INVESTIGATION OF REFRACTORY CONCRETE FAILURE IN FURNACES OF METALS INDUSTRY

K. Andreev, S. Sinnema and M. Hogenboom

(1) Ceramics Research Centre, Corus RD&T, The Netherlands

Abstract

Refractory ceramics is a diverse class of materials used to insulate industrial furnaces and protect them from liquid metals, slags and hot gases. Concretes (based on calcium-aluminates cement binders) make up approximately 40% of all refractories used in the steel and aluminium industry. As an element of a structure consisting of concrete/ceramic layers and the steel shell these materials are exposed to significant thermo-mechanical loads and chemical wear. This paper gives examples of investigation into spalling of refractory concretes in an aluminium melting furnace and a steel teeming ladle. The main tool of the investigation was finite element computer modelling. The models were supported by extensive material testing and post mortem investigations of the failed structures.

1. REFRACTORY CONCRETE

Refractories are bulk ceramic materials composed of oxide and non-oxide components with a rather coarse grain-matrix structure. Their main application is the lining of industrial furnaces, including liquid metal vessels in the steel and aluminium industry. Due to the complex nature of the loads the linings are built of several layers of refractory materials, which are supported by the steel shell. Refractory concretes, referred to as castables or monolithic refractories, make up approximately 40% of all refractories used in the steel and aluminium industry today. Shaped products (bricks) take the remaining share.

Several different bonding systems for refractory castables have been developed, but currently low cement castables are most common [1], table 1. Low cement castables utilizing ultra fine grain materials combined with deflocculation technologies achieve low porosity with low moisture assuring high corrosion resistance and good hot strength. Conventional castables, which contain a high amount of calcium alumininate cement, typically exhibit deficiencies of high porosity and low refractoriness as the result of a high water content required for mixing of the castable and the presence of calciumoxide in the calciumaluminate cement. The choice of the chemistry/mineralogy of aggregates in refractory castable is determined by the chemical and mechanical aspects of the service conditions. Addition of magnesia to the aluminosilicate basis enables spinel formation and improves thermal shock resistance. Silicon carbide containing castables demonstrate good chemical, abrasion and erosion wear resistance. Addition of carbon reduces the wettability by liquid slag and improves chemical resistance. Casting and drying of the monolithic linings can either happen on site or at the concrete production plant. In the later case the supplier delivers pre-fabricated blocks, which are especially useful in the linings of complex shapes.

Table 1 Properties of low cement, clay-bonded and conventional castables [1]

Bonding type	A: Low cement	B: Clay bond	C: Conven-tional	D: Low cement	E: Low cement
Chemical composition (wt %)					
Al_2O_3	56	56	56	49	77
SiO_2	38	38	35	-	-
CaO	0,9	0,5	5,8	0,8	0,9
SiC	-	-	-	44	-
MgO	-	-	-	3	20
C	-	-	-	-	-
Added water content (wt %)	7,5	9,3	13,0	7	7,5
Bulk density (g/cm^3)					
After 110°Cx24h	2,5	2,4	2,2	2,8	2,8
After 1500°Cx3h	2,5	2,9	2,1	2,8	2,8
Apparent porosity (%)					
After 110°Cx24h	14	18	22	14	18
After 1500°Cx3h	17	22	20	18	22
Crushing strength (MPa)					
After 110°Cx24h	37	13	23	30	19
After 1500°Cx3h	77	31	40	56	47
Hot modulus of rupture (MPa)					
At 1400°C	4,4	2,4	0,5	-	-
Permanent linear change (%)					
After 1500°Cx3h	+0,27	+0,10	-0,45	+0,13	+0,48

2. FAILURE MECHANISMS

In furnaces of metals industries the refractory castables are exposed to high temperatures as well as chemical and mechanical wear. The temperature loads in steel making vessels can exceed 1700 °C. Although the temperature of the molten aluminium bath is “only” about 700 °C, the exposure to the gas burners can raise the lining temperature in aluminium furnaces well above 1000 °C. Chemical wear of the refractory castables is caused by the contact with molten slag and metal. Most common mechanical failure mechanisms in the lining is cracking due to thermal shock, compressive failure and bending due to asymmetrical constrains [2]. Thermal shock develops as a result of temperature fluctuation in the vessels utilised for cyclic processes, when e.g. a vessel is filled with molten metal and emptied after some processing steps. Compressive forces develop due to constrained thermal expansion of refractories, which can be due to other refractories layers or the steel shell of the vessel. Cracking due to asymmetric constrain can develop in steps or in T-junctions of the lining.

Apart from the above "macro" causes the castable lining can be damaged mechanically due to "micro" causes, which result from thermal expansion mismatch of different elements composing the microstructure of the material. The mismatch can be caused by the physical-chemical transitions taking place in service, such as reactions with slag/metal, oxidation or phase transition taking place on the hot face of the lining.

3. APPROACH TO ANALYSE MECHANICAL FAILURE

To analyse the cracking and failure of refractory concrete one needs to know the mechanical properties of the material in the whole service temperature range and under various loading conditions. As any non-metallic disordered material the refractory monolithics show different behaviour in tension and compression. Therefore tests need to be done in both modes. Compressive strength is also sensitive to the hydrostatic pressure and the dilatancy is characteristic of the plastic flow. The material properties should be measured "at" the temperature and not "after" the cooling down concluding the treatment at temperature (fig. 1), as the cooling can significantly influence the physical-chemical composition of the concrete Although the latter approach is still widely used and advised in the refractories literature– e.g. table 1.

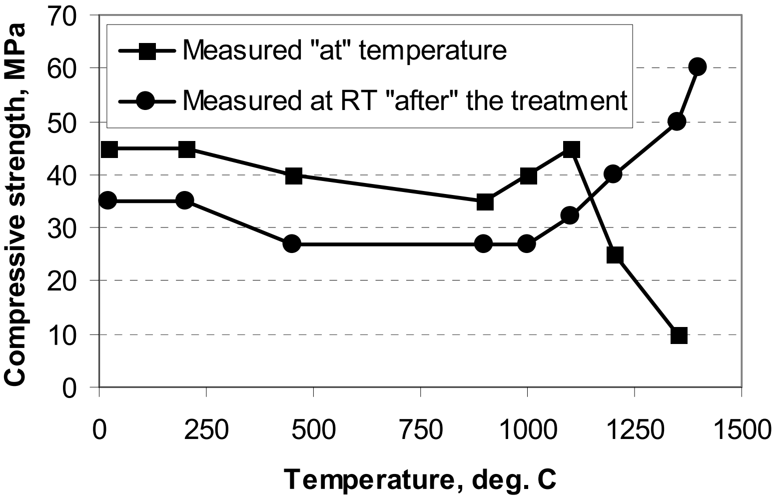


Figure 1: Comparison of compressive strengths, as a function of the measurement approach

The following set of tests is fit for purpose:

- Expansion during drying, the first heat-up and the following heating-cooling cycles;
- Dynamic Young's Modulus measurements for heating and cooling cycles (fig. 2);
- Density and Porosity;
- Three point bending tests at higher temperatures to measure strength, stiffness and post-failure behaviour in tension;
- Compressive stress-strain measurements at higher temperatures (fig. 3);

- Creep/relaxation tests at different loads and temperatures [4];
- Heat conductivity and heat capacity.

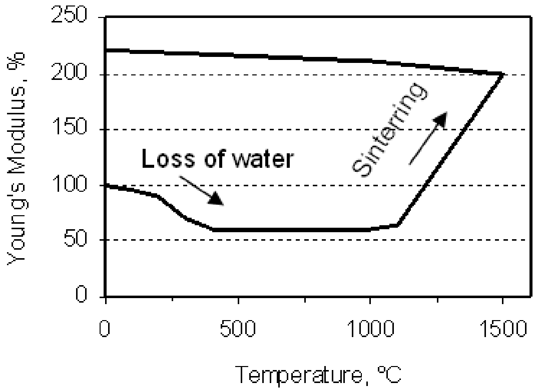


Figure 2: Dynamic Young's modulus of a low cement castable, first heating

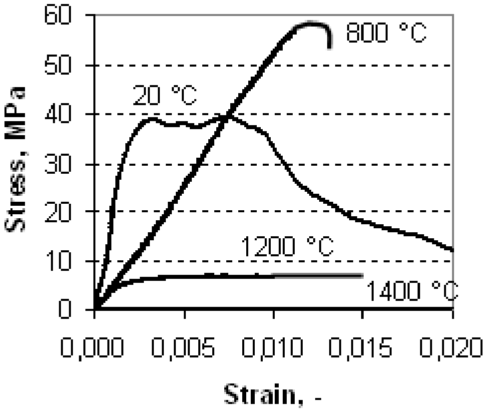


Figure 3: Compressive stress strain curves of a low cement castable. Tests are performed with constant loading rate of 0,002 mm/sec.

Because of the non-linearity of the material behaviour and the complexity of the service conditions computer modelling finds ever greater application in the refractory linings development. Thermo-mechanical FEM analysis is used to predict temperatures, stresses and displacements in the lining. Models used in the cases below were created using the commercially available FEM codes Diana and Ansys, for the case 1 and 2, respectively. The cracking was described using the smeared crack approach. The strain softening was accounted for in the case 1. In the second case no softening was modelled. Another way to model the damage refractories is discussed in [3, 5, 6].

The model validation by the assessment of the thermo-mechanical processes is realised by post-mortem analysis and the monitoring of the stresses and temperature in the lining and shell during the service [7].

4. CASE 1 - CRACKING AND SPALLING IN TEEMING LADLE

A teeming ladle is used in metallurgy for transport and processing of liquid steel (fig. 4). During service the lining is exposed to a multiple number of thermal cycles when the steel, along with the slag, is poured into the ladle, processed and tapped out. The working lining, which comes into contact with liquid steel, is made of spinel forming castable (similar to material E, table 1). The safety lining, between the working lining and the shell is lined with bricks.

During service it was observed that the working lining spalls in plates that fall off one after another causing significant thinning of the lining and the necessity of early ladle relining [8]. Such plates may be 500 mm in diameter and have a thickness of 20-30 mm. FEM analysis was used to analyse the mechanisms responsible for this spalling at the hot face of the concrete.

Observations during service and following numerical simulations established that the first stage in the spalling mechanism is the formation of a net of cracks orthogonal to the hot face. The cracks developed in the monolithic lining during initial drying of the new castable after ladle relining. The cracks could grow during the initial service cycles.

The model presented here (fig. 5) was used to investigate the second and the third phase of the spalling. The model featured parts of the wall lining between two cracks, the safety lining and the ladle shell. An unbreakable block was to model contact with other parts of the lining during thermal expansion. The distance between the castable and the block was equal to material shrinkage during the drying.

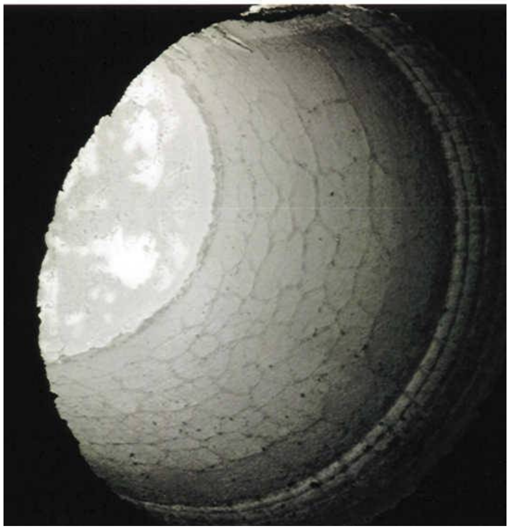


Figure 4: Cracks on the hot face of the ladle lining.

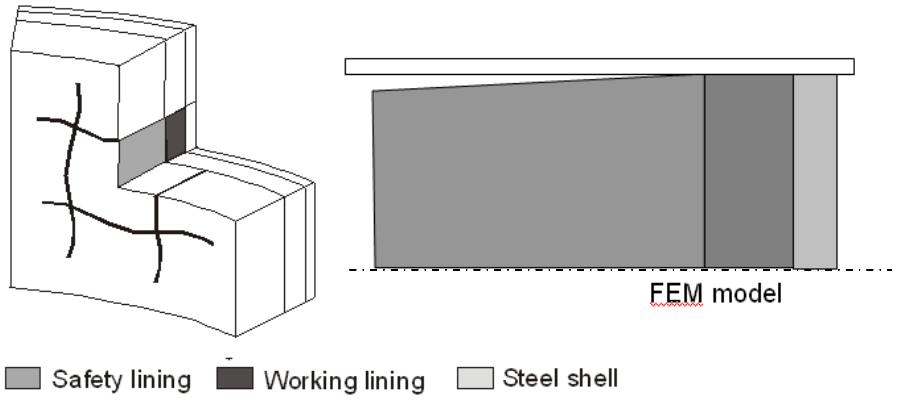


Figure 5: Model for the analysis of the plate spalling (phased analysis); the dotted and dashed line is the axis of symmetry.

The model simulated the heat-up of the dried lining and progressive service cycles. According to mechanical analysis the drying crack begin to close due to thermal expansion at the beginning of the heat-up. After closing compressive stresses directed parallel to the hot face build up in the lining. The values of the stresses are not high enough to cause compressive failure. The first cooling causes tensile stresses and the formation of two crack types (fig. 6.a): cracks orthogonal to the hot face and those parallel to it. The latter starts on the surface of the drying crack some distance away from the hot face. The model predicted the second type of cracks to start 20 – 30 mm from the hot face, which corresponds with the thickness of the spalled plates. Due to the irreversible crack opening and the repeated cooling-heating cycles cracks of the two types could propagate one orthogonal and another parallel to the hot face. Eventually they could intersect (fig. 6.b), which causes the spalling of the lining corner. In the model the spalling was modelled by eliminating the “spalled” elements.

The loss of the corner modified stress patterns developing in the lining. Shear stresses developed in the lining due to mismatch in thermal expansion of the parts of the lining unloaded by the spalling and those still constrained by the contact across the drying crack. With progressive cycles the shear cracks grew parallel to the hot face. Soon they spanned the whole height of the model and caused spalling of a plate (fig 6.c). After this the stress distribution was similar to that of the first phase. Formation of the cracks leading to corner spalling was observed again (fig. 6.d). The corner spalling was followed by the plate spalling and in this way repeated plate spalling was expected.

The proposed spalling mechanism agreed with observations. It was observed that in the ladle the major plate spalling is preceded by the spalling of smaller parts of the lining along the cracks (fig. 4). This initial spalling along the cracks may be the corner spalling observed in the model.

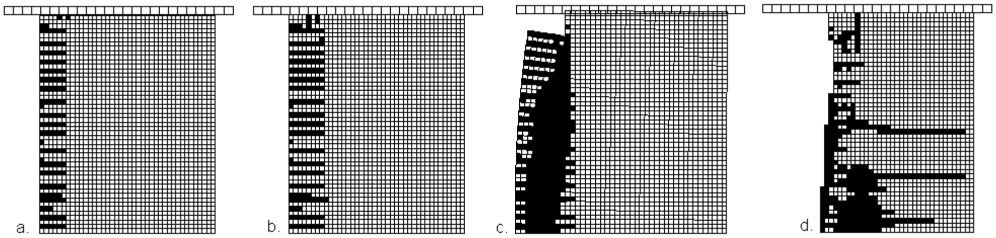
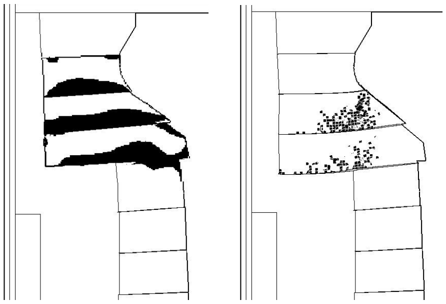


Figure 6: Crack formation in the working lining after a – the first cycle, b – the fourth cycle, c – the end of the fifth filling (displacements are enlarged with factor 15), d – the end of the fifth cycle.

5. CASE 2 - CRACKING AND SPALLING IN AN ALUMINIUM MELTING FURNACE

Case 2 is a channel induction aluminum melting furnace. The structure of the furnace is prismatic with an open top. The furnace is used to melt aluminum scrap. The operation is cyclic – scrap is loaded through the open top, then it is melted and tapped out of the furnace. The melting is realized using induction heating. The tap hole is positioned close to the top edge of the furnace and for tapping the furnace is tilted using trunions. The lining is made of a dense low cement castable (material D, table 1). The bottom of the furnace is cast on site, the walls are made of pre-fabricated blocks. The safety lining is made of insulating castable of low density and insulating board.

The investigation featuring computer modelling was to establish reasons of spalling taking place around the tap hole. Several pre-fabricated blocks lost about 30 % of their thickness in the initial phases of the furnace campaign. Thermal shock was excluded as the mechanism responsible for the failure. The damage started in the few block courses under the tap hole but these were not the only blocks to be exposed to fluctuating temperatures. Thermal shock would have caused much more extensive damage. To analyze structural stresses in the courses a steady state analysis was conducted (fig. 7). The analysis showed that the failure occurred due to the asymmetric constraining in the cracked blocks. Due to the expansion of the lower wall courses the layers of blocks below the tap hole are pushed upwards from below and constrained from the above. The constraining is asymmetric as due to the presence of the tap hole only the cold parts of the courses are constrained, hotter part of the blocks can expand freely. Due to this, bending deformations develop in the block. Tensile stresses in the lower side of the block result from the bending. Cracking patterns predicted by the model agreed well with the observations. Further in the investigation the model was used to develop a new design to prevent the cracking.



a b

Figure 7: Modelling results (a) tensile stress (black areas), (b) cracks (elements which exceeded tensile strength are coloured black).

CONCLUSIONS

The refractory concretes is a diverse class of materials that is used to insulate and protect industrial furnaces. The properties of the concretes are tailored to specific applications by varying the binding systems and the composition of the aggregates. Cracking and spalling of the refractory concretes can occur due to various mechanisms. Every case of spalling has a degree of uniqueness, which results from the variability in design, the variability of applications, complexity of service conditions and the non-linearity of the material behaviour. The combination of computer modelling with fit for purpose material testing is a reliable tool to investigate the spalling mechanisms and develop the ways to improve the lining behaviour.

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