BOF BOTTOM WEAR AROUND TUYERES AND BLOWING ELEMENTS – THERMO-MECHANICAL INVESTIGATION TO OPTIMISE THE LINING PERFORMANCE

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INTRODUCTION

In BOF vessels with bath agitation the bottom wear is often the factor limiting the lining life. The wear is typically concentrated around the gas blowing elements and tuyeres. For the cases when only inert gases are blown through the bottom, the most frequently named causes of the wear are erosion and thermo-mechanical spalling. The erosion has been relatively well investigated but a very limited attention has been given so far to the spalling mechanism. As a result, no straightforward solution for the BOF bottom design and material choice seems to exist on the market.

This study was conducted to obtain a better understanding of the thermo-mechanical wear in MgO-C bricks around blowing elements and tuyeres. Recommendations regarding the most critical material properties and design aspects were to be developed to improve the bottom performance. The analysis was conducted at four levels – practice, laboratory tests, computer FEM modelling and literature survey.

STATE OF THE ART

The majority of investigations into the BOF bottom wear have been devoted to erosion [1-3]. Erosion stresses are caused by the interaction between the gas bubble, liquid metal and the refractories. The intensity of the erosive wear depends predominantly on the diameter of the gas-blowing channel and the flow rate. The wear is expected to decrease with increase of the channel diameter provided that the flow rate is unchanged. There is a correlation between the maximum erosive wear and the gas flow rate, the maximum wear occurs at the rates corresponding with the bubbling-jetting transition point of the gas stream in the bath.

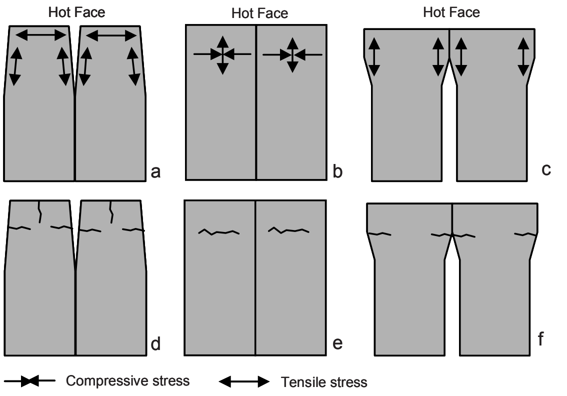


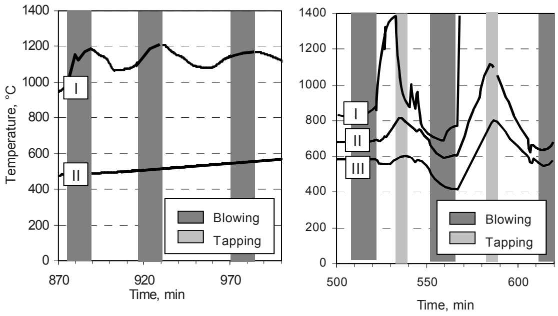
Fig. 1. Spalling mechanisms – (a, d) thermal shock by cooling, (b, e) compressive spalling, (c, f) contact stresses; a-c – directions of stresses, d-f – cracks.

No validated theory explaining the spalling around tuyeres could be found in the literature. A few sources mention the thermal shock as the cause of the cracking (e.g. [2]). The thermal shock is believed to be caused by temperature fluctuations due to the changes in the gas flow. Besides thermal shock spalling in a refractory lining can be caused by contact stresses and compressive failure (figure 1) [4]. The contact stresses are tensile stresses developing at the end of the contact zone between two neighbouring bricks. The compressive spalling is caused by compressive stresses that act parallel to the hot face.

TEMPERATURES IN THE BOTTOM

Lining temperatures were measured by thermocouples (figure 2) and infra red pyrometer. Without the gas blowing (fig. 2.a) the measurements show regular fluctuations of the temperature during the cycle. The temperature starts growing at the beginning of filling. After tapping the lining cools down. The temperatures next to an active bottom-blowing element (fig. 2.b) show a different pattern. During filling and blowing the brick temperature stays at the level reached during the empty time. The temperature starts rising only at the end of the blowing. As in the other measurement, the lining cools down during the tapping and the idle time between the heats.

The temperatures next to the bottom-blowing element follow the pattern of the flow rate. The blown gas is delivered at room temperature. During the blowing the gas will cool down the lining around the gas channel and the cooling effect will be proportional to the flow. rate. The flow rate is rather low during the empty time. Before the filling the flow rate is increased. It stays high during the filling and the oxygen blowing. After the end



a b

Fig. 2 Bottom temperature (a) without bottom gas blowing (thermocouples I and II are 15 and 300 mm from hot face), (b) at an active bottom blowing element (I is 10 mm, II is 35 mm and III is 70 mm from the hot face). "Blowing" – period of time when oxygen blowing was conducted.

of the blowing the rate is reduced. During the periods when the rate is high the lining near the blowing element stays colder than the rest of the lining. The gas blown at the high rate off-sets the heat flow from the bath. Only when the rate is reduced the lining temperature in this part of the bottom begins to rise.

FEM SIMULATIONS

Spalling due to compressive failure

Measured temperature distributions were simulated using FEM models. Material properties defined in the models were determined within the project. The stiffness of MgO-C bricks depends on the temperature; typically, at the beginning of the heat up the material softens, then a reverse trend is observed: above 500-600 °C material becomes very stiff. At even higher temperatures (above 1000 °C) it becomes softer again. A brick treated at higher temperatures (e.g 1400 °C) and cooled down to mid-range temperatures is usually stiffer and stronger than a green sample tested at that temperature.

The model simulates the "cold spot" around a bottom-blowing element during the blowing (figure 3). From the IR images of the bottom emerging from the bath while tapping, the diameter of the "cold spot" around tuyere or a bottom-blowing element was estimated at 200-300 mm. In the model this part of the hot face was kept at the pre-filling level. The rest of the bottom was allowed to heat up simulating the contact with liquid metal. This temperature pattern results in a remarkable stress distribution with compressive stresses developed everywhere in the bottom. These stresses develop due to constrained expansion of the bricks and act parallel to the hot face. In the areas outside the "cold spot" the maximal compressive stresses are seen some distance away from the hot face (fig. 3.b). This is due to the fact that the lining is less stiff at higher temperatures than it is in the range 600-1100 °C. In the "cold spot" the hot face temperatures are in the "stiff" range, as a result, the hot face stresses in this area are higher than in the rest of the bottom.

The compressive strength of the refractories depends on the multi-axial stress state. The stress state on the hot face is such that here the material is less strong than inside of the brick. The combination of this fact and the concentration of the high compressive stresses in the "cold spot" make the bricks around the blowing outlets the most vulnerable to compressive spalling. The analysis shows that the compressive stresses here are high enough to exceed the material strength.

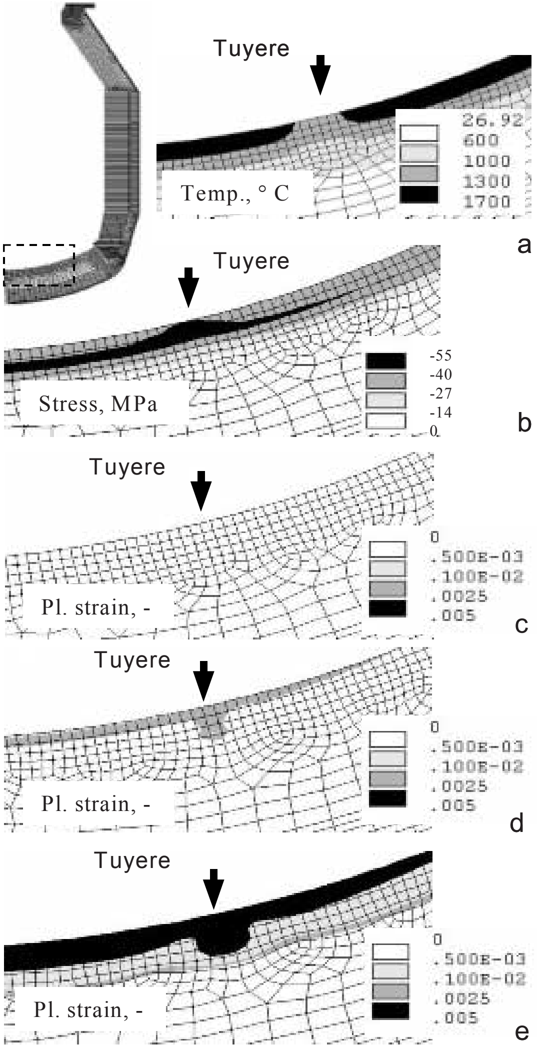


Fig. 3 Modelling results: (a) temperature and (b) radial stresses distribution during blowing - quality C; (c-e) von Mises plastic strains (compressive damage) during blowing, (c) – quality C (d) – quality B (e) – quality A

Validation of compressive failure mechanism

To validate the wear mechanism due to compressive spalling the behaviour of several alternative bricks (table 1, figure 4) was modelled. The comparison of the quality performance was based on a stress/strength ratio (figure 5). This ratio is obtained by relating the radial hot face stress predicted by the model to the material strength at the relevant temperature. The radial stresses act parallel to the hot face of the bottom. The material behaviour is assumed to be linear elastic. The material failure occurs when the ratio is higher or equal to one. At this condition the stress exceeds the strength that results in spalling. If the ratio is in the range 0.7-1.0 the material is close to its failure – micro cracking and other damage takes place. No immediate spalling is expected but the micro cracks weaken the material. The weakened material is considered to be more prone to the erosion.

To support the predictions made with stress/strength ratios, models accounting for compressive failure were used. These models accounted for the dependence of the material strength on the multi-axial stress state (Drucker-Pragger law). The contours (fig. 3.c-e) show plastic compressive strains that develop in the material when stress reaches material strength. In the model the material behaviour is assumed to be perfectly plastic after compressive failure. In practice the areas where compressive failure took place will spall off.

Tab. 1 Properties of the alternative bricks

	A	B	C	D
Green density, kg/m^3	2988	3047	2979	3003
CTE 0-1000°C, 10^{-6} 1/K (red. pre-treated 1600°C)	10.0	11.0	11.0	9.0
Heat cond., W/K/m (red. at 750 °C)	14.0	10.0	10.1	9.7
HMOR, MPa (red. at 1400°C)	4.0	5.9	18.8	16.8

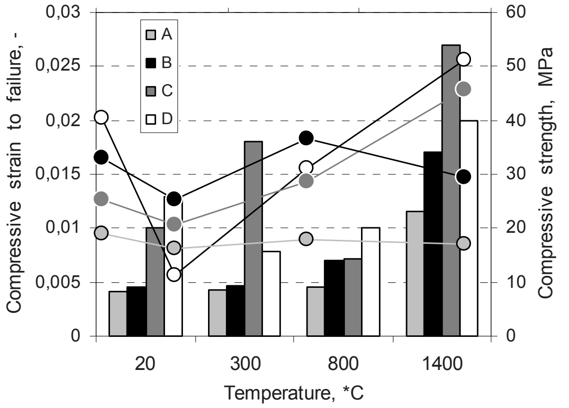


Fig. 4 Compressive stress-strain behaviour of the alternative qualities – strain to failure are bars, strength – lines.

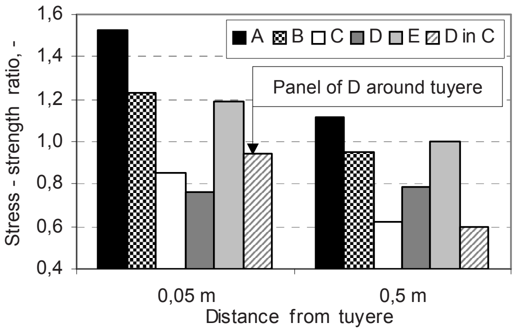


Fig. 5 Stresses in the bottom during the blowing.

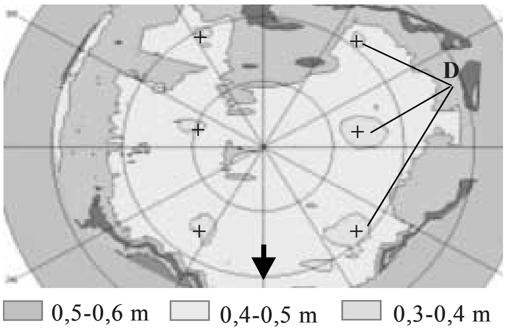


Fig. 6 Laser scan of the bottom wear, the whole bottom is quality C apart from 3 pannels of D, "+" position of the bottom blowing elements, "->" tap hole.

The performance of the bricks C and D was observed in practice (fig. 6). The bottom was lined with C. Around 3 out of the 6 blowing elements, panels of the material D (panel Ø 0.5 m) were installed. The force balance between these materials is such that the material D in the panel surrounded by the material C develops higher compressive stresses than when whole of the bottom is made with this quality. The materials C and D (in the panel) have ratios of 0,82 and 0,94, resp. (figure 3.c, 5). The material D should reach a higher degree of micro-cracking and erosion. Indeed, in practice, the wear profile was that of a crater with the centre at the blowing element. No serious bottom spalling was detected. In agreement with the model, material D wore faster than the quality C.

The stress/strength ratios for qualities A and B are such that the brick B will spall mainly near the gas outlet (figure 3.d), the quality A will spall all over the bottom (figure 3.e). These predictions agree well with the plant experience. The quality A is known to be prone to spalling, often fairly big parts of the bottom were lost. In a combined bottom the wear in quality A was faster than that in B.

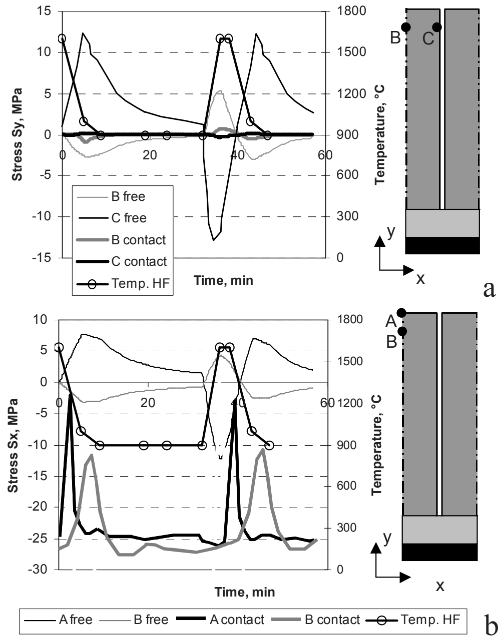


Fig. 7 Stresses in the lining during thermal-shock. “free” – free and unconstrained brick, “contact” – brick constrained by the neighbours. Distance A-B =50 mm. “_._” brick symmetry line.

Thermal shock and the contact stresses

Apart from compression, thermo-mechanical wear can be caused by the thermal shock and the contact stresses. In BOF the bottom wear occurs around the blowing elements during the whole campaign. If the contact stresses are responsible for the wear, then the joints must be opening and closing during the whole compaign. The joints in the bottom are predicted to start closing at a hot face temperature of 200-400 °C, generally these temperatures are reached in the bottom during the heat up. In regular service, apart from really long intervals between the heats, the hot face temperature rarely falls below 600 °C. This means that the joints stay closed during operation and the contact stresses cannot be held responsible for the bottom wear.

If thermal-shock is responsible for the wear then this must happen during gas flow rate fluctuations. Stresses resulting from cooling and heating rates obtained from the thermo-couple measurements were calculated. The model featured joints between the bricks as they can change stress distribution in the lining. To account for the possible visco-elastic effects, the material behaviour during the temperature fluctuations was represented with a stiffness 5 times higher than that used to calculate the heat-up of the material. The model investigated both stresses parallel (figure 7.b) and perpendicular (figure 7.a) to the hot face.

The expansion of the bottom brick is constrained by its neighbours. The predictions for the constrained bottom brick are compared with those for a free and unconstrained brick with the same geometry, and exposed to the same thermal fields. Thermal-shock cracks are caused by tensile stresses; the tensile stresses develop at the hot face and side of the brick during the cooling. During rapid heating tensile stresses are seen inside the brick. For the free brick the magnitude of the stresses is high enough to cause brick failure. The constrained brick is pre-compressed by its neighbours before the thermal shock takes place. Here the stress fluctuations take place in the compressive part of the stress range and catastrophic failure tensile stress values are never reached.

From the thermal-shock models it is seen that the compression of the brick due to the contact with the neighbours prevents tensile cracks to develop. Therefore thermal shock cannot cause the spalling of the bricks around the tuyeres.

CONCLUSIONS AND RECOMMENDATIONS

The numerical analysis supported by practical experience shows that the thermo-mechanical wear around the tuyeres and the bottom blowing elements is caused by compressive failure of the material. Depending on the material properties, this failure can take either the form of micro-cracking or that of spalling. The micro-cracks deteriorate the material integrity and accelerate the erosion of the bricks.

To prevent wear, the factors need to be addressed are the bottom structure, bottom blowing process and material properties. The changes in the bottom structure may involve the use of different qualities around bottom blowing elements and in the rest of the bottom. The other design modification can be the use of expansion allowances in the bottom to reduce the compressive stresses. Changes to the blowing process should reduce the cooling effect of the blown gas and optimise erosion relevant factors (flow rate, channel size, etc.). Regarding the material properties the most important parameters seem to be the material flexibility and strength. High flexibility allows a material to resist the spalling. The strength is a well known indicator of erosion resistance.

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