Arch. Metall. Mater., Vol. 61 (2016), No 1, p. 279–282

DOI: 10.1515/amm-2016-0053

J. VLČEK*, D. JANČAR*,#, J. BURDA*, M. KLÁROVÁ*, M. VELIČKA*, P. MACHOVČÁK**

MEASUREMENT THE THERMAL PROFILE OF STEELMAKING LADLE WITH SUBSEQUENT EVALUATION THE REASONS OF LINING DAMAGE

Based on the operational measurement, of which content was to determine ladle thermal profile, there were analysed causes of possible damage of lining in steel ladles by steel breakout through the ladle shell. There exists connection between thermal state of ladle lining during the operation and its lifetime. There were reached to the conclusion that the cause of failure in the lining of ladle is except for high temperature of bath, also wide interval of temperature change during the tap operation, in consequence with possible insufficient pre-heating of ladle, discontinuous operation of aggregate and damage of insulating lining layer, respectively deformation of ladles shell.

Keywords: ladle, refractory lining, temperature, enthalpy, ladle lifetime

1. Introduction

Owing to a frequent steel breakout through the ladle shell in steelmaking plants there was performed determination of thermal work of ladle with magnesia-carbon working layer. Goal of measurement was in assessing the temperature profile of ladle during its whole working cycle, determination the enthalpy course of ladle according to measured temperatures and calculation the temperature decrease of steel in ladle as a result of the lining thermal losses. Based on these data there could be evaluated composition of lining owing to technology, also could be determined possible steel breakout through the ladle shell and concluded consequent conclusions.

This measurement took place at the steel plant VÍTKOVICE HEAVY MACHINERY a.s. (further also VHM a.s.) that is the traditional producer of large engineering components with a strong position in selected segments of machinery production. These include especially shafts for hydroelectric power plants, rotor shafts for wind power plants, crankshafts, parts for the container of pressurisers, steam generators, heat exchangers and collectors for both conventional and nuclear power engineering. These parts have to be uniformly structured and perfectly balanced, and therefore defect-free. Heavy forging ingots weighing up to 200 tons are used for this production. The steel for this production was melted at electric arc furnace (EAF) followed by processing at ladle furnace (LF) and vacuum degassing (VD). The EAF capacity is approximately 80 tons so the bigger ingots are cumulated from two or three heats. The ladle capacity is 70 tons.

2. Operational experiment

For gaining foundations about ladle lining thermal field in working cycle there was performed extensive experiment in steel plant VHM.

Lining of ladle in plant is often damaged and subsequent situation when steel breakout through the ladle shell is not rare. The wall of ladle is undergoing damage, bottom of ladle works without difficulty.

Working layer of lining was build up as zonal. The wall of ladle (including slag line) was bricked with magnesia-carbon shaped bricks, as well as in the bottom, only thicker ones. Next layers of wall lining are dilation magnesia dusting powder, castable layer, fireclay layer, insulating layer from material Microfibre 1000 and steel shell.

During the bricking of ladle there were installed thermocouple sensors of K and B types approximately in a half of ladle height. To recording the measured data, there were used a data logger GRANT Squirrel, which were put into cooled thermo-insulating box fastened on outside surface of ladle shell.

This arrangement allowed continuous recording of lining temperature during all technological operations, which ladle go through, including ladle transport. Places for measuring temperatures were both on interface of individual materials and in working layer of lining. For measurement there were installed 11 thermocouples in total. During an operational experiment thermal field of lining was observed throughout the preheating of new lining, furthermore during five circulation cycles including lining reheating between cycles. Every circulation cycle consist from tapping, secondary refining processes in ladle furnace, vacuum station, casting, inspection and maintenance.

* VSB-TECHNICAL UNIVERSITY OF OSTRAVA, FACULTY OF METALLURGY AND MATERIALS ENGINEERING, 17. LISTOPADU, 708 33 OSTRAVA, CZECH REPUBLIC

** VÍTKOVICE HEAVY MACHINERY A.S., OSTRAVA - VÍTKOVICE, ČESKÁ REPUBLIKA

Correspondence address: dalibor.jancar@vsb.cz

Results from operational experiment were treated by the model for simulation the thermal processes inside of ladle, which can solves change of enthalpy of ladle lining and thermal losses through the lining on the base of measured courses of temperature in measuring places in lining and other technological data about monitored melting [1].

3. The evaluation of operational measurement

Temperature course of ladle lining was plotted into a several graphs. In Fig. 1, there are presented temperatures inside of lining during the drying process of ladle lining before the 1st tapping. Fig. 2 shows detailed view of the 1st melting.

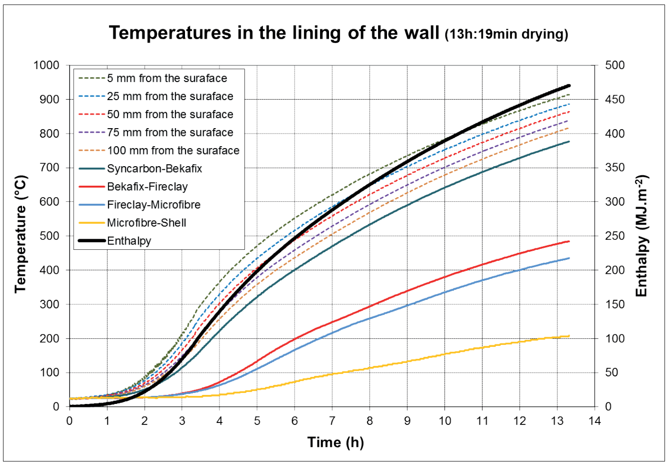

Fig. 1. Temperatures inside the ladle lining during the drying process

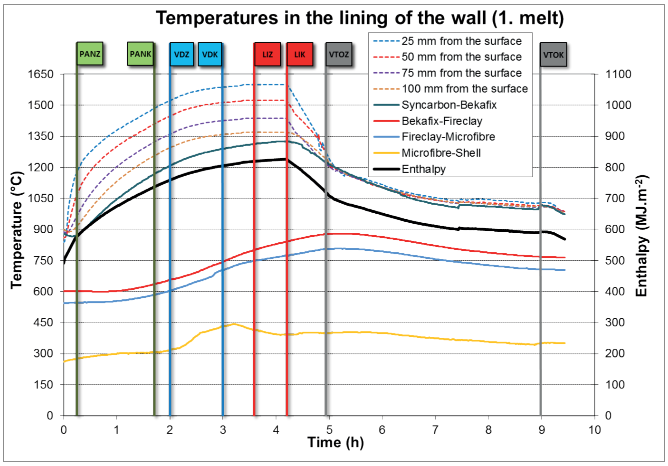

Fig. 2. Detailed view on 1st melt

Explanation of particular abbreviations from Fig. 2:

- PANZ (PANK) - start (end) of steel processing in ladle furnace
- VDZ (VDK) - start (end) of steel processing in cofferdam
- LIZ (LIK) - start (end) of casting
- VTOZ (VTOK) - start (end) of ladle high-temperature heating

Afterwards the measurement of surface temperatures of ladle took place by the thermovision camera FLIR ThermaCAM P25 with adjustable emissivity on value 0.95. The measurement of surface temperatures is insufficient for the purposes of calculation the thermal losses realized by furnaces wall and for calculation of steel cooling speed during the tap age. Measurement by thermovision camera was focused on evaluation the shells temperature in dependence on ladle working time.

Fig. 3 presents thermovision view to ladle immediately after its taking out of the vacuum station cofferdam.

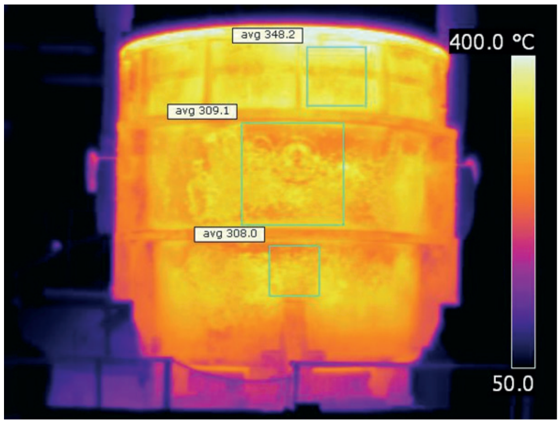

Fig. 3. Thermovision view of ladle

3.1. Evaluation the ladle thermal state

During own circulation at steel plant, ladle can be find in following operational stages: at high temperature heating, tapping, transport of filled ladle, secondary metallurgy in ladle furnace, vacuum degassing in cofferdam, casting, free cooling in the air (before tapping, after steel casting) and cooling under the lid. As the most suitable parameter for definition the ladle thermal state was chosen lining enthalpy. This quantity is time function and generally is given by equation:

$$I(\tau) = \int_V t(x,y,z,\tau) \cdot c_p(t) \cdot \rho_V \cdot \mathrm{d}V \qquad \text{(J)} \qquad (1)$$

where $I(\tau)$/(J) is lining enthalpy at given time τ, $t(x,y,z,\tau)$ is lining temperature at place x, y, z and time τ, $c_p(t)$/(J.kg^{-1}.K^{-1}) is specific thermal capacity in dependence on temperature t, V/(m^3) is ladle lining volume, ρv/(kg.m^{-3}) is bulk density of ladle lining. Since cp is a function of temperature, parameter $I(\tau)$ also characterizes change of accumulative properties of lining in dependence on its temperature [2 - 3]. For calculation the ladle lining enthalpy is primarily essential to know temperature changes in working layer of lining.

Heat losses through the lining are determined as an integral value, which is depended on time for whole ladle lining. Decrease of steel temperature caused by heat losses through lining at given time is determined by relation:

$$\Delta t_{lin} = \frac{Q_{lin}}{m_{st} \cdot c_{st}} \qquad (°C) \qquad (2)$$

where Q_{lin}/(J) are heat losses through lining in chosen time period, m_{st}/(kg) is weight of steel in ladle, c_{st}/(J.kg^{-1}.K^{-1}) is specific thermal capacity of steel [4 - 5]. Heat losses through the ladle lining were processed by method of regression analyse [6].

Information about speed of steel temperature change caused by thermal losses through the ladle lining were processed in individual sections by method of regression analyse as a linear dependence on ladle lining enthalpy at tapping. There was used the dependence:

$$v_{zt}^{n} = a_0 + a_1 \cdot I_0 \qquad (°C·nin^{-1}) \qquad (3)$$

where I_0 is ladle lining wall enthalpy at tapping (MJ.m^{-2}), a_0, a_1 are constants of model for calculation the steel temperature change in ladle, respectively for the model of heat losses through ladle lining for assigned partial section [n].

Total steel temperature change caused by heat losses through ladle lining can be calculated from relation:

$$\Delta t_{lin} = \sum_{1}^{n} (v_{zt}^{n} \cdot \Delta\tau^{n}) \qquad (°C) \qquad (4)$$

By the progressive summation in Equation 3, for the partial time section succession, it can be obtained dependence Δt_{lin} on time.

Heat losses through ladle lining are determined in individual partial sections. Time section between tapping and end of casting was in solving divided into 8 sub-sections:

1. section: steel tapping
2. section: time between end of steel tapping and 10th minute after tapping
3. section: time between 10th minute after tapping and start of processing in ladle furnace
4. section: processing in ladle furnace
5. section: ladle transport between ladle furnace and vacuum station
6. section: processing in vacuum
7. section: ladle transport between vacuum station and casting
8. section: ingot casting

Calculated coefficients for steel temperature change model in particular technological sections in dependence on ladle enthalpy before tapping are mentioned in TABLE 1.

TABLE 1
Coefficients for calculation the temperature changes of steel in ladle

Section	Coefficients for calculation the thermal losses through the ladle lining	
	a_0	a_1
1	31.09	$-4.89 \cdot 10^{-2}$
2	16.61	$-2.33 \cdot 10^{-2}$
3	14.62	$-1.93 \cdot 10^{-2}$
4	10.29	$-1.49 \cdot 10^{-2}$
5	2.43	$-2.50 \cdot 10^{-3}$
6	1.93	$-2.40 \cdot 10^{-3}$
7	1.09	$-1.40 \cdot 10^{-3}$
8	0.44	$-6.00 \cdot 10^{-4}$

4. Evaluation the ladle lining

Ladle lining thermal field and results from thermovision measurement were compared with operational situations and after that there were concluded possible sources of damage the ladle lining:

1. high temperature inside lining
2. wide interval of working layer temperature change caused either by high tapping temperature or by insufficient heating of ladle, or combination of factors
3. frequent total cooling of lining
4. insulating layer damage
5. shell deformation

4.1. High temperature inside lining

High tapping temperature (about 1700°C) along with high quality insulating layer cause the loss of mechanical stability at used refractory lining materials.

During operational measurement there was find out, those temperatures inside the working lining are between 1360 and 1650°C. Refractoriness under load of these materials is between 1400 and 1750°C, depending on quality.

Temperatures inside permanent lining (monolith) were measured between 900 and 1360°C. From the technical data sheets can be observed, that refractoriness of this specific material is 1600°C. Of course for consideration the thermal-mechanical resistance of one-sided strained layers of lining is more suitable, respectively essential the refractoriness under load test. This parameter for this material was unknown, but it can be assumed, that refractoriness under load will be lower about 180 – 300°C in maximum value than refractoriness.

Given these findings, it can be concluded, that under these conditions, very high temperature inside of permanent lining could be the reason of its damage, especially considering following facts:

- thickness of working layer will be reduced by wear, what leading to temperature increase inside the lining
- there exist ladles in steel plant, where some shaped materials are replaced with insulating materials with one third value of thermal conductivity against to current ones, what significantly raises the temperature inside lining

4.2. Big change of working layer temperature

Temperature gradient generated during heating or cooling causes tension in refractory material caused by thermal expansion. Initial thermal tension can disrupt its structure.

There can be discovered from the operational measurement that working magnesia-carbon lining is exposed to big temperature change, mainly at tapping and immediately after tapping, when the temperature on magnesia brick surface is about 1000°C and within 4 minutes after tapping, refractory bricks come into contact with hot melted steel with temperature just below 1700°C. Thanks to these sudden changes in temperature, the crack can occurs in lining and it can lead to the steel breakout through the ladle shell. Possible causes of crack initiation can be summarized into following points:

- temperature alternating in linings working layer
- long waiting of ladle before tapping without lid (lid is particularly substituted by bottom part of furnace), about 30 minutes, what causes leakage of heat which is accumulated in lining during the high temperature heating ⇒ big thermal shock for working layer of lining at tapping

4.3. Cool lining

Considering the economic situation in company, one option of saving the electricity consumption is its purchase at the time, when this energy has the lowest price. Thanks to this strategy the steel plant does not work for two days and in consequence the ladle lining totally cool down to the ambient temperature. This cooling down can occurs even 5 times in whole campaign of ladle, provided realization the slag line repair roughly in a half of campaign. Tension arising in material under this straining during cooling and repeated heating can be source of crack initiation resulting in damage of lining, respectively steel breakout through the ladle shell. The sources of crack initiation in this case are similar like in previous case. Again there is relatively rapid temperature change of magnesia-carbon brickwork, where consequently the value of its coefficient of thermal expansion leads to crack initiation.

4.4. nsulation damage

In the operation of ladle near the end of campaign, when there is a minimum thickness of working layer of lining, here can be thermal sufferableness of insulating material exceeded, thereby it can be destroyed. At this point it happens, that ladle lining loses its insulating ability and the speed of temperature increase will be too big and thus crack arise, what affect the steel breakout through the ladle shell. During an operational experiment, there was maximum temperature 844°C on warmer side of insulation layer of lining. Materials classification temperature is 1000°C, but at the long term strain this is only 950°C. With thickness reduction of working layer the temperature inside lining increases, so that temperature at warmer side of insulation layer will be also higher.

4.5. Shell deformation

The ladle shell can be deformed because of its high temperature, which is caused mainly by closing the ladle into the cofferdam for about 1 hour. During the subsequent "total" cooling down of lining at shutdown or repair of slag line, refractory bricks can "shift", what caused formation of interstice, which no more wholly disappear at repeating heating of ladle. This interstice can be the source of consequent steel breakout through the ladle shell.

Temperature at ladle shell inner side was measured during first 5 circulation cycles by thermocouple, outer side was measured by pyrometer. There was measured maximum temperature of shell inner side 485.5°C and outer side 351°C (no measured during vacuum process, when the shell temperature will be much higher, because of ladle closing in cofferdam) during the monitored period. The highest shell temperatures in the ladle are recorded in the course of vacuum process (on the average 430°C). The average temperature of shell during first 5 circulation cycles was 386°C.

5. Conclusion

The final solution is summarized into following points:

- To reduce the number of total cooling down of ladle lining cycles,
- To change the working layer material (big disadvantage of materials with high MgO content is their low resistance to cracking and flaking), here can be suggested AMC material (with 60-80 % Al_2O_3 content) or magnesia-chromite, in the most strained places fused magnesia-chromite or magnesia-chromite with very low porosity,
- To purchase laser meter for measurement of remaining lining thickness,
- To monitor the steel temperature, for too high steel temperature (up to 1700 °C) do not use magnesia ladles, i.e.:
  a) to operate more types of ladles,
  b) to operate only one type of ladles, but with higher quality working lining,
- To minimise time of no covered ladle with lid, because back then the significant reduction of ladle enthalpy between end of heating and tapping occurs.

Acknowledgements

This paper was created in the Project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility Program" funded by Ministry of Education, Youth and Sports of the Czech Republic and in the project No. SP2015/86 "Reduction of the energy demands of the material production processes".

REFERENCES

[1] P. Yh, G. Ce, B. Bjorkman, Scandinavian Journal of Metal. **32**, 71 (2003).

[2] P. Tvardek, P. Hašek, D. Jančar, Hutnické Listy, **61**, 14 (2008).

[3] Tvardek, P. Zefektivnění řízení technologických pochodů v oblasti pánvové metalurgie pomocí informačních technologií. Technical report H-03-103/824, Mittal Steel Ostrava, a.s. (2006).

[4] D. Jančar, M. Klárová, P. Tvardek, J. Vlček, P. Hašek, F. Ovčačík, Metalurgija 53, 159 (2014).

[5] M. Príhoda, J. Molinek, Z. Klecková, P. Jurecka, Neue Hutte **37**, 379 (1992).

[6] D. Jančar. Měření teplotního profilu licí pánve v ocelárně Vítkovice Heavy Machinery a.s. s následným vyhodnocením důvodu častého protavení vyzdívky. Technical report, VŠB TU Ostrava (2013).

Received:10 March 2015.