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Topical Issues of the Technological Development of Advanced Electrical Steel Grade Production in Russia

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Abstract—The growing competition in the global steel market in the field of rolled products potentially implies an efficient, economical and environmentally friendly approach to the production of electrical steel. The following key elements of advanced strip steel casting are discussed: innovations in the use of cast strips for the production of the initial hot-rolled billet and cold-rolled steel from electrical anisotropic and isotropic steel, as well as amorphous steel strips for magnetic cores of electrical machines, which have been commercially applied in world practice.

Keywords: electrical anisotropic steel, electrical isotropic steel, amorphous steel, integrated casting and rolling facility (CSP, ISP), twin roll caster (TRC), single-roll casting installation

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In 1970, after the first energy crisis, the world metallurgical industry faced a serious restructuring problem [1]. The essence of the restructuring was the simplification and long-term implementation of advanced processes to reduce investments, save energy and produce metal products of thinner standard sizes.

In the mid-1980s, a number of foreign companies, including German SMS and Demag, Italian Danieli, Austrian VAI and Japanese Sumitomo Metal, competed in numerous research and development projects and offered breakthrough technical solutions.

In July 1989, the Nucor Steel Company (USA) took over the CSP (Compact Strip Production) process developed by SMS and set up a production line at the Crawfordsville plant in Indiana (USA), marking the world's first industrial technology of continuous casting and rolling of thin slabs.

The CSP production line, launched by ThyssenKrupp AG (Germany) in March 1999, belonged to the second generation of continuous casting and thin slab rolling lines and for the first time produced non-oriented (isotropic) electrical steel with a silicon content of less than 2.4%.

In August 2001, a new CSP production line was built at the AST (Acciai Speciali Terni) plant in Italy. This line highlighted the development and progress of the CSP process in the production of special alloys with a particular composition (stainless steel, electrical steel, etc.). Its design capacity was 1 million tons of steel per year, including austenitic stainless steel, ferritic stainless steel, non-oriented (isotropic) electric steel (Si < 3.5%), as well as a small amount of high-carbon steels C75 and C100.

In October 2002, a total of 115 thousand tons were produced, including 88 thousand tons of stainless steel, 17 thousand tons of electrical steel and 10 thousand tons of ferritic stainless steel. The electrical steel included isotropic steel with 1.0 and 1.8% silicon, as well as anisotropic electrical steel with 3.0% silicon. Italian experts believed that all grades could be produced by the CSP process, including electrical steel with high magnetic induction.

The development of economically sound technology and commercial production of advanced electrical steel grades is dictated today by the needs of high-tech science-intensive branches of the electrical industry. In the total external and internal consumption of rolled products, the share of advanced electrical steels is currently limited, but they play a key role in ensuring scientific, technical and economic progress and are strategically justified.

The main role in the development of technology and production efficiency is played by the technical level of the applied technological equipment together with innovative technical solutions.

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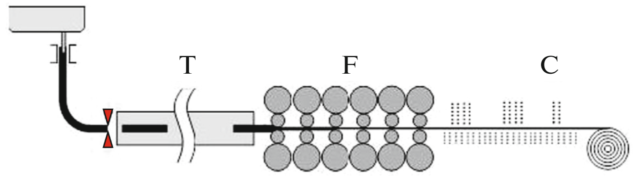

Fig. 1. Main CSP plant elements [3]: T—tunnel furnace; F—finishing mill; C—cooling/coiling.

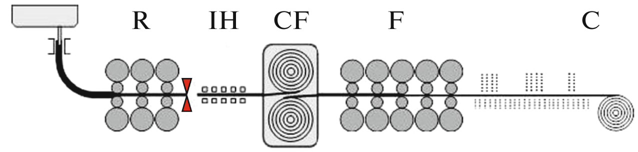

Fig. 2. Main ISP plant elements [3]: R—rough mill; IH—induction heater; CF—Cremona furnace; F—finishing mill; C—cooling/coiling.

1. METHOD FOR COMPACT PRODUCTION OF ELECTRICAL STEEL STRIP

The application of the compact strip production method (CSP) was aimed primarily at solving the problem of strip cracking during electrotechnical silicon steel rolling, increasing productivity and reducing production costs.

1.1. The practice of using CSP and ISP casting and rolling complexes. A number of foreign metallurgical companies have mastered and are widely using the production of electrical steels using the CSP type casting and rolling complexes (CRC), in particular Nucor Steel Crawfordswille, ThyssenKrupp Duisburg, ThyssenKrupp Terni.

The CSP is a compact installation comprising a casting machine, a roller-hearth furnace and a rolling mill [2, 4]. Thin slabs 50–90 mm thick are cast and fed directly into the CSP rolling mill after equalizing the temperature in the roller-hearth furnace and rolled to the thickness of the finished strip (Fig. 1).

Rolled electrical isotropic steel is made from evacuated and non-evacuated metal (vacuum tap degassing) of various alloying groups (Si content 1.0–3.2%) with a high level of magnetic, mechanical and geometric characteristics. Compared with the conventional hot rolled production of isotropic steel (steel casting to obtain thick cast slabs, slab heating in continuous slab heating furnaces followed by rolling on a continuous multi-stand hot rolling mill), the CSP process is more acceptable in the context of temperature control [4].

The use of the CSP process is of particular interest in the electrical anisotropic steel production by the "acquired" inhibitor method, in which the inhibitory grain growth phase is formed in heat treatment of hot rolled steel and cold rolled steel nitriding at the finite thickness stage [5].

The ISP (In-line Strip Production) process was jointly developed by the Mannesmann Demag Huttentechnik metallurgical plant (Germany) and the Italian partner Arvedi in Cremona, which started production using this process in 1993 [6].

The ISP installation scheme is shown in Fig. 2. The installation is distinguished by the technology of "soft" drafting, capable of reducing the slab thickness, while the slab "core" remains in a liquid state, to obtain a cast plate with "soft drafting" from 80 to 60 mm. After leaving the casting machine, the slab enters a tandem group of hot-rolling roll stands, where it is rolled to a thickness of 15–25 mm for coiling in the Cremona furnace.

After rolling in the roll stands, the strip is cut off, then the strip enters the reheating oven, which acts as a buffer between the casting installation and the final rolling mill. The preheated strip is then coiled spirally in a double coil box-type furnace. This furnace receives the strip from the casting module and immediately feeds the precoiled strip to the finishing mill. The finishing mill is a tandem group of hot rolling stands capable of providing strip thicknesses ranging from 12 to 1.5 mm.

The conducted studies of the technological scheme for the production of anisotropic electrical steel using a casting and rolling complex plant of the ISP type (Arvedi, Italy) showed that one of the main characteristics of the obtained hot rolled steel—the textural state—is comparable to the texture of rolled products for a continuous hot rolling mill.

An original technological process designed for a competitive, economically sound and maximally flexible production of hot-rolled and cold-rolled steel is of scientific and practical interest.

1.2. The practice of using twin-roll casters. The world's first commercial twin-roll casting and rolling mill TRC (Twin-Roll Caster) was commissioned by Thyssen Krupp Nirosta in Krefeld in 1999.

In 2000, the Eurostrip research group predicted that the potential demand for cast strip of carbon and silicon electrical steel will exceed the demand for cast strip of stainless steel by 2003 and would reach 2.75 MT by 2008. Therefore, a two-roll casting and rolling unit at Thyssen Krupp Terni [1] was decided to be built.

Significant renewal of the Terni company, including merger of the factories, made it possible by 2002 to master the strip production with a width of 1130 mm with a reduction of up to 40% in hot rolling thickness. The arrangement of the Terni installation for the production of cast strip is shown in Fig. 3.

The design principle of strip casting is that two water-cooled rolls are located horizontally at a certain distance from each other (the gap determines the strip thickness) and, due to ceramic end seals on both sides, a liquid metal bath can be formed between them, replenished with melt through submersible pouring nozzles. When the rolls rotate towards each other, the liquid metal is drawn into the gap between them and crystallizes on the water-cooled surfaces, forming a strip.

In general, the technology of obtaining hot-rolled strip, including for the production of cold-rolled steel by casting on a two-roll casting and rolling unit, according to leading Russian and foreign experts, is the most effective and promising compared to existing methods [1].

The use of a two-roll plant has the following advantages in comparison with the traditional technological scheme of production and plants for casting thin slabs:

(A) Reduction of capital investments during construction;

(B) Reduction of specific capital investments in production (per ton of rolled products);

(C) Reduction of a production area (unit dimensions).

Nucor has mastered the manufacturing of hot-rolled steel for the production of electrical isotropic steel with a silicon content of up to 3.0%.

Terni performs work on the production of hot rolled products for electrical isotropic and anisotropic steel. At Terni, it should be noted that a casting module has been installed upstream of the existing semi-continuous hot rolling mill and rolling can be carried out using both thin slabs and conventional slabs heated in continuous furnaces.

The use of twin-roll casting and rolling units creates opportunities for the implementation of other advanced processes of scientific and technical development at the subsequent stages of the rolled product production with the highest level of technical characteristics.

2. GRAIN-ORIENTED ELECTRICAL STEEL, ORIENTED IN TWO DIRECTIONS, FOR HIGH EFFICIENCY MAGNETIC CORES OF ROTARY MACHINES

Large energy savings in the core of electric motors and other electrical devices makes it possible to reduce the size of electrical products for various purposes, including power motors, generators, and transformers.

Advanced grades of electrical steel, in comparison with materials of ordinary quality, allow providing technology for the production of efficient designs of electric motors and increasing the electric motor power.

The development of technology for the production of textured cold-rolled electrical steel with a cubic texture, oriented in two directions, with extremely high magnetic characteristics (specific magnetic losses

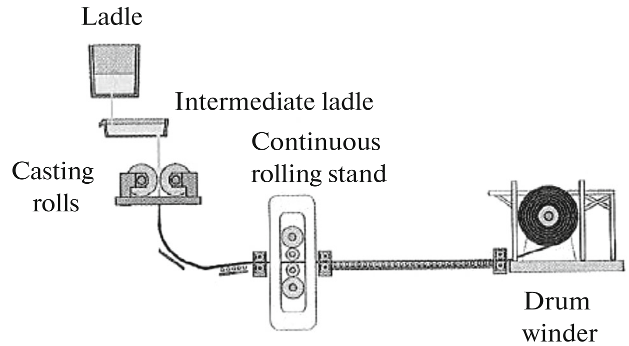

Fig. 3. Structural scheme of TRC module "Eurostrip at Terni" [7].

P1.5/50 < 1.80 W/kg and magnetic induction B50 > 1.71 T at a rolled thickness of 0.35 mm) is currently of particular relevance.

Traditional electrical isotropic steel, as a rule, has a random arrangement of individual crystals with edge {110} ⟨001⟩, cubic {100} ⟨001⟩, octahedral {111} ⟨112⟩ and other intermediate orientations.

The textural components with the {111} and {112} planes in the sheet plane increase the isotropy of the magnetic characteristics. However, the total magnetic properties of the steel becomes limited.

Isotropic steels are relatively fine-grained (the grain size is commensurate with the strip thickness), the magnetic structure is usually characterized by domains with 180- and 90-degree boundaries, while the domain structure of each of the grains is relatively autonomous and depends on the grain size. A significant increase in magnetic induction and a decrease in specific magnetic losses are possible with a significant increase in the cubic component {100⟨*wvw*⟩, {100}⟨001⟩. Mechanisms of texture formation, effective ways to increase the proportion of cubic components and mutual transitions of texture components, remain controversial [7, 8].

Crystallographic orientation adjustment is achieved in the cold rolling process of the original textured billet and recrystallization of cold rolled steel by limiting the crystal formation with the {111}⟨112⟩ orientation, which degrade the magnetic properties, and stimulating the formation of crystals with favorable orientations {100}⟨001⟩ and {110⟨001⟩ improving the properties, as well as the use of additives of special elements as an inhibitor of grain growth, for example, phosphorus and antimony, which makes it possible to control the texture [9–12].

The technologies for this process have been comprehensively researched, with commercial types of such products on the world market, but they are used to a limited extent due to increased production costs. An expert assessment shows that an economically viable production technology is determined by the pre-

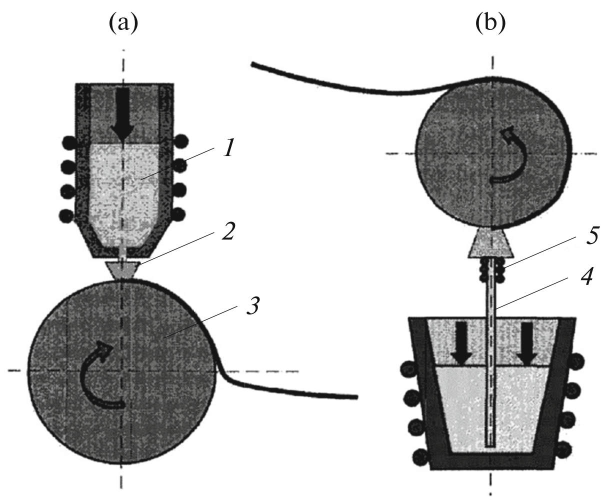

Fig. 4. Scheme of obtaining an amorphous strip on a single-roll installation with a supply of melt from above (a) and from below (b) [14]: (*1*) induction melting furnace; (*2*) pouring nozzle; (*3*) cooled roll; (*4*) metal crucible; (*5*) metal induction heating in the metal crucible

dicted cost of finished textural cold-rolled steel with a cubic texture—about $1200USD per ton.

3. AMORPHOUS ELECTRICAL STEEL FOR NEW GENERATION ELECTRICAL MACHINES

Energy saving has been one of the main tasks in the energy sector in recent years. One of these areas is the replacement of distribution transformers with magnetic silicon steel cores with energy efficient transformers of a new generation with amorphous steel magnetic cores [13].

Since 1984, Russia has been producing rapidly quenched amorphous and nanocrystalline alloys in the form of a thin (micron-sized) strip on an iron, nickel and cobalt base [14]. The strip is made by the method of freezing-out (spinning) the melt onto the polished surface of a water-cooled roll moving at a linear speed of 20–30 m/s [15].

On amorphous alloy casting machines, an induction melting furnace for preparing the melt for casting can be installed above the casting roll or below the roll. Accordingly, the supply of the melt to the quenching roll in the first case is carried out from the top, in the second—from the bottom (Fig. 4).

For the manufacturing of the magnetic core of a power transformer with a capacity of 32 kV A, an amorphous strip of up to 220 mm wide is required. The drop in prices for amorphous steel from $50USD to $3USD per kilogram made the production of “amorphous” transformers economically viable. Experimental and theoretical studies in the technology of manufacturing amorphous and nanocrystalline electrical steels show the reality of achieving specific magnetic losses $P1.5/50 < 0.30$ W/kg and magnetic induction $B50 > 1.75$ T with a strip core ratio of at least 90%.

At the same time, by now, there is a need to develop innovative equipment and master the production of wide strips from amorphous electrical steels with a thickness of 20–30 μm with controlled magnetic properties. The prerequisites for choosing the optimal technical and technological solutions for this innovative direction require the creation in Russia of a specialized site for the production of amorphous and nanocrystalline stripes in cooperation with relevant scientific organizations with manufacturing facilities.

CONCLUSIONS

(A) One of the key directions in solving the problem of the production of high-performance electrical steel grades in Russia is the creation of conditions for advanced development, with allowance for the existing world and domestic scientific and technical experience, the use of various progressive initiatives based on an effective, economical and environmentally friendly approach.

(B) The presented advanced technical and technological directions can take an appropriate place in the innovative projects of Russian enterprises—manufacturers of electrical steel in the framework of technology development strategy programs in order to achieve leading positions in the relevant market segment.

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