal, the consumption of metal per tonne of tubing over the whole process was reduced by 30 per cent, and cases of the downgrading of tubing to a lower quality were ten times less frequent than in production from ordinary ingots.

The cost of production of the tubing was 15 per cent less.

This equipment and technology for producing round bars can be introduced at continuous-casting units of varying designs at very little cost, and they can also be used very successfully to produce electrodes for electro-vacuum and electro-slag smelting.

Continuous-casting of hollow steel ingots in the Soviet Union

The development of many branches of technology is at present hindered by the lack of any satisfactory equipment for mass production of hollow ingots for large-diameter seamless tubes and of tubes and sleeves from warp-resistant steels and alloys. For example, the construction of large thermal power stations is held up because of the difficulty of producing tubes with a diameter of over 500 mm and a wall thickness of between 30 and 70 mm.

The centrifugal method of casting hollow ingots used at present has considerable drawbacks. The ingots produced in this way have to be cut off from the butt and their outer and inner surfaces machined to remove pick-up and non-metallic impurities.

The production of hollow ingots at continuous-casting plants will make it possible to increase the yield of usable metal considerably, to reduce capital expenditure in the construction of new tube mills and, as a result, to reduce the cost of production of tubing, particularly from high-alloy and warp-resistant steels and alloys, and to open up new possibilities for the production of large-diameter seamless tubing.

The question of how to produce hollow steel ingots by continuous-casting has been receiving attention in the USSR and other countries for many years. The Mannesmann Company in the Federal Republic of Germany is working on the matter.

Continuous-casting of ingots of circular cross-section raises greater difficulties than rectangular and square ones. In casting hollow ingots with the use of an internal mandrel certain difficulties arise in connexion with the considerable shrinkage in the solidifying steel. The skin of metal formed on the surface of the mandrel clings to it, which hinders and may even prevent removal of the ingot. At the same time, the frustrated shrinkage causes longitudinal cracks in the skin.

Many attempts have therefore been made to produce hollow ingots by causing the metal to congeal evenly on the surface of the mould without using/an internal mandrel. The ingots produced in this way, however, have had an unacceptable variation in the wall thickness both lengthways and crossways and ring-like cracks running around the outer surface.

Work done in the Soviet Union has shown that the most promising method of continuous-casting of hollow ingots is with an internal mandrel mould. Only by this method, if properly developed, can one be sure of getting billets with a minimum variation in wall thickness both lengthways and crossways and with good external and internal surfaces.

After preliminary theoretical, experimental, design and technological work, the basic principles governing the process of hardening hollow ingots have been established and equipment for vertical-type industrial units has been installed and tried out.

A number of new devices were used with these units, including a mechanism for rotating the pouring apparatus, a special mould ensuring an even solidification face, and induction rotator and screen secondary cooling with an induction device for electro-magnetical treatment of the hot metal and its rotation during the process of solidification.

In casting hollow ingots an internal water-cooled mandrel is installed in the unit mould.

The working part of the mandrel is conical in form. The shape and length of this part depend on the dimensions of the ingot being cast and the type of steel.

Experimental casting has shown that with this equipment and technology hollow ingots are formed and drawn regularly, without the internal skin clinging to the mandrel and without hot metal breaking through into the interior of the ingot. A method has been developed of delivering the metal into the ring-shaped space between the mould wall and the mandrel, and also a method of cooling the internal surface of the ingot.

Hollow ingots produced from carbon steels have good inner and outer surfaces and a satisfactory macro-structure.

Hollow ingots can be produced by this process for tubes, rings, sleeves and other products designed for various purposes. In particular, it is possible to produce large-diameter seamless tubes, high-quality hollow ingots for pilger mills, cheaper and better ingots for wheel rolling and hollow ingots from high-alloy and warp-resistant grades of steel and alloys.

Continuous-cast ingots have the following advantages:

(a) Greater yield of usable metal (about 15 to 20 per cent more than with centrifugal casting);

(b) Minimum variation in the tube wall thickness both lengthways and crossways (2 to 4 per cent compared with 10 per cent for pressed steel sleeves);

(c) High-quality outer and inner surfaces;

(d) A high degree of chemical uniformity in the ingot both lengthways and crossways;

(e) Dispersal of shrinkage defects within the ingot wall to an area away from the working surfaces.

The results achieved make it already possible to set up vertical-type industrial installations for casting hollow steel ingots of various diameters and grades for the production of seamless tubes and wheels.

Process for the production of rails from continuous-cast ingots

The increased volume of goods carried by rail, the greater load carried by each transport unit and the increased speed of traffic makes it necessary to have better-quality rail with a longer life.

One way of increasing the life of rails is to produce them from alloy steel. The use of steel with 0.5 to 1.0 per cent, of chromium, for example, has increased the life of the rails by 50 per cent.

An effective method of improving the quality of rails made from carbon steel is heat treatment, for example, oil hardening followed by tempering, which increases the life of the rails by 80 to 100 per cent. However, this does not solve the problem completely.

One way of doing so is to produce rail from continuous-cast ingots. The higher rate of solidification of the metal in continuous-casting as compared with the traditional method produces a finely divided crystal texture in the skin area on which the surface layer of the rail cap is formed in rolling.

The considerably shorter hardening period for continuous-cast ingots has a good effect on the distribution of additions; continuous-cast ingots are characterized by finely divided non-metallic impurities.

When continuous-cast ingots are used to produce rails their qualities can be exploited to the full.

The trend in Soviet metallurgy towards oxygen-converter steel production has determined the direction taken in rail steel melting research. The combination of the oxygen-converter method and continuous casting gives the best economic results.

One of the main difficulties in the production of rolled steel from continuous-cast ingots for highly demanding uses, the macro-structure of which has to pass inspection, is the presence in the ingot of axial porosity and related axial liquation.

The development of axial porosity in continuous-cast ingot is influenced by the chemical composition of the steel, the size and shape of the ingot cross-section and the basic technological parameters of the casting process.

The higher the carbon content of the steel, the greater shrinkage, and consequently the greater the axial porosity and friability. A similar effect is produced by a reduction in the cross-section of continuous-cast steel, which means a reduction in the specific volume of metal per unit of heat-radiating surface in hardening. This leads to especially marked development of the acicular crystal region and to the occurrence of concentrated porosity along the thermal axis of the ingot. Such concentrated porosity and friability are not, as a rule, removed by subsequent pressure treatment.

Thus, in order to produce rolled steel with a satisfactory macro-structure, it seemed advisable to use large-section continuous-cast steel. It was established that to change over from continuous-cast steel of square section to a rectangular section with a low ratio between the sides helps to disperse shrinkage pores. Increasing the ratio between the sides leads to the appearance of porosity and liquation concentrated along the major axis of the cross-section of continuous cast ingots.

Three alternative methods have been investigated for casting steel continuously in moulds with a section of 280 x 320 and 250 x 360 mm.

A sample batch of ingots of section 280 x 320 mm and another of section 250 x 360 mm were rolled into heavy rails.

The rolling of the continuous-cast ingots into heavy rails and all subsequent finishing operations were carried out in accordance with the technology normally used.

The macro-structure of the sample rails was tested in accordance with quality control standards.

The macro-structure of all rails produced from continuous-cast ingots of section 280 x 320 mm was satisfactory.

The macro-structure of rails from continuous-cast billets of section 280 x 320 mm showed weak axial liquation and there was no non-metallic take-up.

This marked improvement in the macro-structure of the rails was achieved by selecting the optimum technological parameters for smelting rail steel in an oxygen converter and casting in a continuous-casting unit: metal temperature, rate at which the ingot is drawn and intensity of secondary cooling.

The mechanical properties of the rails met the standard requirements and did not differ from those of rails produced from ordinary ingots.

Thus, the structure of the metal of rails rolled from continuous-cast ingots is characterised by a more granular pearlite pattern compared with that of standard rails.

In order to evaluate the economic aspects of the production of heavy rails from continuous-cast ingots of 280 x 320 mm section, after smelting of the steel in 150-tonne converters followed by casting in continuous-casting units, calculations were made which showed that the saving with the new method could amount to 4 roubles per tonne of steel. The economic advantages of the process are due to the possibility of a large reduction in the consumption of metal (by comparison with the traditional method of casting in moulds with subsequent cogging) by 203 kg per tonne of ingots cast and a reduction in irrecoverable losses by 33 kg per tonne. This means a reduction in the relative consumption of deoxidisers and auxiliary materials and reduces the relative volume of expenditure per smelt.

Quality of output produced from continuous-cast ingots

A special characteristic of continuous-cast ingots produced in a casting unit is that solidification conditions remain constant along the whole of their length. This uniformity of solidification conditions at all levels in the billet gives it a high degree of structural and chemical homogeneity.

Regional liquation, both across and up and down, is considerably less than in ordinary large ingots and varies between 5 and 10 per cent. This advantage of continuous-cast ingots is particularly evident in cases when the metal is to be used for products whose sulphur and phosphorus content is strictly regulated (sheet steel for motor-vehicles and for special construction purposes). In such cases ordinary ingots are not wholly suitable because they have considerable liquation in the upper part.

In addition, continuous-cast steel shows a more highly dispersed dendrite structure than the usual kind.

These properties of continuous-cast steel are kept during subsequent hot deformation by rolling, forging or pressing, ensuring uniform properties and composition of the final product of the whole smelt.

Possibility of eliminating uneven distribution of carbon in the axial region of continuous-cast ingots

In the axial region of small-section continuous-cast ingots made from high-carbon steel the carbon distribution is uneven. The maximum degree of non-uniformity K, i.e. the ratio of C_{max} to C_{min}, is 1.60-1.90. After such ingots have been rolled and given the usual heat treatment the non-uniformity of carbon distribution is somewhat reduced as a result of the equalising diffusion which occurs when the metal is kept at a high temperature before rolling. The maximum degree of non-uniformity is 1.36-1.40. However, after deformation, structural non-uniformity occurs, which is not always accompanied by uneven carbon distribution and which is also maintained during the usual heat processes. This non-uniformity combined with even carbon distribution in the axial region is reflected in a difference in grain size and in the macro-structure of the axial region by comparison with the usual metal.

Through the adoption of special plastic deformation and heat processes, the non-uniformity of carbon distribution can be almost completely eliminated, the value of K being reduced to 1.01-1.04. These processes also ensure a uniform granular pearlite structure over the cross-section of the axial region. Etching reveals an even, uniform structure in the rolled steel. A comparison of the properties of metal produced by the usual method and by continuous casting shows that after application of these processes the resistance of the metal to bending is higher for continuous-cast steel than for the usual product, which indicates that the former has a high structural and carbide uniformity. Processes have been proposed which open up the possibility of further improving the properties of continuous-cast steel by 20 to 40 per cent.

Mass-production rolling has shown that for sheets of ordinary steel five to eight passes are enough to reduce the grain size and give the metal the necessary density and mechanical properties. For high-quality carbon steel ten passes are needed and for alloy steel twelve to fifteen.

In processing large carbon-steel ingots a minimum of eight passes are needed to ensure the quality of the finished product, and in the case of alloy steel, twelve.

In rolling small carbon-steel ingots eight passes are needed to ensure quality in the case of carbon steel, fifteen in the case of alloy steel and no less than eighteen in the case of high-alloy steel.

Quality of hot-rolled sheet

In the Soviet Union continuous-cast slabs are now used to produce hot-rolled sheet of construction steel (standard quality steel, ship-building steel), a number of low-alloy steels and stainless steel with or without titanium.

Comparative studies of the mechanical properties of hot-rolled steel produced from continuous-cast slabs of oxygen-converter carbon steel at the Novolipetsk steel works and from open-hearth steel sheet produced by the usual process at the Ilich works have shown that sheet (with a thickness of 10 to 20 mm) from continuous-cast slabs has a strength, yield point and relative elongation which meet the required standards and are equal to those of sheet rolled from ordinary ingots.

The impact strength of sheet steel 14 and 16 mm thick at a temperature of + 20°C is also up to the required standard, being not less than 7 kgm/cm^2.

Tests have been carried out in the USSR to compare the quality of oxygen-converter sheet steel for ship-building de-oxidized with a high proportion of aluminium (1 kg/t) when cast by the continuous method and by the traditional method. The mechanical properties of the steel under tension (strength and plastic properties) and the results of bending tests were identical for steel produced by all the smelting and casting methods tested.

The impact strength of sheet carbon steel (de-oxidised with 1 kg/t of aluminium) from continuous-cast slabs of oxygen-converter steel is greater than that of sheet from ordinary ingots produced by the oxygen-converter and open-hearth processes (at temperatures of + 20°C, 0 and - 20°C).

Smelting and casting method	Impact strength (average figures), kgm/cm², for various sheet thicknesses, mm, and temperatures, °C					
	Sheet thickness 10-12 mm			Sheet thickness 20 mm		
	+ 20	0	- 20	+ 20	0	- 20
Oxygen-converter traditional method	7.9	5.8	4.8	6.8	4.8	3.4
Oxygen-converter, continuous-casting	10.2	7.5	5.5	10.5	7.8	3.7
Open hearth, traditional method	6.4	4.6	3.5	6.0	3.8	2.3

The susceptibility of steel to age hardening, is practically identical whether it is cast by the continuous or by the traditional method.

The hot-rolled sheet and strip of rimmed steel produced at a number of plants in the Soviet Union on an industrial scale from continuous-cast slabs meets all the required standards.

Hot-rolled sheets of stainless steel with or without titanium produced from continuous-cast slabs meet all the required standards for both surface quality and mechanical properties.

Quality of cold-rolled sheet

Automobile sheet steel. Experiments were carried out for a number of years at various plants in the Soviet Union with the continuous-casting of slabs of rimmed open-hearth, electrical and oxygen-converter steel for the production of automobile sheet steel and tin-plate. These experiments were successful in 1968, when a large industrial batch of 10,000 tonnes of oxygen-converter low-carbon steel slabs from the Novolipetsk steel works were rolled into sheet with a thickness of 0.7-2.0 mm.

The yield of grade-one cold-rolled sheet was 93.5 per cent.

The yield of grade-one cold-rolled sheet from "08 kp" steel was 95.1 per cent. As regards drawing properties and micro-structure, the cold-rolled sheet met the required standards for very deep drawing.

Pressing of parts at car factories showed the automobile steel sheet to have good pressing and drawing properties.

Wastage during pressing was either nil or at the current production level, and in any case not greater than 2 per cent.

Tin-plate. At the Elektrostal works and the Magnitogorsk Metallurgical Combine hot-tinned tin-plate has been produced from an industrial batch of cast slabs of "08 kp" steel. The surface quality and mechanical properties were tested according to the current standards. The yield was 98.72 per cent hot-tinned canning-quality tin-plate, 1.26 per cent multi-purpose tin-plate, and 0.02 per cent wastage.

Pressing showed the tin to have good plastic properties. There was no wastage in pressing.

Cold-rolled transformer steel. An insignificant degree of liquation means that the continuous-casting process is efficient for the production of cold-rolled transformer sheet. The electromagnetic properties of this steel are considerably affected by non-uniformity of the macro-structure and chemical composition of the ingot. Whereas in the usual 11-tonne ingot of transformer steel the degree of liquation for carbon, sulphur and phosphorus varies between 150 and 250 per cent, in continuous-cast ingots there is practically no liquation for carbon, manganese, nickel and copper, either vertically or crossways. The small variations in the content of sulphur, phosphorus, chromium and nitrogen are within the limits of analytical accuracy.

The yield of the highest grade of transformer steel from continuous-cast slabs was 65 to 70 per cent.

Quality of profiled rolled metal, wire rod and wire

The mechanical properties of profiled rolled steel with a diameter of 12-14 mm produced from continuous-cast ingots of carbon steel with section 100 x 100 mm meet the required standards.

Carbon steel ingots with section 100 x 100 mm have been used to produce wire rod with a diameter of 6.3 mm, subsequently drawn to wire with a diameter of 2.5 mm, which, after annealing, was drawn to wire with a diameter of 0.98 mm. The mechanical properties of the wire rod and wire met the required standards.

Continuous-cast ingots of rimmed carbon steel with section 150 x 150, 200 x 200, 280 x 320 and 175 x 420 mm have been used to roll steel of round, square and irregular profile. After eight passes, a grade of steel with a satisfactory macro-structure was obtained, which met the required standard.

Experimental batches of continuous-cast ingots with section 250 x 360 mm of alloy steel smelted in an oxygen converter were rolled to dimensions 100 x 100 mm. The results of mechanical tests showed that the rolled steel met the required standards.

Ingots of carbon, low-alloy and alloy steel with section 280 x 280 mm are produced industrially at plants in the Soviet Union. Such ingots are used to produce high-grade rolled steel with a diameter of 120 and 130 mm and as electrodes for electro-slag smelting. The quality of the rolled steel after not less than five or six passes meets the required standards.

Continuous-cast ingots with section 280 x 320 mm and rolled ingots with section 300 x 300 mm have been rolled into channel bars and girders.

The mechanical properties of profile steels from continuous-cast ingots are found to be the same as those from rolled ingots. Their structure is dense, all the way across, without any vestige of the cast structure, and the sulphur distribution is even.

Satisfactory results have been obtained in rolling seamless water pipes with dimensions 89 x 3.25, 60 x 3.75 and 60 x 3.5 mm from continuous-cast hollow ingots with section 150 x 150 mm.

Production of hollow ingots by combined continuous-casting and rolling

With a view to the production of hollow ingots by combined continuous-casting and rolling in three-roller stands a unit has been set up in the USSR consisting of a continuous casting plant of the radial type (with a mould of clover-shaped cross-section), a high-frequency inducter for equalising the temperature across the section of the ingot, a continuous rolling mill with four three-roller stands, equipment for cutting the rolled metal as it moves along and withdrawal equipment.

In this unit the combined process has been operated regularly at casting rates up to 4.0 m/min. Success has been achieved in equalising the temperature across the section of the continuous-cast ingot before the mill with the aid of a mobile induction device fed from a high-frequency generator. A system of controlling the combined unit from the continuous-casting unit control post has been developed and successfully operated.

Tube blooms are made from the round ingots produced at the unit on tube-piercing mills. The blooms are rolled into finished tubing. Tests to investigate the piercing of ingots on conical forms have shown that rolling the ingots in the combined process makes the central region more solid and improves the conditions for the formation of the tube's internal cavity. Thus the use of ingots produced by the combined continuous-casting and rolling method ensures the production of tubes with good internal surface quality.

In the production of hollow ingots in a combined unit the throughput of metal starting as liquid steel is reduced by 275 kg/t as compared with the usual method of production from traditional ingots and by 63 kg as compared with production from rectangular continuous-cast billets rolled on a tube-rolling mill, owing to the reduction of waste and the elimination of end scrap during rolling.

Conclusion

Soviet-designed plant for the continuous-casting of steel is used to produce ingots for subsequent rolling in rolling mills.

Continuous-casting units produce round, square, rectangular and irregular-shaped ingots.

At new large-capacity plants in the Soviet Union equipped with converters or electric arc furnaces, different types of continuous-casting units are used, depending on their technical and economic advantages.

The productivity of continuous-casting plants is constantly growing as a result of increases in the rate of ingot drawing and widespread use of the "melt on melt" method of casting, without any break in the flow, which considerably increases the machine working time and the productivity of the continuous-casting unit.

Further improvements in continuous-casting equipment and in the quality of refractory materials in the USSR will undoubtedly bring the "melt on melt" method into wider use and will make it possible to organise continuous-casting more or less on a round-the-clock basis, which will considerably improve the performance of plant at large steel works, particularly with a substantial reduction in the number of units and hence in the capital expenditure involved.

In order to improve the quality of the ingots cast wider use is being made of continuous-casting methods involving insulation of the flow and meniscus of the metal from reaction with atmospheric oxygen, placing the metal in a vacuum in the ladle and actually in the unit in the process of casting, processing of the metal with synthetic slags, magnetic fields and ultrasonic sound and the use of combined or consecutive continuous-casting and rolling processes.

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