Utilization of a numerical model of the temperature field of a conti-casting and prediction anti-break systems at the continuous caster of the steelworks division plant to improve the production quality at U. S Steel Košice, Ltd.

Dagmar Fedáková[1] and *Pavol Marek*[1]

Využitie numerického modelu teplotného kontinuálneho odlievania a "anti-break" systémy kontinuálneho odlievacieho stroja divízneho závodu pre vylepšenie kvality výroby v U.S. Steel Košice, Ltd.

The paper presents the optimization elements at the continuous caster (CC) from the view of the quality management and the cost-saving program at U. S. Steel Košice, Ltd. The presented issue represents a partial problem within one step of the production cycle, which is connected with the quality of slabs and with managing their subsequent processing. The solutions to reduce the occurrence of slab defects are presented. The authors describe the utilization of anti-break systems of the continuous caster and an original numerical model of the non-stationary temperature field of a conti-casting for CC#2, which solves current thermo-kinetic problems generally, as well as individually. This model helps to optimize the primary and secondary cooling at CC#2 and to improve the surface quality of slabs.

Introduction

Within EUREKA project, in cooperation with the Technical University in Brno and VUHŽ Dobrá, a.s., Czech Republic, a mathematical model of the non-stationary temperature field of a conti-casting at CC#2 has been developed and the OPTIMA slab quality prediction system is being developed. The research in this field continues by verifying the model. Different variants of the optimization of the casting process will be simulated. The research team will analyze these results in detail and, based on these results, a technology that appears as the optimal will be recommended and then trial runs will be made. These steps can only be made in combination with Datamining in an interactive analytical environment for the support of the optimization of the casting process at CC#2, which is established at the workstation with the SAS system at the Section of the GM Research and Development.

Continuous casting

By developing continuous casters (CC), the effective steel casting was resolved to a significant extent. The development of classical continuous casters has been finished, in fact. The basic technological procedures have been managed and the achieved technical and economic parameters are more favorable than in conventional casting. However, the optimization of technological parameters and the possibility of the backward influencing of the slab quality have not been managed yet. Considering the fact that it is the question of a continuous production process, it is also very important to evaluate the quality of a conti-casting in course of the production cycle. This can be achieved the most effectively by creating numerical models, expert systems and systems making it possible to predict quality, which are based on the utilization of modern mathematical methods, statistical methods, as well as Datamining methods. Such a system is a basis for the optimization of technology. Production can effectively be managed only after implementing this system (Fig.1).

Objectives of the management of the continuous casting process

Achieve a maximum yield of metal

To fulfill this objective, it is necessary to provide casting in long sequences, with the optimization of the production program in such a way that the lengths of transition slabs with a mixed chemical composition can be minimal. Achieving the required surface and internal quality of slabs and the required geometrical shapes is conditioned by the good adjustment of CC, the trouble-free function of all the machinery parts and by controlling the steel casting parameters under as stable conditions as possible in the automated control system with possible correction during changing the ladle, the tundish, etc. Conti-castings must be cut into the optimum lengths, so that the cutoff losses in rolled products can be almost zero.

Reduce the energy consumption in steel making

The implementation of continuous steel casting itself provided a significant reduction of energy consumption. But the implementation of continuous steel casting and subsequent direct rolling with hot slab

[1] *Ing. Dagmar Fedáková, doc. Ing. Pavol Marek, CSc.:* Unit of the GM Research and Development, U. S. Steel Košice, Ltd.
(Recenzovaná a revidovaná verzia dodaná 19.11.2003)

charging is a really revolution measure. Here, the energy savings are multiple. The implementation of this technology necessitates the production of conti-castings without defects, with the perfect harmonization of the production of steel-making facilities, e.g. oxygen converter, secondary metallurgy, continuous casting, and particularly logistical planning between the Steelworks Division Plant and the Hot Rolling Mill Division Plant. This requirement cannot be met without computer technology and without technological processes automated control systems.

Assure the slab quality

An important role of the steel production automated control systems is to obtain all necessary information on molten steel making and casting, so that a given slab can be assigned with a particular quality evaluation. Crucial controlled parameters include the optimum temperature of the cast metal characterized by overheating above the liquidus temperature and the corresponding casting speed, the oxygen activity in molten steel, maintaining a constant metal level in the mold, controlling the primary and secondary cooling, cooling of the caster, so that a conti-casting with a sufficiently strong casting shell can come out from the mold. The secondary cooling control must ensure the conditions excluding the formation of surface and internal cracks, as well as the required thermal profile of a conti-casting. Parts that are in contact with the surface of a conti-casting must have a non-deformed and smooth surface (Fedakova, 2003).

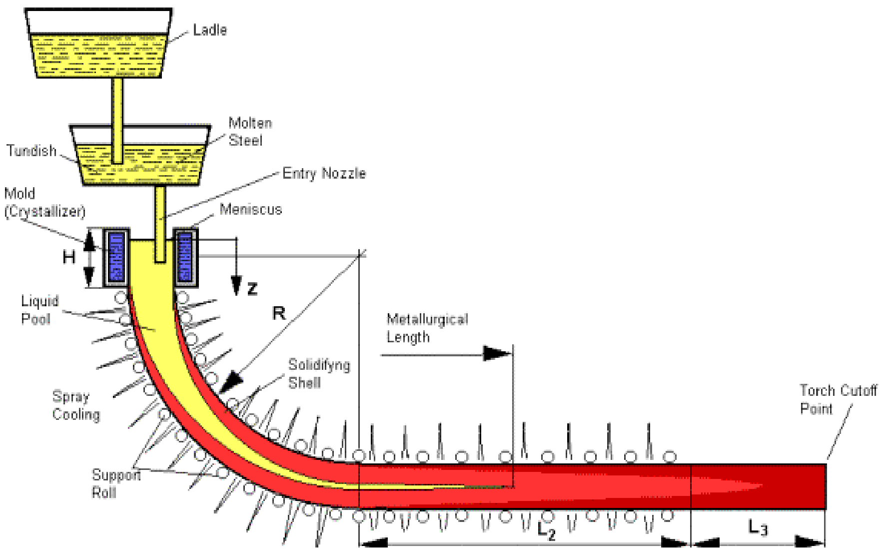

Fig.1. Scheme of a continuous caster – CC.

Mathematical model of the non-stationary temperature field of a conti-casting AT CC2

Nowadays, it is impossible to optimize production at continuous casters with the aim to achieve maximum savings and maximum quality of slabs without the perfect knowledge of the course of the solidification and cooling of a conti-casting. From the thermo-kinetics point of view, the solidification and cooling of a classical casting (gravitational casting) and the simultaneous heating of the mold represents a three-dimensional (3-D), non-stationary heat and mass transfer in *the conti-casting – mold – surroundings* system. If the mass transfer is neglected and the conduction is considered as the most decisive heat transfer from the three basic types of heat transfer, then the problem is reduced to the solution of Fourier equation:

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial T}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + Q_{source} \quad (1)$$

Fig.2 shows the thermal balance of an elementary volume representing a general node of the network (i, j, k). Thermal conductivities expressed in [W/K] can be described in all the directions of all the main axes, e.g. in the z-axis direction:

$$VZ_{i,j,k} = \lambda \frac{S_z}{\Delta z} \quad \text{or} \quad VZ_{i,j,k-1} = \lambda \frac{S_z}{\Delta z} \quad (2)$$

Thermal flows [W] flowing through a general elementary volume, also e.g. in the z-axis direction from above and from below, can be described as follows

$$QZ1_{i,j} = VZ_{i,j,k}(T^{(\tau)}_{i,j,k-1} - T^{(\tau)}_{i,j,k}) \quad (3)$$

$$QZ_{i,j} = VZ_{i,j,k+1}(T^{(\tau)}_{i,j,k+1} - T^{(\tau)}_{i,j,k}) \tag{4}$$

The unknown temperature of a general node of the network at the next moment (τ + Δτ) is given by an explicit formula:

$$T^{(\tau+\Delta\tau)}_{i,j,k} = T^{(\tau)}_{i,j,k} + (QZ1_{i,j} + QZ_{i,j} + QY1_i + QY_i + QX1 + QX)\frac{\Delta\tau}{c_v.\Delta x.\Delta y.\Delta z} \tag{5}$$

In case of continuous casting, it is necessary to solve the solidification and cooling of a conti-casting passing through the continuous caster and the heating of the mold. The temperature field of the mold (so-called primary cooling zone) is described by the equation (1) and the temperature of its elementary volume is given by the equation (5). The temperature field of a conti-casting passing through the continuous caster, i.e. through the primary, secondary and tertiary cooling zones (in a simplified way - in the direction of one coordinate with the w_z speed), is expressed using Fourier – Kirchhoff equation:

$$c_v\left(\frac{\partial T}{\partial t} + w_z\frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial T}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + Q_{source} \tag{6}$$

The equation (6) must describe the temperature field of a conti-casting at all the three stages, above the liquidus temperature (molten metal), in the liquidus-solidus interval (co-called mushy zone) and below the solidus temperature (solid phase). Therefore it is convenient to introduce a thermodynamic function of the specific volume enthalpy ($i_v = c.\rho.T$) dependent on the temperature. The thermal conductivity λ, the specific heat capacity c and the density ρ are thermo-physical properties, which are also functions of the temperature. The equation (6) is then transformed as follows:

$$\frac{\partial i_v}{\partial t} + w_z\frac{\partial i_v}{\partial z} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial T}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) \tag{7}$$

The unknown enthalpy of a general node of a conti-casting at the next moment (τ + Δτ) is given by an analogical explicit formula:

$$i^{(\tau+\Delta\tau)}_{v_{i,j,k}} = i^{(\tau)}_{v_{i,j,k}} + (QZ1_{i,j} + QZ_{i,j} + QY1_i + QY_i + QX1 + QX)\frac{\Delta\tau}{c_v.\Delta x.\Delta y.\Delta z} \tag{8}$$

The thermal flow in the z-axis direction, i.e. in the conti-casting motion direction, is given by the following formula:

$$QZ_{i,j} = VZ_{i,j,k}(T^{(t)}_{i,j,k+1} - T^{(t)}_{i,j,k}) - VZ_{i,j,k}\Delta z w_z i^{(t)}_{v_{i,j,k}} \tag{9}$$

where: T - temperature [K]
- l - specific quantity of enthalpy [Wm^{-3}]
- τ - time [s]
- c_γ - specific quantity of heat capacity [$J.m^{-3}.K^{-1}$]
- ρ - density [$kg.m^{-3}$]
- x,y,z - axes in the given direction
- QX,QY,QZ - thermal flow in the given direction [W]
- VX,VY,VZ - thermal conductivity in the given direction [$W.K^{-1}$]

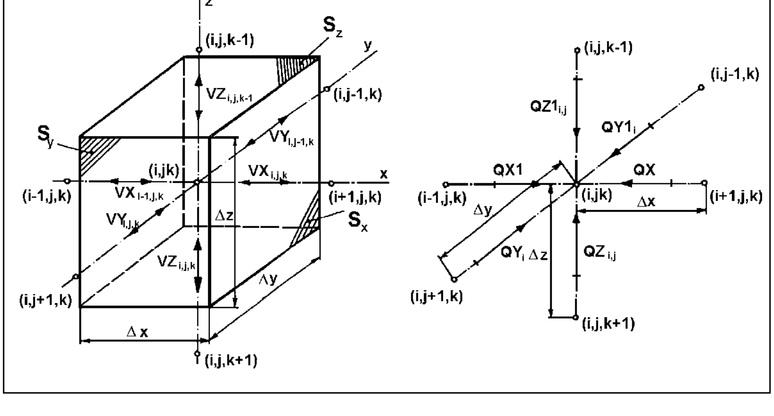

Fig.2. Scheme of thermal balance of a general node of the computing network.

A 3-D model, which was developed for CC2 at U. S. Steel Košice, Ltd., is based on the explicit numerical method of finite differences. The simulation of generation of latent heat of phase or structural transformations is made by introducing an enthalpy function. The program is equipped with an original network generator, so-called *preprocessing*, as well as *postprocessing,* i.e. graphical processing of results. The number of computing nodes can be $10^6 \div 10^7$. Such a network density in the direction of each of *x*, *y*, *z-axes* is sufficient. This network density also makes it possible to consider the linear distribution of temperatures between the network points and between the periods of time. The accuracy of the numerical solution not only depends on the spatial (size of the network mesh) and time discreteness (size of the time step $\Delta\tau$), but it also depends on the accuracy with which the thermo-physical properties of all the materials entering the system are determined. The accuracy of the derivation of the boundary conditions of the solution is also of a great importance. The application of the numerical model of the temperature field of a conti-casting requires systematic experimental research and measurements of operational parameters at CC#2, as well as laboratory research. The results of measurements, particularly of temperatures, not only serve to verify the accuracy of the model, but also to ensure the linkage of the procedure: ***real process → obtaining input data → numerical analysis → optimization → correction of real process*** (Stetina et all., 2003).

Spatial and time discreteness

The program makes it possible to solve the temperature field of steel slabs with a length from 800 to 1600 mm and a thickness from 120 to 250 mm while they are passing through a continuous caster. In Fig.3 it can be seen how many nodes of the computing network can be selected in the **x**, **y** and **z**-axis directions of one half of a rectangular profile. The **z**-axis is perpendicular to the profile and it is identical with the conti-casting motion direction. Only a half of the cross-section is solved, considering the symmetrical heat removal from the conti-casting according to the vertical symmetry axis of the rectangular profile. For each task, it is necessary to know the chemical composition of steel of the given conti-casting and slab, the casting temperature, the conti-casting motion speed and the types of used nozzles in each secondary cooling zone.

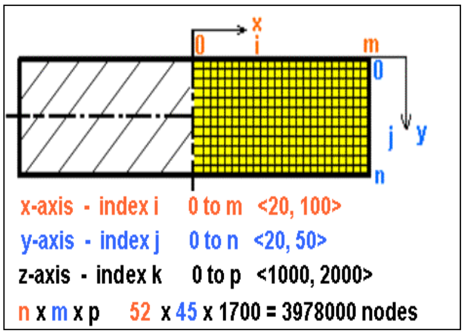

Fig.3. Scheme of division of the slab section profile half into computing nodes.

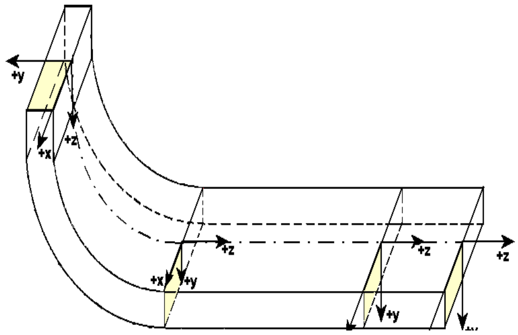

Fig.4. Solved area with indicated planes of the coordinate system.

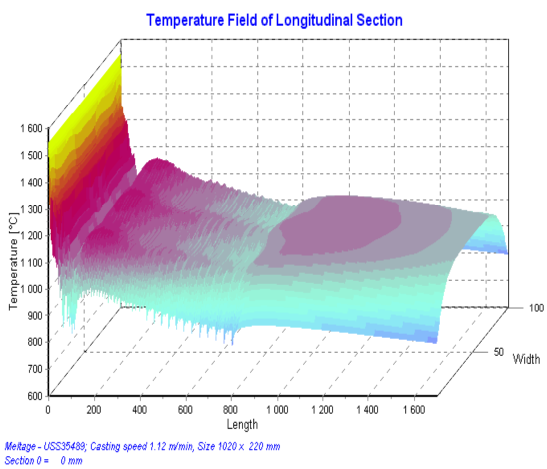

Fig.4. Temperature field of the right part of the small radius surface.

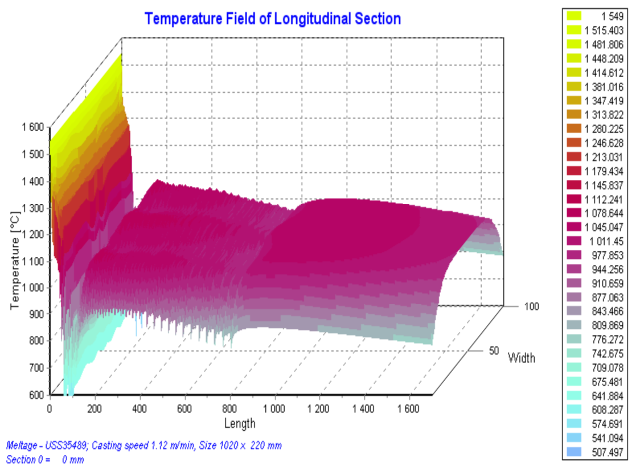

Fig.5. Temperature field of the left part of the small radius surface.

Fig. 4 shows the basic coordinate system with which the program works. The beginning of the coordinate system is on the steel level in the mold, i.e. in the meniscus, on the small radius in the center of a slab. Considering the fact that the level position varies, the positions of the secondary cooling nozzles are entered from the bottom edge of the mold.

D representation of temperature above the longitudinal section of a conti-casting

The three-dimensional representation of the temperature field of CC#2 after calculating the right part above the small radius surface and 113mm below it is in Fig.4 and the calculation of the left part is in Fig.5 (Stetina et all.).

Based on there first results, today we can state the asymmetry in cooling a conti-casting at CC#2 and the research should be focused on the optimisation of secondary cooling with a possible proposal of change of the characteristics of the nozzles and the spray plans. The verification of the model will also be made with planned trial experiments of casting speeds, pouring powders, etc.

Boundary conditions in the primary cooling zone – mold

It is the most difficult to define the boundary condition, i.e. the heat-transfer coefficient on the surface of a conti-casting during its staying in the mold, in the primary cooling zone. The heat transfer depends on the conti-casting motion speed, on the quantity and quality of pouring powder, on the moment of formation of the gap and on the mechanism of its growth. In any case we cannot simplify the character of this interface to the ideal physical contact. The model utilizes temperatures measured by the anti-break system PPZ2 (Fig.6), which has 48 thermocouples on the wide and narrow mold plates in two horizontal planes. These measurements and information on the way of cooling the mold (water flow rate, water temperature at the entry and the exit, etc.) formed a basis for the study of the thermal balance of the mold.

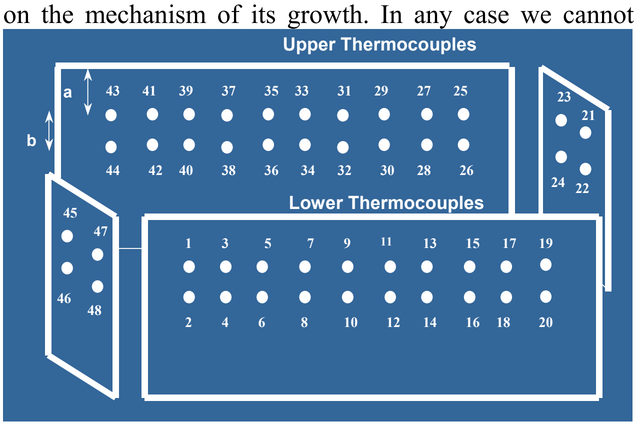

Fig.6. Scheme of installation of thermocouples on the CC2 mold plates

The temporary substitution of the direct solution of heat transfer between the conti-casting and the working plate of the mold led to an estimate of the heat-transfer coefficients in the upper zones of the mold below the meniscus, which is ca 150 mm below the upper edge of the mold. Towards the lower edge of the mold, the coefficient values continuously decrease. The distri–bution of the boundary conditions (heat-transfer coefficients) at the mold – conti-casting interface can also be entered in the form of continuous courses (Fig.7).

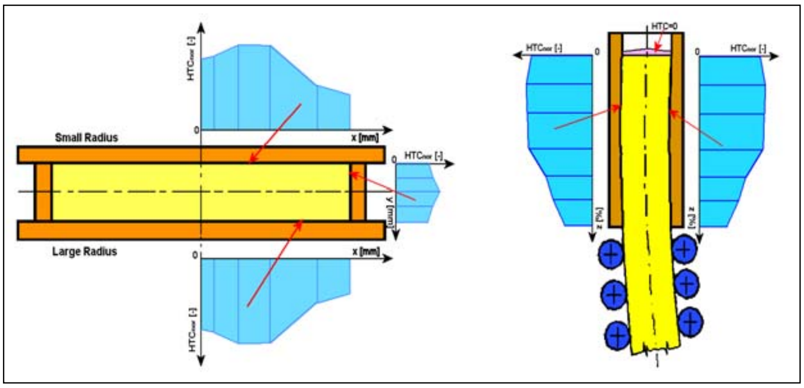

Fig.7. Scheme of distribution of the heat-transfer coefficients in the mold

This distribution is calculated from the data of the anti-break system, the thermal balance of the mold and its plates. The most important input data are:

- *basic* (information on the heat, the temperature, the casting speed, etc.)
- *on primary cooling* (entry and exit temperatures of the mold cooling water and its flow rate in l/min),
- *on the mold* (information on the dimensions, the structure and the material),
- *on secondary cooling* (information on the nozzles and the water circuits in the secondary cooling zones).

Boundary conditions in the secondary cooling zone

To determine the heat-transfer coefficients on the surface of a conti-casting after coming out from the mold, i.e. in so-called ***secondary cooling zone***, it is necessary to make experimental measurements under laboratory and operational conditions. Experimental tests of the relative motion of the nozzle and the material were made at the Aeronautical Institute of the Technical University in Brno, at the Heat Transfer Laboratory (Fig.8). The measurements were made on an experimental stand, which enables the study of the following parameters influencing the cooling intensity: *nozzle type, water/air pressure, distance of the nozzle from the surface, conti-casting motion speed*.

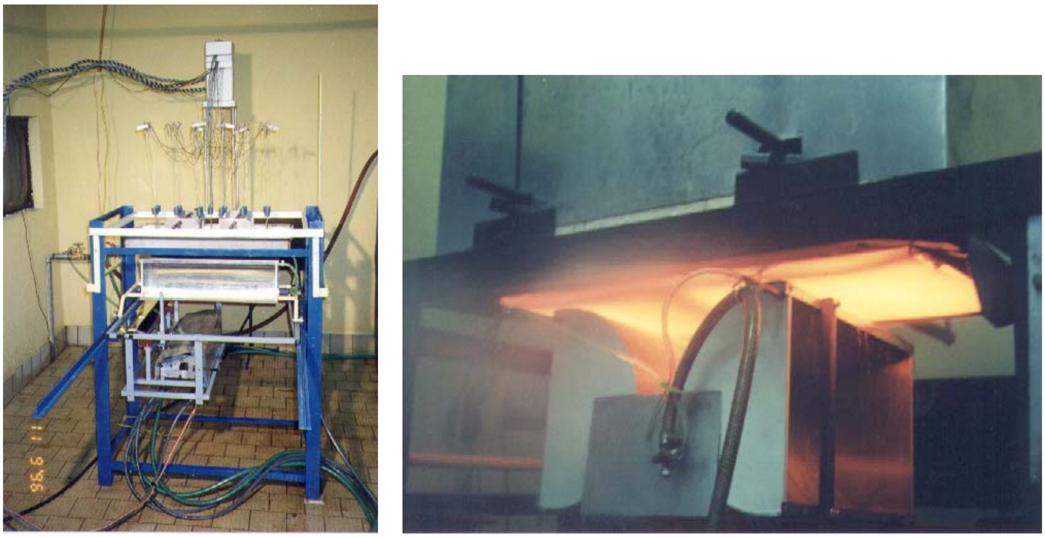

Fig.8. Laboratory equipment of the Technical University in Brno for experimental measurements.

The temperature courses were evaluated using an inversion task and correction functions of the heat-transfer coefficient were determined for radiation and natural convection from the tested plate. The radiation effect is also measured on the model plate of the equipment.

In addition, a trial experiment to measure the surface temperatures of a conti-casting was made on CC#2. The measurements were made on the casting strand 2 of CC#2. The measurements were made continuously, in four points of one horizontal plane below the mold and in one point of the casting curve before the conti-casting entered the straightening rolls. The measurements were started after synchronization with the operating time of the control system and after the integration of data into the decision and production management support system at the Steelworks DP - OKO1.

References

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