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Automated Control Systems for Thermal Hardening of Rolled Products in Rolling Mill Train

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Abstract—This article discusses specific operation features of automated process control systems (APCS) designed for a controlled cooling device of rolled products focused on accelerated cooling and engineering features of equipment. The objectives and structure of two-level APCS have been defined, and control algorithms of the cooling mode have been described for controlled the cooling facility in a rolling mill train.

Keywords: automated control system, rolled products, thermal hardening, controlled cooling, rolling mill
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Thermomechanical treatment in a rolling mill train, which combines rolling with subsequent thermal hardening by controlled accelerated cooling to preset temperature, is sufficiently efficient, since it allows to achieve the required set of service properties of rolled products using a minimum amount of alloying elements. Accelerated cooling immediately after finishing a train of rolling mill is the main method of thermal treatment by means of heat contained in metal [1, 2]. In most cases, this process is controlled by feeding coolant (water jet most often) onto metal surface [3]. Such cooling method allows to provide both the required properties of metal and their homogeneity on the surface of rolled products [4].

Controlled cooling device (CCD) in a rolling mill train allows to perform the following technological procedures: discontinued cooling after rolling, quenching, quenching with self-tempering, accelerated cooling of semi-finished rolled products between roughing and finishing rolling, and others. In order to achieve a steady level of the required mechanical properties during thermal hardening after rolling heating, it is required to accurately provide the final temperature of cooling and temperature rate variation during accelerated cooling of rolled products. The main temperature control parameters of rolled products, that is, intensity and duration of cooling, are determined by water flow rate to section and the conveyance rate of rolled products across the facility. In order to provide the preset cooling mode of rolled products, it is required to coordinate the CCD operation with adjacent systems, in particular with a roll mill stand, roller tables, pinch rolls, as well as continuous data exchange about the thermal treatment procedure, position and current temperature of rolled products, as well as some others. Therefore, the production process stability in controlled cooling facilities can be provided by an automated control system.

In recent years, OAO VNIIMT experts in cooperation with some specialized companies were involved in the design and commissioning of CCD equipped with APCS:

—CCD in the plate rolling train 5000 (OAO Severstal') [5];

—thermal hardening of reinforcing bars in the medium section mill train 350 (OAO Severstal') [6];

—thermal hardening of reinforcing bars in the small section mill train 280 (GUP Sheet rolling plant (Yartsevo, Smolensk oblast, Russia) [7];

—equipment for fabrication and thermal treatment of joint bars, OOO NSMZ (Nizhnyaya Salda, Russia) [8].

CCD operation is characterized by numerous input signals from object and output control signals to actuators (more than 750 variables), as well as thermal hardening rate (low time). ACS of cooling in such devices, regardless of the profile of cooled rolled products, are characterized by the common concept based on a unified approach both to the design of cooling devices and to the achievement of required engineering properties for thermally treated rolled products. Nevertheless, control algorithms for controlled cooling of plate rolled products differ from those of thermal hardening in the train of continuous mills and process lines.

Plate rolling mills are characterized by a wide range of rolled products in terms of sizes, chemical composition, and service properties. Accordingly, it is required to implement a wide range of thermal hard-

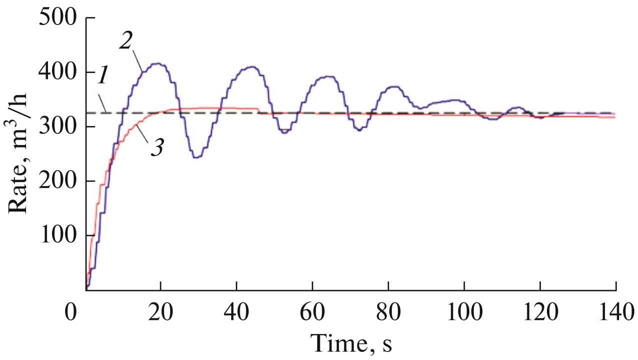

Fig. 1. Water flow rate at cooling section as a function of time to reach preset value: (*1*) preset flow rate; (*2*) with PID control; (*3*) with step (proportional) control.

ening procedures: from soft accelerated discontinued cooling with moderate cooling rates to direct quenching. Under actual conditions, a batch of rolled products treated by soft accelerated discontinued cooling can be replaced or interrupted by a batch of rolled products exerted to direct quenching or discontinued quenching with self-tempering. Herewith, a minimum batch can be comprised of a single workpiece. In such a case, rapid readjustment of the cooling device is required with a variation of operating cooling sections and water flow rate per sections. Since the arrangement of rolling line equipment facilitates independent operation of CCD and the finishing mill stand, the main CCD variable of online control to preset the temperature is the conveyance rate of rolled products (cooling duration).

On continuous rolling mills and production lines, thermal hardening is carried out at the rate of production process, that is, it is impossible to adjust the cooling rate. At steady initial and final temperatures of rolling, the main variable of process control is the cooling intensity, that is, water flow rates per sections.

While developing APCS, specific features of devices and processes of thermal hardening of rolled products are necessary to be taken into account.

ADJUSTMENT OF WATER FLOW RATES

Multi-circuit systems of water cooling (several parallel water supply pipelines) are characterized by mutual influence of circuits during the variation of water flow rates, as well as adjustment inertia in each circuit. During the variation of water flow rate, the inertia of flow meters to achieve new readings can be as high as 2–3 s, which can be accounted in regulator tunings. Despite the fact that the induction flow meters applied by OAO VNII MT are the most optimum in terms of response and measurement accuracy, PID control turned out to be inefficient in order to achieve the preset water flow rates with required accuracy; step (proportional) control was more reasonable.

Figure 1 illustrates variations of water flow rate in the course of reaching a preset value for the CCD section's upper collector of the mill 5000, OAO Severstal'.

MEASUREMENT AND PROCESSING OF CURRENT TEMPERATURES OF ROLLED PRODUCTS

The temperature gradient across the cross section of rolled products after discontinued cooling is determined by the cooling intensity, rolled product thickness, and thermal physical properties of steel. During subsequent holding in air, the temperature across the cross section is equalized, the surface temperature increases to reach average value, and the increase rate of surface temperature decreases with time. In order to measure the temperature of rolled products close to its average value, the pyrometer, used for measuring surface temperature of rolled products after cooling, should be located at a sufficient distance from the last section of CCD. APCS includes a mathematical model for the cooling of rolled products, which allows the prediction of average temperature of rolled products by its surface temperature. The predicted average final temperature of cooling will be reliable in the case of the correct pyrometer installation at the CCD output.

The surface temperature of rolled products before and after CCD is measured by pyrometers. The radiation flux from hot rolled products (especially sheet products) during propagation in the spherical region is detected by a pyrometer before and after the instance when the front or back edge of the rolled product crosses the pyrometer optical axis. The rolled product's surface before and after cooling has segments covered with scale. Overcooled segments can be generated on sheet products after cooling caused by insufficient water removal from the sheet surface. Reinforcement bars due to movement across the roller table, especially when leaving the run-out roller table to cooler, can escape from the pyrometer sighting area. Therefore, the detection and monitoring of temperature of rolled products passing under a pyrometer are required in the case of metal's sensor signal in the vertical plane of pyrometer optical axis.

In order to exclude the influence of scale, escape of reinforcement bars from the pyrometer sighting area, as well as other negative factors, the measurement results of the current temperature are statistically processed [8] to determine temperature distribution across the length of rolled products, initial and final temperatures of cooling.

MONITORING POSITION OF ROLLED PRODUCTS IN COOLING DEVICE

Metal sensors detect only the rolled product entry into the device and escape from it. The rolled product position in the device is determined by its conveyance

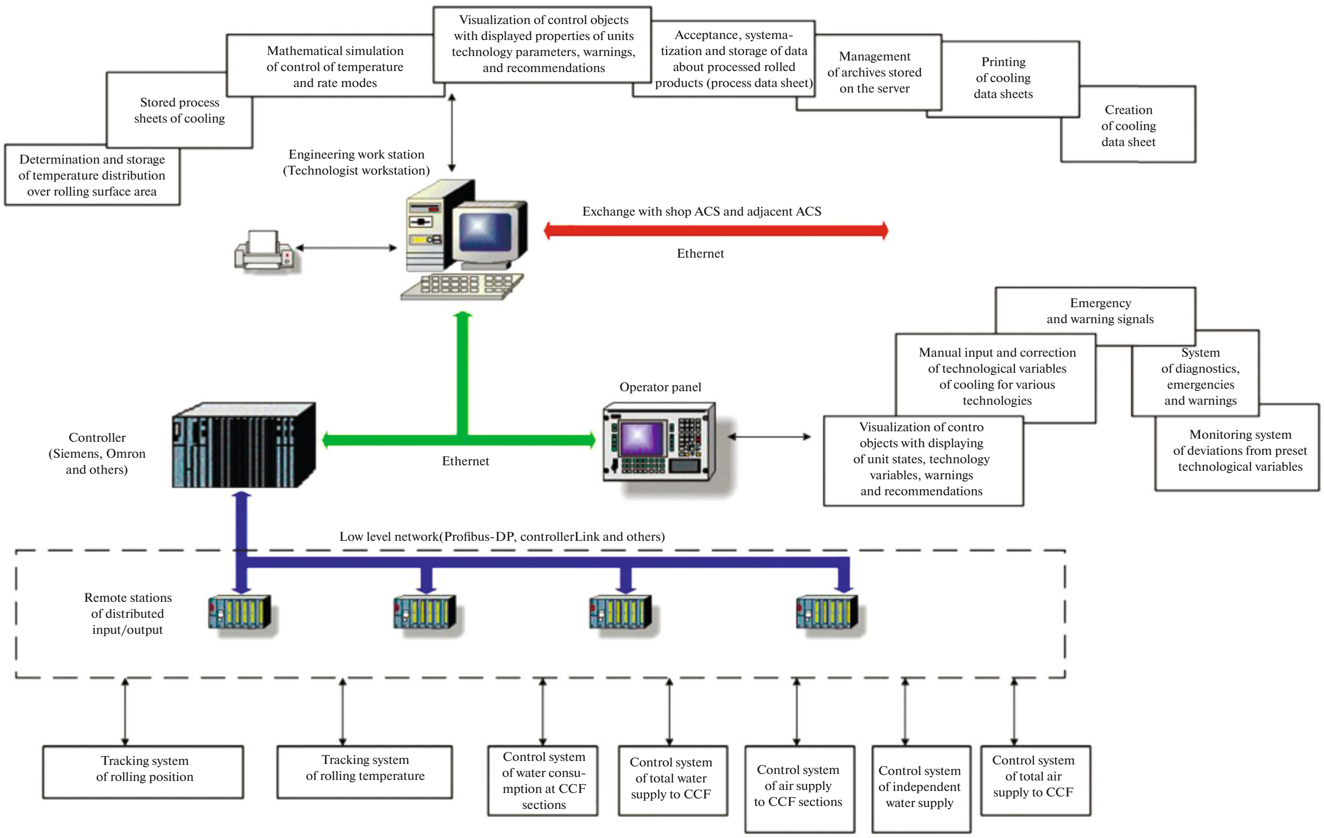

Fig. 2. APCS flowchart for cooling of rolled products.

speed over the roller table. Water should be fed onto the cooling sections only when rolled product is in a section. However, on the case of slipping (especially at low conveyance speed) of rolled product over the roller table, its position can be predicted incorrectly, which leads to excessive water flow rate.

In order to implement automated control of a controlled cooling device, the APCS has a two-level structure (Fig. 2). Low level executes measurements, monitoring and direct control according to presets from top level or CCD operator, intermediate processing of obtained data, and exchange with the top level.

The top level, including operator workstation and server (engineer station), provides optimization of cooling, data exchange with the basic low level, as well as network data exchange with shop ACS and adjacent ACS. The interaction flowchart between single components of CCD APCS is illustrated in Fig. 3. A software runs on the server responsible for the interaction between controller and database, mathematical model of the process, as well as receiving all required data from adjacent ACS.

Database contains the following data:

—initial data on the rolled products;

—operation variables of cooling device (instrumentation readings, emergency warnings, and others) and adjacent systems;

—temperature state of rolled products before and after cooling device, obtained by statistic processing of pyrometer readings;

—data predicted by the mathematical model;

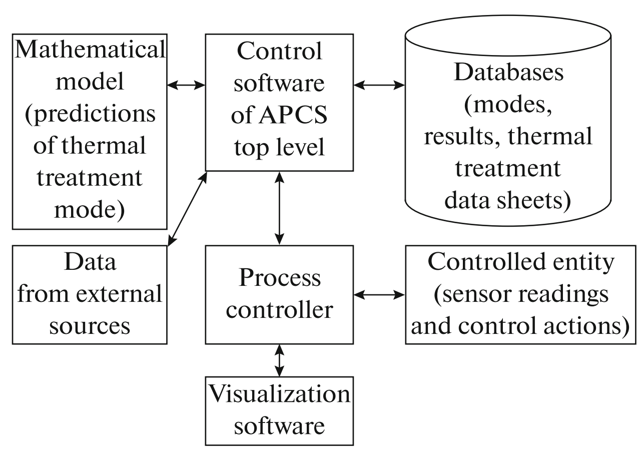

Fig. 3. Component flowchart of controlled cooling device for rolled products.

—regulatory data on thermal hardening (specifications, operation flowcharts, and others) determining CCD operation mode as a function of steel grade and profile of rolled products.

APCS efficiency in the mode of online control is provided by the mathematical model of accelerated cooling at the top level. The mathematical model is based on the solution to one-dimensional differential equation of heat conductance in boundary conditions of the 2nd and 3rd order with variable thermal physical properties. The boundary conditions are based on densities of thermal flow as a density function of water spray rate of the rolled surface in CCD, which is experimentally determined during commissioning. The practice of APCS commissioning demonstrated that the prediction accuracy regarding specific CCD is 5% before adapting to the mathematical model of specific CCD variables and is 2–3% after the adaptation.

Prior to treatment of a batch in CCD, the ACS of rolled products transfers to APCS information about the sizes of rolled products, initial and final temperatures of cooling, steel grade, and so on. Depending on technological requirements, CCD APCS selects the amount and number of involved sections, and determines water flow rate for the sections. Sections are selected and flow rates are determined using the algorithm developed by OAO VNIIMT, where predictions are based on the mathematical model of temperature variation across the cross section of rolled product during thermal treatment in CCD.

When rolled products leave CCD, actual final temperature of cooling is measured. If its deviation from preset value exceeds allowable limits, APCS introduces a correction regarding the main adjustment variable. During thermal hardening of the plate product, the main variable is the conveyance speed of rolled product across the sections, and the water flow rate is constant.

In CCD APCS of plate rolling mill 5000, the conveyance speed is predicted:

—before initiation of cooling during the prediction of cooling mode by preset variables of workpiece;

—after achievement of actual variables of workpiece after rolling, as well as the workpiece temperature measured by pyrometers before CCD (initial temperature of cooling) and after CCD (final temperature of cooling).

In the latter case, the conveyance speed is adjusted for the next workpiece. On continuous rolling mills, the conveyance speed is constant equaling to the rolling speed in the last operating stand. Therefore, during treatment of bar and shape products, the main adjusting variable is water flow rate in the last involved section of CCD. Variations of final rolling temperature on bar and shape mills in steady modes are generally within the preset ranges.

For instance, in APCS of thermal hardening devices of the mill 350 reinforcement bars, the adjustments are predicted and entered as new presets for flow rate regulators, as long as the five successive bars' unallowable deviation of actual temperature from the specified value was detected. Commercial operation practice confirmed sufficiently high reliability of the adopted control principles.

After termination of thermal hardening, on the basis of actual temperatures, flow rates, and conveyance speed for each workpiece (bar), the mathematical model predicts the actual density of thermal flow detected in each active section. Furthermore, the database generates rolled product specifications, including all required information about thermal treatment.

Operators can use the mathematical model of rolled product cooling running in the Advice mode. This mathematical model variant is intended for personnel training, preliminary evaluating predictions, and allows variable predictions of thermal treatment for accelerated cooling, cooling of semi-finished rolled products, quenching, and experimental cooling modes. Initial data for predictions are preset by operators, and predicted results are displayed on screen.

CONCLUSIONS

The developed APCS of thermal hardening are characterized by their accountability for specificity of accelerated cooling, operation modes of rolling mills (process trains), and engineering features of equipment. Peculiar attention during the development of software for APCS of thermal hardening is statistically focused on data array processes of current rolling temperature, thus facilitating reliable determination of surface temperature and plotting temperature distribution along the rolling length. The mathematical cooling model developed by OAO VNIIMT makes it possible to perform rapid and reliable control of thermal hardening and to obtain preset working properties of rolled products.

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