Heating Steel in Annular Furnaces

O. V. Dubina\textsuperscript{a}, V. I. Timoshpol'skii\textsuperscript{b}, Yu. A. Samoilovich\textsuperscript{c}, and I. A. Trusova\textsuperscript{b}

\textsuperscript{a}OAK NAK Ukraina, Kiev, Ukraine
\textsuperscript{b}Belorussian National Technical University, Minsk, Belarus
\textsuperscript{c}Platan Production and Research Center, Yekaterinburg, Russia

Received September 28, 2009

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.

DOI: 10.3103/S09670912090900204

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 multivariant 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.

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.
Heating steel in annular furnaces 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 BILLETS 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
where $D$ is the elastic-constant tensor of the billet

$$
D = \frac{E(T)}{(1+\mu)(1-2\mu)} \begin{bmatrix}
1-\mu & \mu & 0 \\
\mu & 1-\mu & 0 \\
0 & 0 & 1-2\mu/2
\end{bmatrix}. \tag{2}
$$

Equation (1), which takes account of the nonsteady temperature field $T(x, y, \tau)$, is supplemented by the equilibrium equations

$$
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = K_x, \quad \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} = K_y,
\frac{\partial \sigma_z}{\partial z} = K_z, \tag{3}
$$

where $K$ is the bulk-force vector.

The mathematical model is used in attempts to further improve thermal furnace operation in the 250 mill at Dneprovsk Metallurgical Works and to develop conditions of billet heating in the annular furnace of a pipe-rolling system at Belorussian Metallurgical Plant that has produced seamless hot-rolled pipe at a rate of 250000 t/yr since 2007.

Note that, in selecting forced asymmetric heating of large billet (diameter 230 mm or more), so as to increase furnace productivity and ensure satisfactory heating, two problems must be solved:

1. determination of the permissible heating rates and hence the temperature difference over the billet cross section—or, essentially, calculation of the thermal stress in the billet;

2. analysis of the possibility of reducing the temperature difference (and consequently the thermal stress) by adjusting the billet position.

**Determination of the Permissible Heating Rate**

As an example, the heating of cylindrical carbon-steel billet (diameter 0.27 m) is shown in Fig. 4, where the variation in temperature of the heating gas ($T_{U}$) and hearth ($T_{L}$) is determined from the formulas

$$
T_U = 1160 + 360\tanh\left(\frac{\tau}{2400} - 1.2\right); \\
T_L = 1250 + 290\tanh\left(\frac{\tau}{2400} - 1.2\right).
$$

The heat-transfer coefficients for the upper and lower surfaces of the billet are assumed to be $3 \times 10^8$ and $1 \times 10^8$ W/(m$^2$ K$^2$), respectively. This corresponds to their position at the furnace hearth with a gap equal to ~25% of the diameter.

The calculation results show that the thermal center of the billet is shifted considerably downward from the geometric center of the cross section. The tensile stress is recorded at the geometric center and gradually increases to a maximum during heating, with subsequent decline. Analysis of the distribution along the vertical cross section of the primary stress-tensor components ($\sigma_x$, $\sigma_y$) shows that the center of the $\sigma_y$ distribution is at the geometric center, whereas the center of the isotherms is shifted significantly downward from the geometric center.

Note that the rise in metal temperature is relatively slow, and correspondingly the thermal stress in the billet is low. This indicates significant scope for increasing annular-furnace productivity. To tap that potential, the growth rate of the heating-gas temperature ($T_{U}$) in the preheating zone may be increased; the thermal stress sets a limit on sharp rise in $T_{U}$. As an example, consider the heating of a 0.27-m bearing-gas billet; such steel is more prone than carbon steel to fracture (Fig. 5). Analysis indicates that 25–30% increase in $T_{U}$ in the preheating zone reduces the total duration of the process. The longitudinal tensile stress $\sigma_1$ at the billet axis is almost twice $\sigma_3$: $\sigma_1 = 200–210$ N/mm$^2$ (while the strength of the steel is $650–700$ N/mm$^2$). This indicates that forced preheating poses no risk of fracture and significantly reduces the total heating time.

STEEL IN TRANSLATION  Vol. 39  No. 9  2009
HEATING STEEL IN ANNULAR FURNACES

823

The proposed model and formulas are used to develop recommendations for the heating of (140–160)-mm billet in the furnace of the pipe-rolling mill at Belorussian Metallurgical Plant. Appropriate temperature conditions are calculated for carbon, alloy, and bearing steels with different billet positions on the hearth.

The temperature variation of the two types of heat carriers is expressed as follows, on the basis of production data and experimental and theoretical results from [17, 29]

\[
T_U(\tau) = 1250 + 290 \tanh(\tau/1000 - 1.2);
\]

\[
T_L(\tau) = 1190 + 330 \tanh(\tau/1000 - 1.2).
\]

As an example, the results for the heating of 150-mm 40XH steel billet in the furnace of the pipe-rolling mill at Belorussian Metallurgical Plant. Appropriate temperature conditions are calculated for carbon, alloy, and bearing steels with different billet positions on the hearth.

The temperature variation of the two types of heat carriers is expressed as follows, on the basis of production data and experimental and theoretical results from [17, 29]

\[
T_U(\tau) = 1250 + 290 \tanh(\tau/1000 - 1.2);
\]

\[
T_L(\tau) = 1190 + 330 \tanh(\tau/1000 - 1.2).
\]

As an example, the results for the heating of 150-mm 40XH steel billet are shown in Fig. 6. Analogous calculations are conducted for practically the whole range of pipe produced on the mill at Belorussian Metallurgical Plant.

The results obtained here for billet heating in annular furnaces during pipe and shaft rolling provide the basis for new heating designs, which are covered by Belorussian patents [30–33].

Reducing the Temperature Difference by Adjusting the Billet Position

In research on the thermal operation of annular furnaces and on means of ensuring satisfactory metal heating, insufficient attention has been paid to the positioning of the metal in the annular furnace, although the temperature field over the cross section is very nonuni-
form in heating large-diameter billet. In particular, the repositioning of billet in roller furnaces was considered in [4]; the dynamics of the temperature field in billet on repositioning was simulated in [10]. In our view, billet repositioning was most thoroughly considered in [17].

We now consider the temperature state of 0.27-m billet in the annular furnace of the 250 mill at Dneprovsk Metallurgical Works on the basis of a mathematical model [34]. To this end, the axial billet is rotated by 90° and 180° at the end of the welding zone (taking account of the technological and design features of the annular furnace). The temperature variation at characteristic points of the billet cross section and the isotherms are shown in Fig. 7 with and without billet adjustment. Thus, analysis shows that, without repositioning, the thermal center is shifted to the lower surface of the billet, where the temperature is 1184°C, whereas the temperature at the upper surface is 1204°C. Repositioning moves the thermal center closer to the geometric center; this is especially apparent for 180° rotation.

Heating of axial billet with 180° rotation has successfully undergone industrial trials in the annular furnace of the 250 shaft-rolling furnace at Dneprovsk Metallurgical Works. Thanks to the reduction in total heating time, the total fuel consumption is reduced by 60–90 m³/h (depending on the furnace productivity).

The introduction of the proposed technology increases the productivity of annular furnaces, reduces...
the fuel consumption by 0.5 kg/t, reduces scale forma-
tion by 0.3 kg/t, and improves product quality.

CONCLUSIONS

Between 1980 and 2008, Belorussian and Ukrainian specialists undertook fundamental research on the heating of cylindrical billet in the annular furnaces of shaft and pipe-rolling mills and developed the fundamental scientific principles regarding annular furnaces.

On the basis of numerous industrial experiments and mathematical simulation of annular-furnace operation in the 250 shaft-rolling mill at Dneprovsk Metallurgical Works over the period from 1980 to 2000.

To supplement the work of Ukrainian specialists (including N.Yu. Taits, M.K. Kleiner, and M.Ya. Pekar-
skii), we have gained new information on the repositioning of cylinder billet in order to regulate the heating process and ensure maximum temperature symmetry of the billet at exit from the furnace.

The development of new heating conditions for 0.23-, 0.27-, and 0.29-m billet used in the production of locomotive and railroad-car axles and heat-treatment conditions for hollow and nonhollow shafts, as well as cooling conditions for rolled axles prior to heat treat-
ment, significantly improved the performance of the 250 shaft-rolling mill at Dneprovsk Metallurgical Works over the period from 1980 to 2000.

On the basis of the research results and existing principles of annular-furnace operation, recommendations have been developed regarding the heating of cylindrical billet in the annular furnace of the pipe-roll-
ning mill at Belorussian Metallurgical Plant in the period prior to its official startup.

REFERENCES

1. Timoshpol’skii, V.I. and Samoilovich, Yu.A., Teoreticheskie osnovy teplovoi obrabotki stali v truboprokatnom proiz-
2. Grigor’ev, V.N., Kol’tsevyye pechey dlya nagnyva metalla (Annular Furnaces for Metal Heating), Moscow: Metall-

gizdat, 1958.
3. Grigor’ev, V.N., Mekhanizirovannye i avtomatizirovan-
4. Taits, N.Yu., Tekhnologia nagryva stali (Steel Heating Technology), Moscow: Metallurgizdat, 1962, 2nd ed.
7. Taits, N.Yu., Grushevaya, T.F., and Samylin, A.K., Fur-

nance Conditions and Heating of Ingots Prior to Piercing, Stal, 1954, no. 4, pp. 335–343.
13. Kleiner, M.K. and Uдовченко, V.P., Numerical Inves-
tigation of the Heating of Round Ingots in Annular Fur-

15. Sitkovskii, I.S., Emmanuel, G.A., Tur, V.G., et al., Improved Heating of Ingots in Annular Furnaces, Metal-

lurg, 1976, no. 1, pp. 32–33.

18. Lisienko, V.G., Volkov, V.V., and Goncharov, A.L., Matematicheske modelirovanie v pechakh i agregatakh (Mathematical Modeling in Furnaces and Related Sys-


OJSC Scientific-Research Institute of Metallurgical Heat Engineering (VNIIMT) established in 1930 as Ural Division of All-Union Heat Engineering Institute is widely known in Russia and the CIS. The Institute focuses on development of high-technology heat engineering units, energy efficient and ecologically friendly technologies in ferrous and non-ferrous metallurgy, machine-building and other fuel-consuming branches of industry.

Highly-qualified academic researchers, unique experimental and production facilities and own research and design centre enable efficient scientific-and-research, design-and-experimental, engineering and project works, delivery of equipment, designer's supervision and commissioning works including execution of turnkey contracts in the following areas:

**Sintering:**
- development of techniques and modes of metal raw material heat treatment;
- design of energy-efficient agglomeration hearths and agglomeration gas heat recovery circuits allowing to reduce energy consumption and dust and gas emissions.

**Pellet production:**
- optimal traveling grate pelleting furnaces for heat treatment of iron-ore pellets from various concentrates (hematite, magnetite, etc.) with optimal automatic process control system.

**Preparation of metallic and nonmetallic raw materials:**
- technique of iron-ore raw material dephosphorization by roasting and leaching;
- installations for drying high-moisture dispersive materials of various designs;
- efficient techniques of magnetizing roasting and subsequent dressing;
- technique of rare-earth element extraction (for example, germanium from germanium iron ores).

**Blast-furnace ironmaking:**
- explosion-proof near-furnace systems of blast furnace slag granulation giving a high-quality product for cement production;
- optimal control system for hot blast stoves;
- an innovative bench for drying hot metal and steel-smelting ladles;
- copper coolers and tuyeres of blast furnaces.

**DRI (direct reduction of iron)**
- improvement of the reduction technique in shaft furnaces for radical improvement of technical and economic indicators of their operation (productivity is increased twice);
- technique of raw material reduction in rotary furnaces using coal as the reductant.

**Lime production:** development of the technique and increase of lime production process efficiency:
- in shaft furnaces;
- in double-shaft furnaces;
- in rotary furnaces;
- in “stacked-tower preheater - rotary furnace” installations;
- in “shaft calciner - rotary furnace” installations (VNIIMT innovative technology).

**Granulation of metal melts:**
- development of technologies and designs of explosion-proof plants for near-furnace granulation of metallurgical slag, molten metal, etc., including heat recovery;
Reheating furnaces:
- development of new and update of the existing designs of furnaces for stock heating;
- high-performance systems of reheating furnace firing with recovery and regeneration firing systems based on the innovative burner units designed by VNIIMT;
- switching the furnace firing systems to cheaper fuel types;
- development and implementation of optimal furnace operating parameters.

Heat-treatment furnaces development of techniques and equipment for heat treatment of roll stock and metal products including those with protective atmospheres:
- thermochemical treatment conditions ensuring retention or directional change in chemical composition of metal surface;
- gas dampers for heat-treatment furnaces;
- spray quenching units and other elements of convective cooling systems;

Furnaces with protective atmosphere and gas treatment units:
- development of the furnace structure, design, manufacture, delivery and commissioning works;
- development of a technology for treatment of articles and devices for protective gas generation;
- calculation, development and manufacture of endogas and exogas atmosphere generators for metal product thermochemical treatment units;
- gas analysis systems for monitoring and control of physico-chemical properties of protective process atmospheres.

Reheating, heat-treatment and drying furnaces with convection heat transfer:
- development, design and manufacture using industrial heat-resistant (up to 900 °C) furnace fans designed by VNIIMT.

Rolled products:
- techniques and units for controlled high-speed air-to-water cooling (quenching) of rolled ferrous and non-ferrous metal products including thick plate on mill 5000;
- replacement of oil quenching technology with VNIIMT's eco-friendly air-to-water technique;
- innovative technique of oily mill scale processing;
- line of wire rod accelerated air cooling with process improvement.

Manufacturing manufacture and delivery of:
- high-performance burner units;
- heat-resistant (furnace) fans (up to 900 °C);
- copper coolers for blast furnaces and nonferrous furnaces based on VNIIMT technology;
- Pitot tubes for measuring flow rates and pressures.

OJSC VNIIMT developments are widely used in metallurgical enterprises of Russia, Ukraine, Kazakhstan, China, India and others. For detailed information on institute developments, please visit OJSC VNIIMT site at www.vniimt.ru

Contact details:
Lik Zajnullin
General Director
OJSC VNIIMT
Tel: +7 (343) 374-03-80, fax: +7 (343) 374-29-23
16 Studencheskaya St., Yekaterinburg, Russia, 620137,
e-mail: aup@vniimt.ru,
website: www.vniimt.ru