ASSESSMENT OF THERMAL EXPANSION AND CONTRACTION OF REFRACTORY SYSTEM IN BLAST FURNACE HEARTH

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ABSTRACT

The refractory system in the blast furnace hearth is exposed to harsh conditions and fluctuating high temperatures. Temperature fluctuations may generate undesirable refractory cracking and gap formation due to successive thermal expansion and contraction, which could allow hot metal / gas infiltration into the hearth and decrease the efficiency of the hearth cooling system. Minimizing crack / gap formation and optimizing the bricking pattern, materials, and expansion allowances can improve the campaign life of the blast furnace hearth.

This paper presents a novel assessment methodology which uses advanced finite element techniques to predict refractory failure, mortar joint opening, and gap formation around ramming mix in the hearth. Using this methodology, locations of potential hearth refractory system failures during initial heat-up of the furnace and following temperature fluctuation during operation can be identified and mitigated during the design stage. This methodology can also be applied to assess root causes of hearth refractory wear in existing furnaces.

INTRODUCTION

The harsh conditions experienced by the blast furnace hearth include complex chemical attack and thermal-mechanical loading, as well as temperature fluctuations. Hearth temperatures vary during the campaign life, from high temperatures during initial heat-up to reduced and fluctuating temperatures due to skull formation, process changes, skull building / loss, refractory wear / erosion, and potential furnace shutdown or idling due to operational problems or damage.

Irreversible structural responses of hearth materials, such as brick cracking / crushing, mortar joint gap opening, compaction of ramming mix, and steel shell yielding, mean that thermal and structural performance changes over time. Material failure and gap formation may allow infiltration of process gas / metal and reduce the cooling system effectiveness, which will eliminate expansion allowance, accelerate refractory wear, and limit the campaign life.

Numerous competing hearth design philosophies exist, such as big-beam blocks, small blocks/bricks, ceramic pads/cups, varied bricking configuration and materials, etc. Effectively comparing these disparate designs is challenging, particularly the effects of thermal expansion and contraction considering irreversible structural behaviour. This paper presents a novel assessment methodology which captures complex material behaviours observed in-service using finite element analysis (FEA). This methodology can be used to more reliably compare hearth performance under temperature fluctuations, identify potential design flaws which may limit the campaign life, and recommend hearth design improvements for better performance and reliability.

BACKGROUND AND APPROACH

The refractory hearth comprises refractory bricks, brick-to-brick joints, ramming mix, and the steel shell. Each component has different non-linear material properties such as stiffness, tensile / compressive strengths, and thermal expansion. Taken together, they form a complex heterogeneous structural system. For a quantitative structural assessment to be valid, all relevant physics must be captured.

A number of papers [1][2][3][4] have presented quantitative structural assessment of the blast furnace hearth with varying levels of complexity; approaches have variously included 2D analysis, linear elastic material properties, bonded brick-to-brick interfaces, homogenized interface behaviour, etc. The merits of these various approaches have been discussed in other works [5].

A novel 3-dimensional structural refractory assessment approach is presented in this paper. This approach explicitly models each component of the hearth, taking into account behaviours including refractory brick cracking / crushing; compression, separation, and frictional sliding of mortar joints; ramming mix inelastic compression; and nonlinear shell deformations.

The 3D assessment approach, which has previously been applied to as-built furnace hearths under initial heat-up [5][6], is applied here for both initial heat-up and the subsequent temperature fluctuation, in which the temperature fluctuation causes both thermal expansion and contraction. This approach is demonstrated using two different existing blast furnace hearths: one with a small-brick ceramic cup (Fig. 1) and one with a big-beam ceramic pad at bottom and double-ring sidewall (Fig. 2).

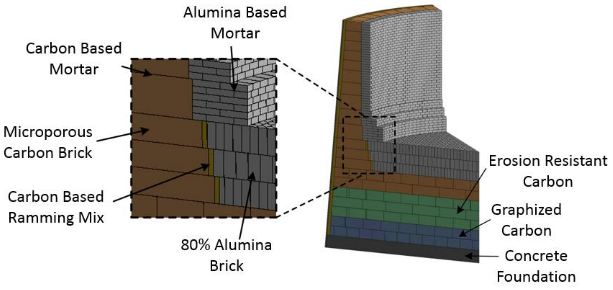

Fig. 1: Small-brick ceramic cup hearth

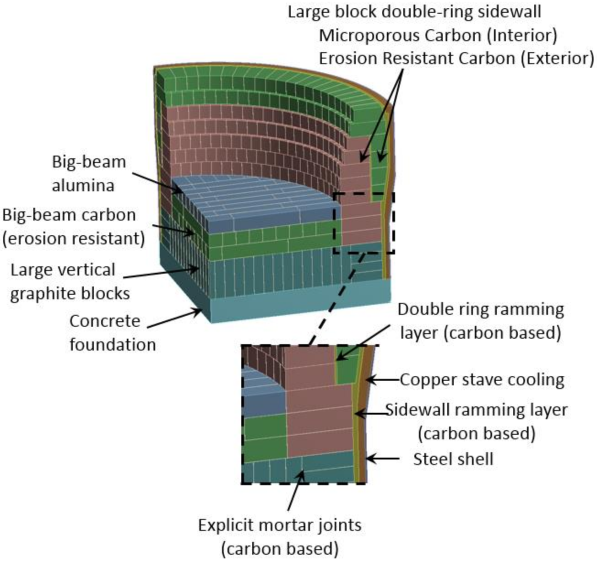

Fig. 2: Big-beam hearth with double-ring sidewall

The small-brick ceramic cup hearth is represented by a 3D wedge model, while the big-beam hearth is represented by a 3D quarter model, in order to capture the non-axisymmetric structural response of the big-beams which would not be accurately reflected in a 3D wedge model.

MATERIAL BEHAVIOUR

Representative material behaviour is a critical component of quantitative structural assessment, and has been described in detail in previous publications [6][7].

Refractory bricks are generally brittle, with varied thermal and mechanical properties based on their composition. Brick material, geometry, and layout are key considerations in the hearth design, and affect the structural behaviour and the thermal performance / skull formation during operation. The assessment described here uses a Drucker-Prager concrete model [8] to capture pressure-dependent brick cracking and crushing, allowing more accurate assessment of the brick stresses, displacements, and failure modes.

Brick-to-brick joints - dry or mortared - reduce compressive stresses in the hearth by absorbing a portion of the thermal expansion under increasing temperature. Failure of these joints in compression, tension or shear may allow infiltration of metal or process gas, which could accelerate refractory wear and reduce cooling effectiveness / skull development. The assessment methodology described here uses micro-modelling to explicitly capture temperature-dependent axial and shear behaviour of mortar joints, allowing separation and frictional sliding.

Ramming material provides expansion allowance for the hot face refractory layers and reduces expansion-related stresses on the shell, particularly in ceramic cup designs where the hot face bricks (e.g. alumina) have a higher thermal expansion coefficient than typical carbon bricks. Ramming layers must be thick enough to provide adequate thermal expansion. However, ramming material shrinks permanently under compression, and therefore overly thick ramming layers will form gaps when the refractory cools and thermally contracts.

Use of overly simplified material models for ramming will compromise the validity of the assessment and prevent accurate determination of the hearth thermal and structural performance. The assessment described here uses a modified Cam-Clay[8] material model to capture pressure-dependent compaction and shear failure, which matches well with published test data for a carbon-based ramming material[5].

ASSESSMENT IMPLEMENTATION

The hearth refractory system assessment was implemented using finite element analysis (FEA), incorporating the material behaviours described above. ANSYS® [8] software was used to create representative FEA models for the existing small-brick ceramic cup hearth and big-beam hearth.

The effects of thermal expansion and contraction were captured by performing the assessment in two steps. First, mechanical loads (refractory self-weight, burden weight, ferrostatic pressure, and process gas pressure) were applied in combination with initial temperatures up to 1550°C on the hot face of the refractory. Mechanical loads and initial heat-up temperatures are shown in Fig. 3 and Fig. 4 for the two hearths under consideration.

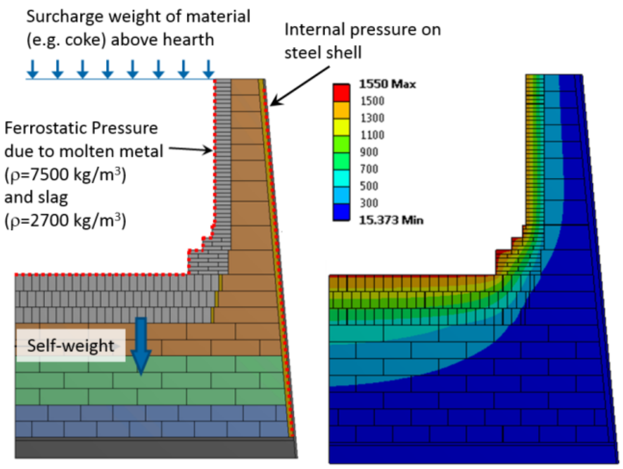

Fig. 3: Mechanical Loads and Initial Heat-up Temperature for Small-Brick Ceramic Cup Hearth

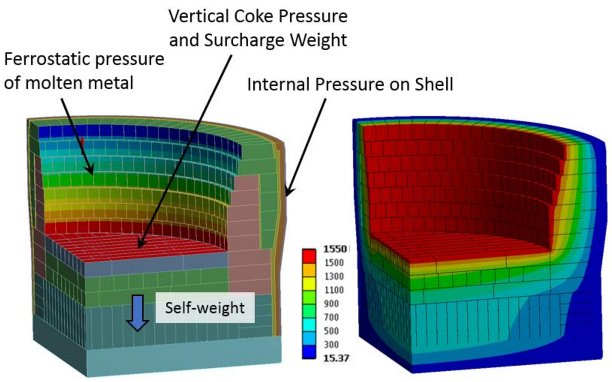

Fig. 4: Mechanical Loads and Initial Heat-up Temperature for Big-Beam Hearth

In the second step, mechanical loads were kept constant, and temperatures were decreased, to capture the effect of hearth cooling due to skull formation and cooling system operation.

HEARTH STRUCTURAL RESPONSE & COMPARISON

The structural behaviour of the two existing hearths was fundamentally different under temperature fluctuation and the corresponding thermal expansion / contraction, as described in this section.

Initial Heat-Up

For both hearth designs, the assessment predicted substantial thermal expansion, brick movement, and mortar joint failures at the maximum design hot face temperature of 1550°C. Gaps were predicted to form in the lower portions of the sidewalls in both cases. As noted previously, gap formation presents a risk of gas / metal penetration, reduced cooling system efficiency, and refractory wear / erosion. These conditions could accelerate the formation of the commonly-observed "elephant foot" type wear pattern.

Since hearth erosion was considered a risk to the safety and campaign life of both furnaces, non-destructive testing (NDT)[9] was performed to quantify the remaining refractory thickness. The measured refractory thickness / wear patterns are shown in Fig. 5 and Fig. 6, alongside the predicted deformations.

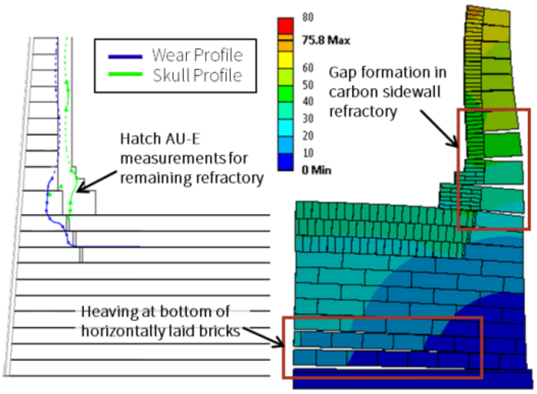

Fig. 5: Refractory Erosion Profile (NDT) Measurement vs. Total Deformation (mm) for Small-Brick Ceramic Cup Hearth (Scale × 10)

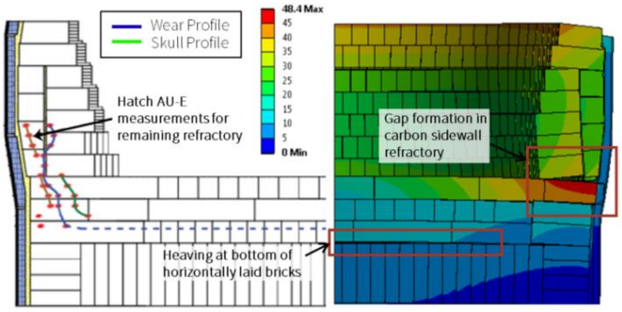

Fig. 6: Refractory Erosion Profile (NDT) Measurement vs. Total Deformation (mm) for Big-Beam Hearth (Scale × 10)

As shown above, the observed wear patterns matched well with the predicted deformation and gap locations in the structural models.

Vertical heaving of bricks and gap formation in the lower region of the hearth was observed in both furnaces, as well as formation of vertical gaps between hearth sidewall blocks, as shown in Fig. 5 and Fig. 6. These gaps may also have substantial effects on the efficiency of the hearth cooling system. The gaps were more localized in the big-beam hearth, likely due to the additional flexibility imparted by the additional ramming layer between the inner and outer sidewalls, lack of highly expansive ceramic cup, and less confining steel shell (sloped outward rather than inward) compared to the small-brick ceramic cup design.

Likely brick cracking and crushing locations were assessed by considering the maximum and minimum principal stresses. Peak stresses typically occurred at a hot face temperature of approximately 800°C, corresponding to the onset of high-temperature softening in the alumina bricks. Results are shown in Fig. 7.

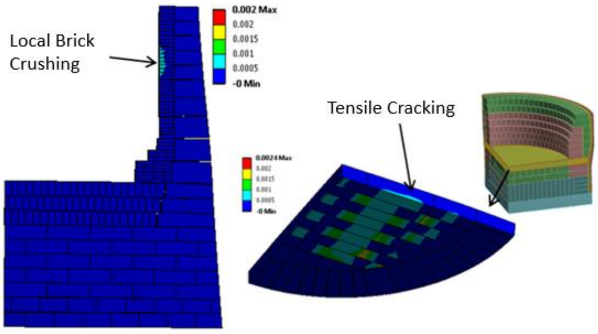

Fig. 7: Plastic Strains Accumulated in Hearth Refractory

As shown, cracking / crushing were predicted only in very localized areas for the small-brick ceramic cup hearth. For the big-beam hearth with double-ring sidewall, substantial tensile cracking was predicted on the cold face of the uppermost alumina layer in the hearth bottom (ceramic pad).

Temperature Fluctuation (Cool-Down)

Two cool-down scenarios were considered for each of the two existing furnaces: Scenario 1, in which the hot face of the refractory was reduced from 1550°C to 700°C; and Scenario 2, in which the hot face of the refractory was further reduced from 1550°C to 300°C. These scenarios represented thermal conditions for different process conditions / skull thickness during operation. For the small-brick ceramic cup hearth, deformed hearth shapes at maximum temperature, and after cool-down for Scenarios 1 and 2, are shown in Fig. 8.

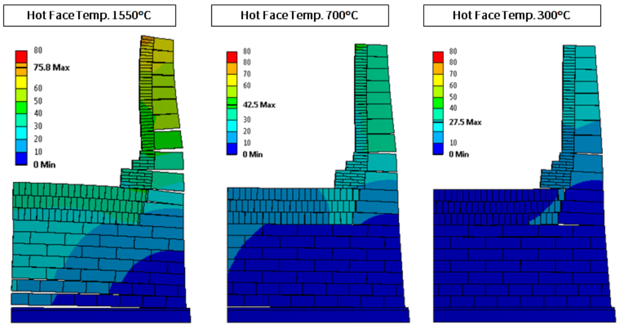

Fig. 8: Brick Displacements and Gap Opening in Small-Brick Ceramic Cup Hearth (Scale × 10)

In this furnace, vertical gaps formed in the sidewall during heat-up began closing during cool-down, due to thermal contraction. However, the reversal in deformation caused new gaps to form around the ramming material (Fig. 9), which was permanently compacted by the compressive load applied to it during heat-up. These new gaps are more pronounced in Scenario 2, as the alumina and carbon bricks contract further toward the centre of the furnace and away from the compressed ramming rings.

Gaps sizes at the ramming locations are shown in Fig. 9. For Scenario 1, gaps at the ramming around the bottom of the ceramic cup (between alumina bricks and carbon bricks) were up to 5 mm wide. Gaps at the ramming adjacent to the shell varied along its height, also peaking at 5 mm. For Scenario 2, further cool-down increased the gaps at the ceramic cup ramming to a maximum of 9 mm and those adjacent to the shell to 12 mm.

These gaps, particularly those between the ramming and the shell, are problematic as they may result in overheating in the sidewall refractory without corresponding increases in the thermocouple or cooling water temperatures. In this case, there will be no warning sign to the furnace operator, and damage may propagate unnoticed.

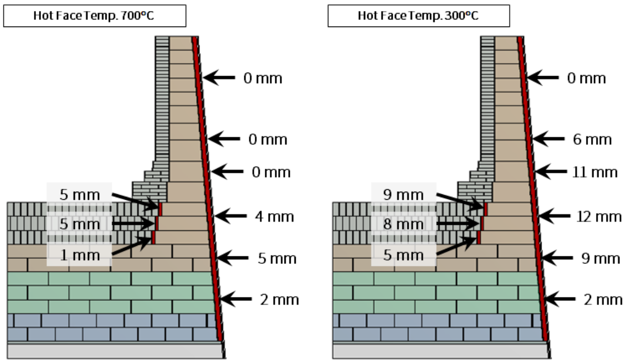

Fig. 9: Gap Opening Adjacent to Ramming Material in Small-Brick Ceramic Cup Hearth (Scale × 10)

For the big-beam hearth, similar trends were observed in the sidewall ramming as in the small-block ceramic cup hearth, with gaps at the ramming location up to 2 mm in Scenario 1 and increasing to 6 mm in Scenario 2. The lower number of mortar joints in the big-beam hearth compared to the small-brick ceramic cup hearth also lead to the formation of discrete gaps between the ends of the big-beams. Gap sizes and deformations are shown in Fig. 10 and Fig. 11.

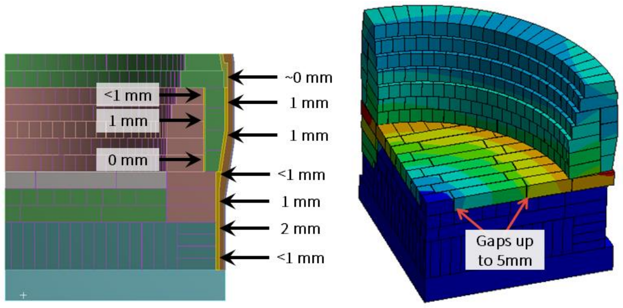

Fig. 10: Gap Formation in Big-Beam Hearth for Scenario 1: Hot Face Temperature at 700°C

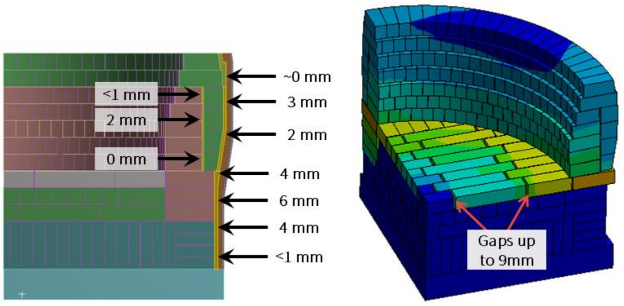

Fig. 11: Gap Formation in Big-Beam Hearth for Scenario 2: Hot Face Temperature at 300°C

As shown, the gaps between the ends of the big-beams were up to 5 mm in Scenario 1 and up to 9 mm in scenario 2. These large gaps could allow significant gas/metal attack to the hearth bottom. Solidified iron infiltration into the gaps may also eliminate some of the radial expansion allowance and result in brick crushing and/or shell yielding on a subsequent heat-up.

Performance Comparison

The structural assessment results demonstrate the fundamentally different behaviour of the two hearths studied.

The small-brick ceramic cup hearth had a nearly axisymmetric bricking layout, and the primary gap formation was in the sidewall and at the ramming locations. The relatively high thermal expansion of the ceramic cup caused the ramming layers to compress irreversibly, such that large gaps formed and were present after cool-down. This result demonstrates the need for expansion allowances to be carefully considered, particularly if a ceramic cup is used.

The big-beam hearth showed smaller gaps at the ramming locations, potentially due to its lower inherent thermal expansion. However, the gaps in the hearth bottom were much larger and concentrated in discrete locations, compared to those in the small-brick ceramic cup hearth bottom, where they were smaller and more uniformly distributed.

Both hearth designs demonstrate flaws associated with thermal expansion and contraction due to temperature fluctuation. The assessment method described here can be applied to recommend incremental changes that would improve the hearth behaviour, or to assess the performance of a completely different hearth configuration.

CONCLUSIONS

The methodology described here can add substantial value to new blast furnace hearth designs and relines, by quantitatively comparing the performance of different hearth types. It can also be used to better understand and explain hearth wear and issues in existing furnaces. In particular, the effects of thermal expansion and contraction can be compared, and design decisions can be made with confidence to prolong campaign life safely and cost-effectively.

Different hearth designs have substantially different structural responses, including material failure and gap formation which may promote erosion and decrease cooling system effectiveness. The FEA-based assessment methodology presented here can be combined with detailed thermal assessment [10] and applied to furnaces with different materials, bricking configurations, expansion allowances, cooling systems, and process conditions. For furnaces in operation, effects of operational and process changes can be assessed by considering the associated temperature fluctuations.

Performing quantitative structural assessment early in the design cycle allows designers and operators to predict issues, make incremental improvements, and safely maximize blast furnace campaign life and performance.

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