CAREFUL CONTROL OF REFRACTORY LINING CONDITIONS ENSURES PROLONGED CAMPAIGN OF BLAST FURNACE

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Introduction

- Intensive operation of blast furnace allows increase in production of hot metal and profitability of Iron & Steel Works.
- However, blast furnace life could be sacrificed if no measures are taken to protect refractory lining and to build stable accretion.
- CherMK and Hatch developed a systematic approach to monitor conditions of BF hearth lining using Acousto Ultrasonic-Echo (AU-E) non-destructive testing developed by Hatch.
- Multiple testing of blast furnaces revealed problematic areas with accelerated refractory deterioration and minimal thickness, formation of elephant foot, extent of accretion and speed of refractory wear, cracks and other anomalies.
- Improvement in coke quality, periodical staves washing, the addition of titania, grouting etc. were recommended and implemented to prolong furnace life while maintaining the intensity of furnace operation.
- This paper outlines how Non-Destructive Testing (NDT) was used at CherMK blast furnaces to monitor and reduce refractory wear in the hearth while maintaining intensive operation.
## NDT versus Thermocouples

Need to include NDT as part of regular BF health monitoring

<table>
<thead>
<tr>
<th></th>
<th>Thermocouples</th>
<th>NDT</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractory wear</td>
<td>Yes, but only with accretion</td>
<td>Yes</td>
<td>NDT gives more accurate results as this allows separate estimates of lining and accretion and cracks location</td>
</tr>
<tr>
<td>Accretion thickness</td>
<td>No, only combined with refractories</td>
<td>Yes</td>
<td>NDT gives more accurate results as this allows separate estimates of lining and accretion and cracks location</td>
</tr>
<tr>
<td>Location of cracks</td>
<td>No</td>
<td>Yes</td>
<td>NDT has advantage</td>
</tr>
<tr>
<td>Salamander</td>
<td>Yes</td>
<td>Yes</td>
<td>NDT gives more accurate results as this determines cracks location</td>
</tr>
<tr>
<td>Critical thickness</td>
<td>Yes</td>
<td>Yes</td>
<td>NDT gives more accurate results as this determines cracks location</td>
</tr>
<tr>
<td>Verification of thermocouple readings</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Shell conditions</td>
<td>No</td>
<td>Yes</td>
<td>NDT has advantage</td>
</tr>
<tr>
<td>Refractory wear if no or one thermocouple</td>
<td>No</td>
<td>Yes</td>
<td>NDT has advantage</td>
</tr>
<tr>
<td>Refractory wear in the furnace stack, bosh, belly</td>
<td>No</td>
<td>Yes</td>
<td>NDT has advantage</td>
</tr>
</tbody>
</table>
CherMK’s BF’s Design and Operating parameters
CherMK is a Russian Iron & Steel giant, producing 12.5 million ton of steel annually

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BF 1</th>
<th>BF 2</th>
<th>BF 4</th>
<th>BF 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Last major reline, year</td>
<td>2,009</td>
<td>2,010</td>
<td>2,005</td>
<td>2,006</td>
</tr>
<tr>
<td>Furnace useful volume, m³</td>
<td>1,007</td>
<td>1,033</td>
<td>2,700</td>
<td>5,500</td>
</tr>
<tr>
<td>Furnace working volume, m³</td>
<td>865</td>
<td>913.5</td>
<td>2,466</td>
<td>4,648</td>
</tr>
<tr>
<td>Hearth diameter, m</td>
<td>7.65</td>
<td>7.65</td>
<td>11</td>
<td>15.1</td>
</tr>
<tr>
<td>Metallic burden Fe_total (fluxed), %</td>
<td>60.04</td>
<td>59.93</td>
<td>60.38</td>
<td>61.21</td>
</tr>
<tr>
<td>Coke rate (dry), kg/thm</td>
<td>406.0</td>
<td>412.6</td>
<td>404.6</td>
<td>402.5</td>
</tr>
<tr>
<td>Natural gas rate, Nm3/thm,</td>
<td>142</td>
<td>144</td>
<td>100</td>
<td>117</td>
</tr>
<tr>
<td>Oxygen enrichment, % in blast</td>
<td>31.39</td>
<td>31.29</td>
<td>26.84</td>
<td>30.15</td>
</tr>
<tr>
<td>Blast temperature, °C</td>
<td>1156</td>
<td>1164</td>
<td>1220</td>
<td>1172</td>
</tr>
<tr>
<td>Average daily production, thm/day</td>
<td>3,062</td>
<td>2,925</td>
<td>6,881</td>
<td>12,871</td>
</tr>
<tr>
<td>Specific productivity, thm/m³/day (WV)</td>
<td>3.54</td>
<td>3.202</td>
<td>2.895</td>
<td>2.77</td>
</tr>
<tr>
<td>Specific productivity, thm/m²/day (hearth Ø)</td>
<td>66.65</td>
<td>63.67</td>
<td>72.44</td>
<td>71.91</td>
</tr>
<tr>
<td>Slag rate, kg/thm</td>
<td>283</td>
<td>288</td>
<td>279</td>
<td>232</td>
</tr>
</tbody>
</table>
Parameters of CherMK’s blast furnaces operation (cont-d)

- CherMK blast furnaces operate with comparatively high total iron in fluxed metallic burden, with values in the range of 59.93% – 61.21% (highest total iron in metallic burden of Russian Blast Furnaces).

- Additionally, the furnaces operate with high levels of oxygen enrichment (26.84% - 31.39%), moderate rates of coke and supplemental fuels, and blast temperatures above 1,150 ºC.

- As a consequence of high total iron, the furnaces have comparatively low slag volume in the range of 232 to 288 kg/thm.

- CherMK’s blast furnaces operate with relatively poor coke quality: CSR = 46.9 – 53.7% and CRI = 31.1 – 35.2%, which complicate the effectiveness of their operation.

- Despite poor coke quality, the smelting process is quite intensive with specific productivity ranging from 2.77 thm/m³/day for the largest in Russia and Europe BF #5 and 3.54 thm/m³/day for BF #1.
+ Parameters of CherMK’s blast furnaces operation (cont-d)

- Blast furnace #4 is the oldest in service with its campaign reaching 11 years.
- The service life of blast furnaces #1, 2 and 5 is 7, 6 and 10 years, respectively after last major reline.
- Blast furnaces #1 and 2 have complete cast iron hearth’s cooling system.
- BF #4 and #5 hearth is equipped with copper and cast iron staves while copper plates are used for the cooling of the low stack area of BF #4.
- The bottom of the blast furnaces #1 and 2 hearth are lined with domestic carbon blocks, while blast furnaces #4 and #5 use imported carbon blocks.
Parameters of CherMK’s blast furnaces operation (cont-d)

- Walls of the hearths of all furnaces are lined with high alumina mullite - corundum blocks and blast furnace grade fire clay bricks.
- Intensive operation of blast furnaces requires careful monitoring of refractory lining conditions in the furnace hearth.
- This monitoring allows for the application of timely preventive measures to retard premature refractory wear and to create a stable protective accretion on the walls of the hearth, preventing chemical and thermal attack by hot metal.
Parameters of CherMK’s blast furnaces operation (cont-d)

+  

- Blast furnaces ##2, 4 and 5 are equipped with embedded thermocouple and have thermal models to estimate the remaining lining profile (thickness of refractory plus accretion).

- However, over time many thermocouples have been damaged, leaving none or sometimes only one thermocouple in a given area.

- Blast furnaces #1 does not have any thermocouples.

- In 2013 CherMK decided to engage Hatch in AUE testing of BF #1 (in 2003 CherMK first time employed Hatch’s AU-E non-distractive technique for estimation of remaining refractory thickness for blast furnace ##2 and #5).
• CherMK and Hatch developed a systematic approach to monitor conditions of blast furnace hearth linings. This approach involves annual inspection of all blast furnaces.

• Results of each inspection are thoroughly discussed with plant management and operators, and subsequent measures were implemented to retard or stop further refractory deterioration and to prolong blast furnace campaign life.
AU-E – reflection (echo) of acousto-ultrasonic wave
Typical AU-E signals in frequency domain
Mathematical foundations

• The thickness of the layer of material for the AU-E technique is estimated by the following governing equations:

\[ T = \frac{(V_p \beta \alpha) / 2fp}{2} \]

\[ T_n = \frac{(V_p)n \alpha \beta}{2} \left[ \frac{1}{f} - \sum_{i=1}^{n-1} \left( \frac{2T_i}{(V_P)_i \alpha_i \beta_i} \right) \right] \]

Where \( T \) is the thickness or depth of the reflecting surface; \( \beta \) is the P-wave frequency; \( V_p \) - is the propagation speed of P-wave in the material; \( \alpha \) - is the temperature correction factor; \( \beta \) - is the shape factor

• The shape factor \( \beta \), accounts for the reduction in velocity due to various furnace shapes, such as cylindrical or rectangular. For blast furnaces where lateral dimensions are at least six times the thickness of the lining, the \( \beta \) factor is 0.96.

• The thermal correction factor, \( a \) is the ratio of refractory Young's modulus of elasticity under service conditions (Ex) to the modulus of elasticity at room temperature (Eo): \( \alpha = Ex / Eo \). In most cases it is assumed that the Young’s modulus of elasticity of the refractory changes linearly between the hot and cold face as a function of temperature.
Results of AU-E testing of the hearth and tuyere region of BF #1 (July 2015 and September 2014)*

*First tests were conducted in 2013
Results of AU-E testing of BF #1 - conclusions:

- The test results showed significant increase of wear of the walls of the low hearth over time and the formation of the “elephant foot”.
- Formation of “elephant foot” in the blast furnace sump can be attributed to the conditions of the “dead man” which forms the flow of the metal in the low hearth region.
- The “dead man” should be floating and permeable for the hot metal to avoid excessive high velocity peripheral flow of the hot metal and erosion of refractory lining.
- Shallow sump of blast furnace #1 does not create good floating conditions for the “dead man”. In this case the quality of coke becomes even more critical.
Results of AU-E testing of BF #1 - conclusions (cont’d):

• Ceramic layer and the first carbon slab layer of the hearth bottom were worn. The second bottom slab layer was partially worn.

• The average remaining refractory was 768 mm in July 2015, with the original average refractory thickness of 1170 mm. This was equivalent to a remaining refractory thickness of 58%. There was a 2% reduction in remaining thickness since July 2014.

• The minimum remaining refractory thickness detected was 280 mm or 27% of original thickness of 1035 mm

• There was uneven wear in the hearth’s walls with more intensive wear at left side of taphole 1 and also opposite side to this taphole. An average of 695 mm (49% of the average original remaining refractory) was detected in these areas.
Results of AU-E testing of BF #1 - conclusions (cont’d):

• Aligned anomalies located within the remaining refractory are likely connected (i.e. a single lengthy crack measured at more than one location) possibly forming the type of cylindrical anomaly (or crack).

• If any molten metal penetrates through the gaps/cracks, or any movement at the crack may cause the front of the block to fully separate along the crack. This sudden event can cause thermal spikes. These regions should be thermally monitored to identify the thermal spikes.

• On average, the remaining refractory thickness was greater than 30% of the original build and had not yet reached the absolute acceptable minimum of 200-250 mm.
Results of AU-E testing of BF #1 - conclusions (cont’d):

- Stable accretion was formed on the hearth walls protecting it from further intensive deterioration.

- The average remaining refractory thickness at tuyere level was 552 mm, about 65% of the original average thickness of 843 mm.

- All the sections of tuyere level showed thickness of partially worn. The minimum remaining refractory detected was 290 mm. The original average refractory thickness was 843 mm.
Results of AU-E testing of BF #2 - conclusions:

- Blast furnace #2 was tested first time in July 2015.
- Results of AU-E measurements for blast furnace #2 are very similar to those for blast furnace #1.
- However, this furnace is in better conditions with minimum refractory thickness of 640 mm and 380 mm. for furnace hearth and tuyere regions, respectively.
Results of AU-E testing of BF#4 hearth (July 2015 г.)
Results of AU-E testing of BF #4 - conclusions:

+ The first and second layers of the furnace hearth slabs were worn out. Wear had started at the third layer of the hearth slab.

+ There were possible aligned cracks within the refractory at elevations below the third layer hearth slab.

+ The overall average remaining refractory thickness was 860 mm, about 52% of the original average thickness of 1664 mm.

+ The minimum detected remaining refractory thickness was 380 mm.

+ Stable accretion was formed on the hearth walls protecting it from further intensive deterioration.

+ Possible aligned cracks were found in the hearth’s walls.
Results of AU-E testing of BF #4 – conclusions (cont’d):

• Continuous thermal monitoring at these possible crack regions was recommended for the detection of any thermals spikes, which would indicate the spalling of material at the hot face of the crack or metal penetration.

• Test results showed the formation of the “elephant foot” in the furnace sump mainly surrounding the taphole regions.

• The average remaining refractory thickness in tuyere region was 650 mm (77% of the average original thickness of 843 mm).

• The minimum remaining refractory thickness at tuyere region was 380 mm (47% of the average original thickness of 843 mm).

• Refractory lining of BF4 was in workable conditions and comparatively far from reaching absolutely critical thickness of 200-250 mm.
Results of AU-E testing of BF#5 hearth (July 2015 г.)
Results of AU-E testing of BF #5 – conclusions:

• No ceramic layer was detected at the top of the hearth slab. The first and second layers of the furnace hearth slabs were worn out. Wear had started at the third layer of the hearth slab.

• The overall average remaining refractory thickness was 1391 mm, about 50% of the original average thickness.

• There was uneven wear in the furnace walls. In some regions of the hearth’s walls the average percentage of remaining refractory was less than 40%.

• The minimum remaining refractory thickness was 760 mm. This thickness was about three times greater than the absolute acceptable minimum thickness of 200-250 mm.

• Stable accretion was formed on the hearth walls protecting it from further intensive deterioration.
Results of AU-E testing of BF #5 – conclusions (cont’d):

• Some of the bricks in the hearth were possibly cracked. Signals were reflected from shallower region. Ongoing temperature measurements at these cracked regions should be monitored frequently to observe any progressive thermal anomalies.

• It was noted that anomalies/cracks which are aligned are likely connected (i.e. a single lengthy crack measured at more than one location). Likely anomalies form some kind of cylinder around the furnace hearth. These regions should be thermally monitored to identify the thermal spikes.

• Test results showed the formation of the “elephant foot” in the furnace sump in area opposite to the tap holes.

• Cast house level had an average remaining refractory thickness of 1110 mm, about 78% of the original average refractory thickness of 1413 mm.
Results of AU-E testing of BF #5 – conclusions (cont’d):

- The minimum remaining refractory thickness at cast house leve was 550 mm.
- In general, this level was in good condition and no maintenance was required at this stage.
- The average remaining refractory thickness at tuyere leel was 584 mm (85% of the original thickness of 690 mm).
- The minimum remaining refractory thickness was 450 mm.
- Refractory lining of BF5 was in workable conditions and comparatively far from reaching absolutely critical thickness of 200-250 mm.
Comparison of AU-E with reconstructed location of cracks (BF#2, 2003 г.)
Accuracy of AU-E NDT measurements – level of comparison.
Accuracy of AU-E measurements

- The comparison of the AU-E results and the physical measurements confirmed that AU-E accuracy is about 4 to 7%.
- The core drill result revealed remaining refractory thickness of 530 mm whilst AU-E measurements indicated a refractory thickness of 500 mm. This generates a difference of 6%.

<table>
<thead>
<tr>
<th>Line</th>
<th>Level</th>
<th>Remaining Refractory Measurement in February 2015 (mm)</th>
<th>Difference, (+/- mm)</th>
<th>Difference, % of AU-E</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hatch AU-E Measurement</td>
<td>Plant Physical Tape</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurement</td>
<td>Measurement</td>
<td></td>
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</tr>
<tr>
<td>3</td>
<td>8</td>
<td>550</td>
<td>530</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>780</td>
<td>750</td>
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<td>9</td>
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<td>650</td>
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<td>50</td>
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<tr>
<td>11</td>
<td>8</td>
<td>700</td>
<td>720</td>
<td>20</td>
<td>3</td>
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<td>15</td>
<td>8</td>
<td>570</td>
<td>520</td>
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<td>Average</td>
<td></td>
<td>652</td>
<td>607</td>
<td>45</td>
<td>7</td>
</tr>
</tbody>
</table>
Comparison AU-E results with core drills at Siderar, Argentina

- Profile obtained through CINI model
- Profile obtained through AU-E (2006)
- Profile obtained through Core drilling – Graphite not visually affected (2006)
- Profile obtained through Core drilling – Altered graphite
- Profile obtained through Core drilling – Floor
- Profile obtained through AU-E (2004)
Between first and second AU-E testing of the blast furnace #1 the average refractory wear progressed by 12% and 7% for tuyere and hearth regions, respectively, which corresponds with the average refractory wear rates of 0.71% per month and 0.4%/month. As a result of protective measures applied by CherMK the average wear rate for this 12 months period of time between July 2014 and July 2015 was reduced to 0.33%/month or 4.7 mm/month.
Some measures to retard refractory wear

• Addition of titania containing materials in amount of 7-10 kg TiO2/thm. TiO2 forms titanium carbide and titania nitrides, which precipitates on a hearth walls.

• Installation of cigar or Hatch finger coolers for local cooling and forming of accretion in critical points could be recommended to prolong the furnace campaign life.

• Grouting in critical points of low thickness of refractory could be another approach to repair lining without a long period of furnace shutdown

• Stave washing allows the removal of scale from water pipes, thereby improving the heat transfer efficiency. This helps to create stable accretion.

• Periodical slower run of the blast furnaces to form accretion on the hearth’s walls.
Some measures to retard refractory wear

- Improvement in coke quality from CSR 45-55% to 63-65% and reduction in CRI – from 31-34% to 23-24%. In addition to other benefits, this improvement allowed for an increased permeability of the “dead man” and a reduced circumferential velocity of hot metal which promotes the formation of “elephant foot”.

- The CSR index should be high to avoid destruction of coke and allow the formation of permeable “dead man”.

- The CRI index should be kept as low as possible to shift the solution loss reaction to the higher temperatures, but at the same time should be in the range which guarantees satisfactory carburization of hot metal.
Conclusions

• Intensive operation of the blast furnace requires careful control of the hearth refractory lining conditions.

• The case studies at CherMK showed that AU-E is a reliable technology which enables the estimation of the thickness of refractories, accretion and location of cracks or anomaly within the accuracy of 4-7%.

• The application of AU-E technology for CherMK blast furnaces revealed conditions of the refractory lining, formation of accretion and the most worn regions in the furnaces.

• This allowed CherMK and Hatch to develop and implement preventive measures to prolong furnace campaign and continue safe furnace operation.
Conclusions

• These measures include (but are not limited to):
  • the addition of titania materials
  • stave washing
  • grouting
  • utilization of higher quality coke
• All of these allow CherMK to carefully control blast furnace conditions while maintaining their intensive operation.
Acknowledgements

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Thank you

For information please visit: hatch.www.com