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MONITORING BLAST FURNACE LINING CONDITION DURING FIVE YEARS OF OPERATION

Yu. S. Semenov,[1,2] E. I. Shumel'chik,[1,2] V. V. Gorupakha,[1,2] A. V. Nasledov,[1] A. M. Kuznetsov,[3] and A. V. Zubenko[3]

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Changes in lining temperature for the shoulders, bosh, and shaft, their mean-square deviation with respect to furnace surroundings, and also overall thermal loads of the cooling system for blast furnace No. 3 at the Enakievo Metallurgical Plant are analyzed for five years of operation: from December 2011 to September 2016. Limiting values of temperature are established that point to partial or complete shaft lining wear. Features are revealed for the effect of blast-furnace smelting production conditions on the change in blast-furnace lining temperature. The furnace well condition is evaluated.

Keywords: *blast furnace, lining, thermocouples, coneless charging unit (CCU), coke quality, charge pellet content, cooling system thermal load, furnace well.*

The efficiency of contemporary blast furnace (BF) operation is determined by substantiated use of information from contemporary melting process control facilities. The Enakievo Metallurgical Plant (EMZ) BF-3 with respect to structural solutions and level of equipment with automatic facilities corresponds to the world standard, and it was put into operation after reconstruction in October 2011 [1, 2], equipped with a single-channel coneless charging unit (CCU) from the firm Paul Wurth, and it is also equipped with a set of contemporary monitoring facilities, including shaft lining thermocouples over the furnace circumference and height [3] installed at a depth of 100 mm with a planned lining thickness of 300 mm. Thermocouples were installed at fixed BF-3 shaft levels, and also in the bosh, shoulders, and zone beneath the tuyeres. Over the furnace circumference thermocouples were installed as follows: eight thermocouples each at the shoulder level, bosh and three lower shaft levels, six thermocouples at each of the next two higher levels, and four thermocouples at the upper level [3]. The lining over the furnace shaft height was made of refractory materials of two types:

1) for zones from the bottom of the shoulders to the middle of the shaft, the refractory material contained silicon carbide (in order to provide resistance on contact with cast iron and slag), and its good thermal conductivity makes it possible to reduce the temperature of the lining hot surface followed by formation of a protective skull layer. The refractory has high strength under working conditions;

2) in the central and upper parts of the shaft, the refractory material with a high alumina content based on chamotte. The use of this material makes it possible to achieve good resistance to chemical action and abrasive wear in a reducing atmosphere.

During the five-year period of BF-3 operation analyzed, repair was carried out twice with shotcreting of the shaft: in June 2014 and September 2016. Analysis of the dynamics of change in lining temperature was performed for two zones over the furnace height: a lower zone, i.e., for the average lining temperature for the bottom of the shaft, bosh, and shoulders,

[1] Nekrasov Institute of Ferrous Metallurgy, National Academy of Sciences of Ukraine, Dnepr, Ukraine; e-mail: yuriy.semenov@isi.gov.ua.
[2] DChM Scientific-Technical Enterprise, Dnepr, Ukraine.
[3] Enakievo Metallurgical Plant, Enakievo, Ukraine; e-mail: aleksandr.kuznetsov@metinvestholding.com.

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and upper zones for the average temperature of the lining of the shaft middle and top (Fig. 1). The change in temperature is shown in Fig. 1*a* during the first shaft campaign (up to June 2014), and in Fig. 1*b* during the second shaft campaign (up to September 2016). Analysis of the dynamics of change in mean-monthly lining temperature during the two furnace operating campaigns (see Fig. 1) made it possible to establish limiting values for temperature that point to partial or complete wear of the shaft lining.

Lining temperature of the BF-3 middle and top of the shaft. From the instant of starting blowing BF-3 in October 2011, the average lining temperature of the middle and top of the shaft was 175–200°C, and it was maintained at this level for eight months up to June 2012. Then, the average temperature started to increase gradually at these levels, which was connected with deterioration of shaft material quality due to transfer to highly basic locally produced sinter, having low quality, abstention from "premium" class coke, absence in the composition of the blast furnace charge of washed materials, and the search for solutions for the choice of CCU charging regimes aimed at stabilizing the distribution of the gas flow under complicated furnace operating conditions [4]. An increase in average lining temperature for the middle and top of the shaft in June 2012 was due to operating BF-3 under conditions of the formation of an extremely developed peripheral gas flow. An increase in temperature to the level of 400°C occurred during the following seven months, i.e., up to February 2013. For this furnace operating period, the increase in temperature pointed twice to a significant reduction in lining thickness at the levels of the middle and top of the shaft.

From February 2013, in BF-3 there was fundamental reconsideration of the approach to the choice of rational distribution for CCU charging, and a new arrangement [5, 6] was installed, after which within the composition of the blast furnace charge manganese-containing materials were added exhibiting flushing properties. In combination, this made it possible to restore the coke charge and redistribute the gas flow. Starting from this operating period, the average lining temperature of the middle and top of the shaft was maintained with insignificant deviation at the level of 400°C up to January–February 2014, after which it increased to 450°C and was maintained at this level up to shotcreting the shaft in June 2014. Visual examination of the shaft before shotcreting in this period showed a lack of lining, which made it possible to conclude that an average temperature of the middle and top of the shaft at the level of 450°C points to complete lining wear.

The start of the second shaft campaign was accompanied by complex economic and political situations in the region: twice BF3 was stopped for a prolonged period (87 and 43 days) without tapping iron [7]. During nine months from the instant of the start of blowing (from July 2014 to March 2015), the average lining temperature for the middle and top of the shaft was 200–250°C. Values of 350°C were reached in December 2015, and then during operation on a "gasless" charge with blast moistening the temperature at this level was maintained before the introduction of natural gas into the blast composition with which the lining temperature again decreased to 300°C.

The start of assimilation of technology for blowing coal-dust fuel (CDF) led to a sharp increase in lining temperature for the middle and top of the shaft. After exceeding a value of 450°C in July 2016 (being a sign of lining wear as was established from the results of analyzing the first shaft lining campaign), thermocouples recorded the temperature of the peripheral gas stream that before the next shaft shotcreting reached 550°C.

Assimilation of CDF blowing technology in BF-3 with consumption of more than 120 kg/ton of iron (18–20 tons/h) coincided with the end of a two-year shaft lining campaign, which concerning the condition in December 2016 did not make it possible to draw clear conclusions on BF-3 condition with respect to the effect of CDF on refractory lining wear rate. In this case, as already noted, the more thermally stressed peripheral zone over the height of BF-3 with CFD blowing was the middle of the shaft. First, this is connected with the use in the blast furnace workshop of atypically high air tuyeres, and also operation with a high pressure under the bell. This solution is entirely possible with intense lining wear with high CDF blowing consumption, since expenditure for repair of the upper part of the shaft lining is significantly less than replacement of the lining of the shoulders, bosh, and bottom of the shaft.

Lining temperature of the shaft bottom, bosh, and shoulders of BF-3, consisting of silicon carbide materials. In the lower zone of the furnace with rational introduction of smelting there is formation of a protective skull, and therefore analysis of the dynamics of change in lining temperature at these levels was performed taking account of these governing factors.

From the start of the BF-3 campaign, the lining temperature of the lower zone of the furnace varied in the range 200–250°C, and from June 2012, as in the case of the upper shaft levels, with worsening of smelting production conditions the average temperature of the lining of the bottom of the shaft, bosh, and shoulders started to increase, and in October 2012

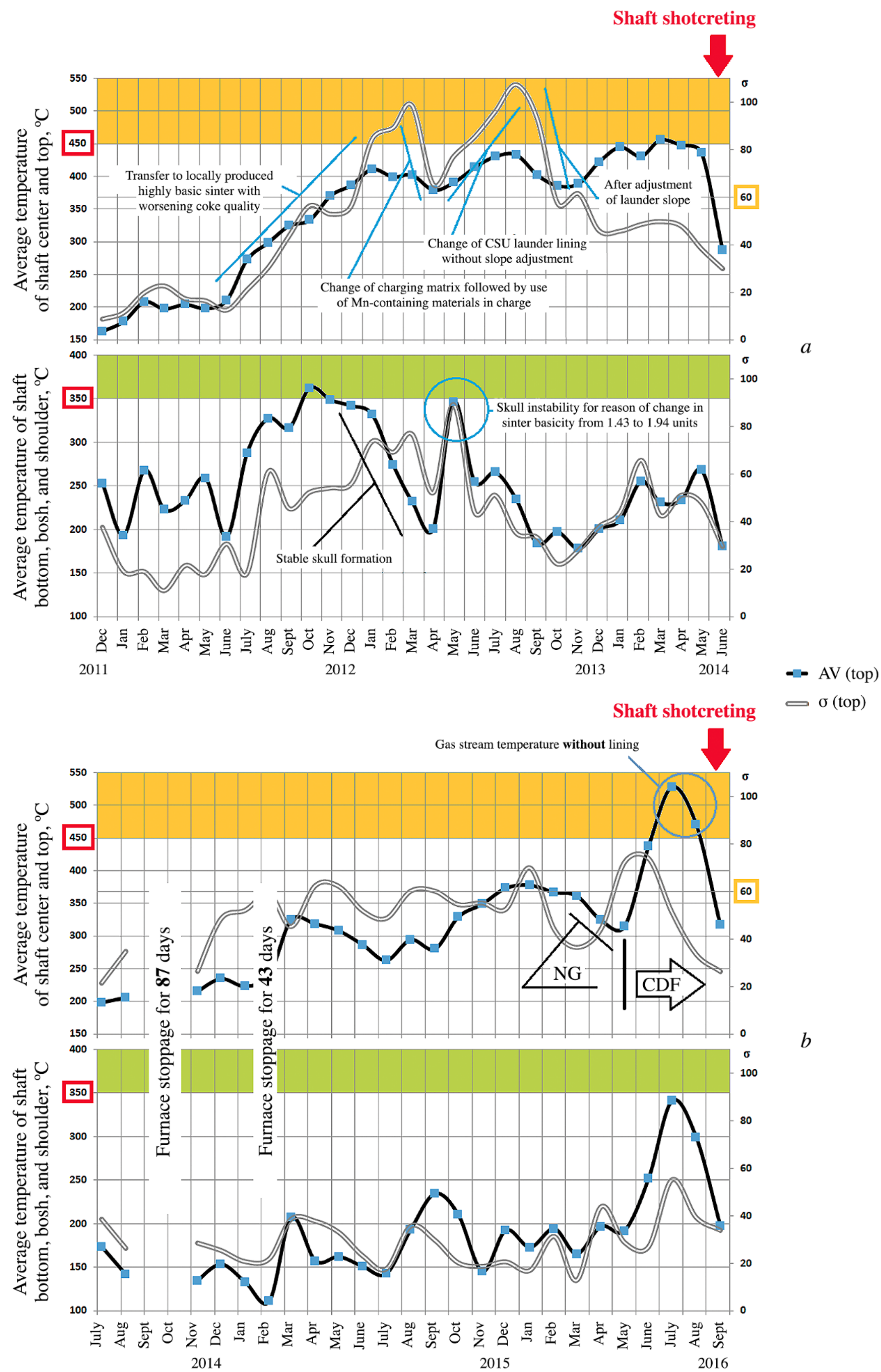

Fig. 1. Dynamics of BF-3 lining temperature variation during first (*a*) and second (*b*) shaft campaigns.

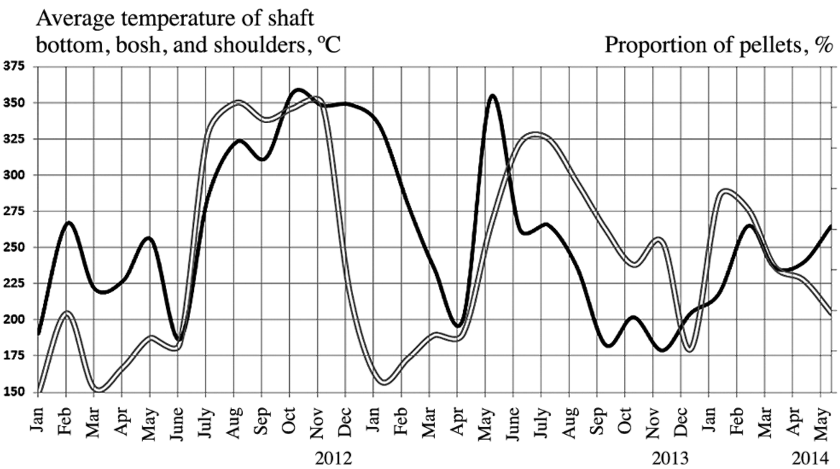

Fig. 2. Change in average lining temperature of shaft bottom, bosh, and shoulders, and also content of pellets mixed with sinter during BF-3 first campaign.

it exceeded 350°C. This feature was due to a sharp increase in the content of pellets in the iron ore part of the charge (Fig. 2) in the absence of regimes of a rational ratio of sinter and pellets during charging with the formation of their required ratio in the furnace peripheral zone. This led to the formation in the lower zone of the furnace of an unstable skull and finally its almost complete slumping.

Then, from December 2012 with a reduction in the proportion of pellets the lining temperature of the lower zones started to decrease considerably and reached 200°C, as also at the start of the furnace campaign. In May 2013, with an increase in proportion of pellets a sharp increase in temperature was noted again to 350°C, and with a reduction in the amount of pellets in the charge the average temperature of the lower furnace zone again decreased to 175–200°C, and before shotcreting the shaft it did not exceed 275°C. This was a consequence of using rational regimes for the formation of the charge material portions.

During the second shaft lining campaign for BF-3, the average lining temperature at the bottom of the shaft, bosh, and shoulders was characterized by a relative stable change, and the temperature of the lining of the lower zone of the furnace did not exceed 250°C. This was due to the use in BF-3 of rational regimes for forming the portions of a charge that provide formation of a relatively stable skull with a variable proportion of pellets in the iron ore part of the charge. This trend or the change in lining temperature for the lower zone of the furnace was observed up to the end of June – start of July 2016, when the blast furnace smelting started to use a greater amount of CDF. In July 2016, the average lining temperature of the bottom of the shaft, bosh, and shoulders was 350°C, and in August it decreased to 300°C. After that, there was blowing of BF-3 for major overhaul.

Therefore, as a result of analyzing the change in temperature of the lining of the shaft, bosh and shoulders of BF-3 for five years of furnace operation it has been established that the mean-monthly lining temperature for the middle and upper shaft of 400°C points to significant wear. Then, lining breakdown slows down and before reaching 450°C it is necessary to monitor the lining temperature constantly. On exceeding the value of a mean-monthly temperature of 450°C, as shown in the two campaigns, the lining of the middle and top of the shaft is almost entirely absent. With a mean-monthly temperature for the bottom of the shaft, bosh, and shoulders of 300°C in the lower zone of the furnace there is formation of an unstable skull that requires adjustment of the composition and regime for formulating charge portions. An increase in lining temperature of the lower zone with a value of 350°C points to the complete absence of a protective skull. A mean-monthly temperature of the lining of the lower zone above 350°C during five years of operation was hardly noted, and consequently exceeding this temperature level may point to lining breakdown.

Analysis of the dynamics of change in *overall thermal load of the cooling system* during five years of BF operation (Fig. 3) showed that on exceeding 24000 kW the shaft lining was entirely absent. At the same time, a lack of shaft lining may also be observed at lower levels of overall thermal loads.

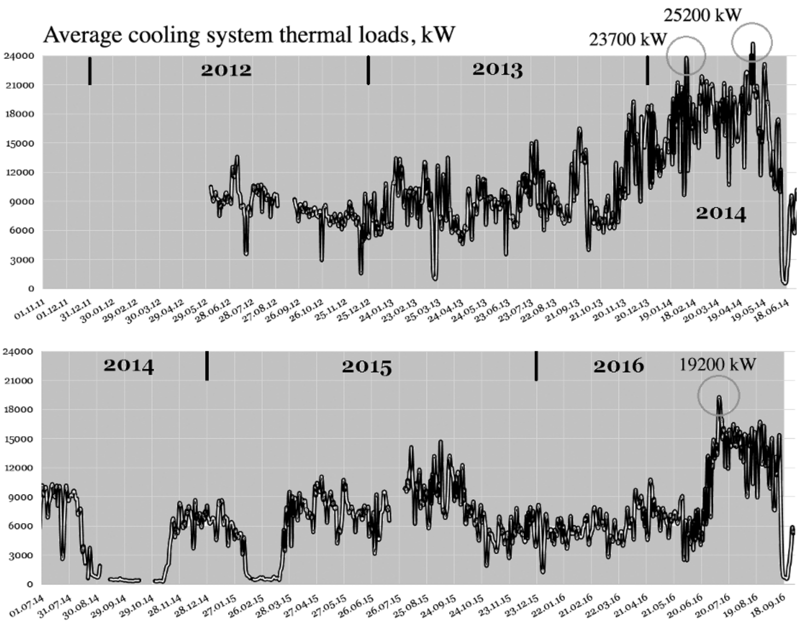

Fig. 3. Dynamics of change in BF-3 cooling system thermal loads during five years of furnace operation.

During the first BF3 shaft campaign, the tendency of an increase in overall thermal load on the cooling system followed by exceeding a value of 24000 kW was observed from the start of 2014. During the BF-3 shaft campaign, a sharp increase in overall thermal load index (by a factor 2.0–2.5) coincided with greater CDF consumption, and also with a longer time for furnace shaft lining operation. At the end of the second BF-3 shaft campaign, the increase in overall thermal load was insignificant, i.e., from 9000 to 19000 kW (on average). At the end of the first furnace shaft campaign, this index was significantly higher both with respect to absolute value (up to 25000 kW), and also with respect to the length of furnace operating period with high values of the index. A high value of overall thermal load of the cooling system in the first BF-3 shaft campaign was due to an extremely developed peripheral gas flow (that led to an increase in coke consumption, balancing thermal losses), and also higher (compared with use of CDF at the end of the second shaft campaign) position of the core of the material viscoplastic condition zone in the column of the shaft within the furnace working volume.

As a result of research for determining the *permissible range of change in shaft temperature over the height and the vicinity of BF-3*, it was assumed that as an index of furnace favorable operation it is possible to use the mean square deviation of lining temperature over the furnace circumference (σ). It has been established that values of σ exceeding 20% of the average shaft lining temperature point to disruption of furnace operation. For the levels of thermocouple installation in the lining of the middle and top of the BF shaft, the value of σ did not exceed 60°C, and the permissible limit for the shaft bottom, bosh, and shoulders is 40°C. The change in mean-monthly value of σ for the BF-3 lining of the middle and top of the shaft (*a*), bottom of the shaft, bosh and shoulders (*b*) for five years of furnace operation is given in Fig. 4.

Analysis of the change in this index during five years of furnace operation showed that the following production variations from normal furnace operation occurred with an increase in established values of σ:

1) assimilation of melting technology for highly basic sinter produced locally with simultaneous deterioration of coke quality (from the second half of 2012 to October 2013). In this BF operating period, there was partial slippage of the unstable skull formed. Production measures aimed at stabilizing the furnace operation were; optimization of the quantitative and qualitative composition of sinter [8], a fundamental change in the charging unit operation, checking of methods for charge material portion formulation, facilitating the formation of a stable skull, and use within the blast furnace charge composition of manganese-containing materials;

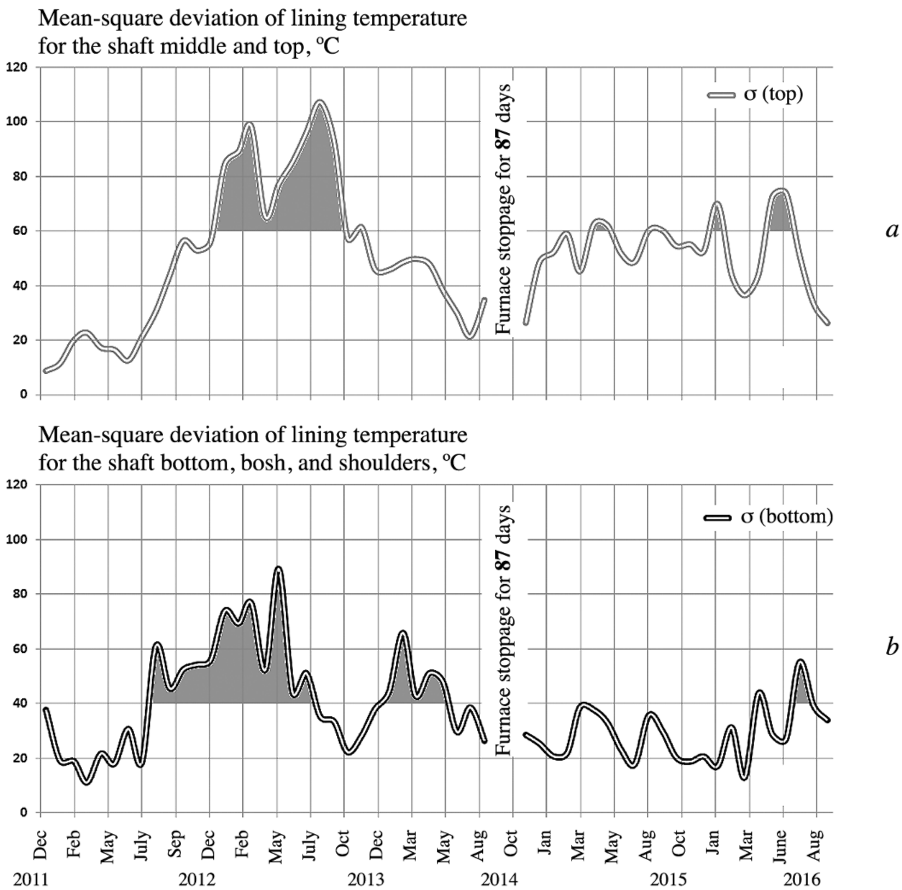

Fig. 4. Change in average monthly values of BF-3 lining for middle and top of shaft (*a*), shaft bottom, bosh, and shoulders (*b*) for five years of furnace operation.

2) an insignificant (up to 63°C) mean-quarterly deviation of the permissible lining temperature for the middle and top of the shaft (from the end of March to May 2015) was caused by the second start of blowing during operation after prolonged (43 days) stoppage;

3) BF operation on a "gasless" charge with moistening of the blast (at the start of 2016) was a reason for an increase in values of the mean-square deviation of the lining temperature for the middle and top of the shaft; and

4) an increase from May 2016 in the value of the mean-square deviation of lining temperature over the whole BF height was due to operation with CDF consumption with simultaneous shaft lining wear, whose campaign reached two years at this time.

In future, monitoring the change in the values of σ for a BF lining over the circumference will make it possible to assess the disruption of furnace operation and after finding reasons for their occurrence to take the adopt substantiated action by implementing the required production measures.

State of the BF-3 hearth and bottom lining. The lining of the BF furnace well was made of refractory materials from Graftech International (USA) and NDK (Japan). The working surface of the furnace well was protected by a ceramic cup from Saint-Gobin International (France).

Dynamics of the change in lining temperature in areas of thermocouple installation and the thermal load on the cooling system for the whole furnace campaign showed adequate resistance of the ceramic cup and lining of the furnace well as a whole. After five years of BF-3 operation, the calculated wear of the ceramic cup is only observed in the zone of iron taphole sectors, at the level of the coolers of the lower hearth and the upper hearth bottom. Maximum wear of the ceramic layer was revealed of 25% of the planned value (100 mm with a planned value of 400 mm). There was no lining wear of the ceramic cup opposite the iron tapholes.

Conclusion. Dynamics of the change in lining temperature have been analyzed for the shoulders, bosh, and shaft, and also the overall thermal load of the BF-3 cooling system for five years of operation, i.e., from December 2011 to September 2016. As a result of analyzing the change in temperature for the lining of the shaft, bosh, and shoulders in BF-3 for this furnace operating period, it has been established that the mean-monthly lining temperature for the middle and top of the shaft is 400°C, and it is an index of its significant wear, then lining breakdown slows down and after reaching a temperature of 450°C it is necessary to monitor this index. On exceeding the value of mean-monthly temperature of 450°C, as two campaigns have shown, the lining of the middle and top of the shaft is entirely absent.

With a mean-monthly lining temperature of the bottom of the shaft, bosh, and shoulders of 300°C, in the lower zone of the furnace there is formation of an unstable skull that necessitates adoption of solutions for adjustment of the composition of the regime for formulating charge portions. With a lining temperature for the lower zone >350°C, a protective skull is entirely absent. A mean-monthly temperature of the lower zone of the furnace >350°C for the five years of furnace operation was hardly noted, and, consequently, exceeding this temperature level may point to lining breakdown.

It is assumed that as an index of stable furnace operation it is possible to use to the mean-monthly deviation of lining temperature over the furnace circumference. It has been established that values of mean-quarterly temperature deviation exceeding 20% from the average shaft lining temperatures point to disruption of furnace operation. For the levels of thermocouple installation in the lining of the middle and top of the BF shaft, the value of mean-quarterly temperature deviation over the furnace circumference should not exceed 60°C, and the permissible limit of the mean-quarterly deviation of the temperature of the bottom of the shaft, bosh, and shoulders should not exceed 40°C.

Analysis of the condition of the hearth and bottom for five years of BF operation showed the efficiency of the planned solution for use of a ceramic cup, whose wear was only 25% in zones of cast iron taphole sectors.

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