Heating Steel in Annular Furnaces

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Abstract—The heating of cylindrical billet in annular furnaces in shaft and pipe rolling is investigated. The laws of billet heating and rough-shaft heat treatment are established, as a function of the state of the furnace hearth, the increment of billet supply, and the adjustment of the gas lines to regulate the heating process and ensure uniform heating. Improved conditions for billet heating and heat treatment and the cooling of rolled shafts have been introduced at the 250 shaft-rolling mill at Dneprovsk Metallurgical Works.

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Annular furnaces are widely used at metallurgical plants for shaft rolling and pipe production. However, a literature review reveals a lack of research on the heating of steel in annular furnaces.

Such research may be divided into three stages [1]. Between 1930 and the 1960s, the heating of metal was industrially introduced. Operational experience with furnaces was reviewed in fundamental monographs by Grigor'ev [2, 3]. In the second stage (from 1950 to 1980), more profound study of the heating of cylindrical billet was undertaken, and calculation methods were developed [4–16]. Fundamental research on annular furnaces may be found in [4–9]. Comprehensive research was undertaken at the All-Union Institute of Thermal Research [10–16]. In the third stage (1980–2008), external and internal heat transfer was considered, and rational heating technologies were introduced. The relevant results were analyzed in [1, 17, 18].

The modern annular furnace is a highly automated system capable of continuous operation with pipe- and shaft-rolling mills of any productivity (Fig. 1). The basic benefits of such furnaces include high efficiency and low fuel consumption, as well as increased output thanks to small loss of metal.

The first comprehensive research in the period 1975–1990 (beginning with the startup of shaft production at Dneprovsk Metallurgical Works) focused on bringing equipment up to its design power and improving the thermal conditions of annular furnaces at the unique 250 mill, which is still the world’s only mill for the manufacture of rolled railroad axles [19–24]. The research covered the whole heat-treatment cycle in production: heating of billet (diameter 23, 27, and 29 cm) in annular furnace 1; cooling of the rolled axles before heat treatment; and heat treatment of hollow and nonhollow axles in annular furnace 2. Numerous industrial experiments have been undertaken to determine the temperature field in the billet and the working space of the furnace on heating and heat treatment. Mathematical models for multivariable calculations have been developed. This permits the determination of the basic laws of billet heating and shaft heat treatment and the establishment of the relation between the conditions of metal heating and heat consumption experiments. It is found that rational heat treatment in terms of metal quality is optimal in terms of fuel consumption. The introduction of such heating condi-

\textsuperscript{1} This article commemorates the 120th anniversary of Dneprovsk Metallurgical Works.

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Fig. 1. Annular furnace: (1) gas and air lines; (2) lateral burners of inner ring; (3) lateral burners of outer ring; (4) foundation; (5) heated billet; (6) hot-air line; (7) cold-air line; (8) exhaust channel; (9) recuperation system; (10) furnace lining; (11) mobile annular floor; (12) viewing window; (13) charging window; (14) flat-flame roof-mounted burner.
tions improves the annular-furnace performance of the 250 mill: the consumption of conventional fuel for the heating furnace (furnace 1) is reduced by 6.3–13.5 kg/t and scale formation is reduced by 2.0–4.8 kg/t, depending on the state of the hearth. For the heat-treatment furnace (furnace 2), the corresponding figures are 5 kg/t and 1 kg/t; the productivity of the rolling mill is increased by 2%. Inventor’s Certificates have been obtained for the new heating and heat-treatment technologies [25, 26].

This research provided the basis for expansion of research and further improvement of ladle-furnace operation in the period 1995–2008.

EXPERIMENTS ON THE HEATING OF CYLINDRICAL INGOTS AND BILLET IN ANNULAR FURNACES

The temperature fields of cylindrical blanks in the 250 mill at Dneprovsk Metallurgical Works are studied experimentally in view of existing data on the nonuniformity of heating, which grows more severe as the hearth is worn in prolonged furnace operation [27]. The new results permit more profound analysis of the thermal operation of furnaces.

The experiment is conducted by an improved version of the method in [17, 28, 29]. In particular, XA thermocouples with an electrode diameter of 0.5–0.8 mm are employed and installed in special holes not only at characteristic points of the cylinder but in a selected cross section over the perimeter, so as to expand the information obtained regarding the temperature field.

As an example, experimental measurements of the temperature fields for billet with a diameter of 27 cm are presented in Fig. 2. The results show that, up to the middle of the heating zone, the furnace temperature and the surface temperature of the metal both increase rapidly. The temperature difference over the billet cross section is a maximum (270–300°C) at the beginning of the first welding zone. In the second welding zone and the malleabilizing zone, the temperature is equalized, with a difference of 20–30°C at exit from the furnace. The temperature is greatest at the ends of the billet and in the sections of surface furthest from the hearth. The temperature of the billet axis and the adjacent sections of surface varies by 10–20°C over the whole heating period. The experiments confirm the considerable asymmetry of billet heating relative to a plane perpendicular to the hearth.

RESULTS

The basic mathematical model of the heating of cylindrical billet in an annular furnace, taking account of the heat-flux variation over the billet perimeter, is presented in [1, 17, 24]. The results of model identification are shown in Fig. 3.

The model is modernized by introducing two types of heat carrier, each characterized by two pairs of characteristics: the temperature of the heating medium and the hearth temperature; and the radiant and convective heat-transfer coefficients. The model is supplemented by equations for determining thermoelasticity and the nonsteady thermal conductivity of round billet

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = D \begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix} - \alpha \begin{bmatrix}
\alpha \\
1 + \mu
\end{bmatrix} (T - T_0),
\]

(1)