CONVENTIONAL REFRACTORY LINING FOR NON-OXIDISING FURNACE OF THE GALVANIZING LINE - THERMO-MECHANICAL COMPUTER ANALYSIS TO FIND AN ALTERNATIVE FOR CERAMIC FIBRE.

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INTRODUCTION

Selection of a suitable lining for a heating furnace is restricted by several parameters like process conditions, health and safety regulations, requested availability, cost, etc.. The non-oxidising furnace (NOF) of a galvanising line, in general, is lined with insulation bricks or with ceramic fibre. Within Corus IJmuiden only bio soluble ceramic fibres are allowed. As bio soluble fibres for temperatures above 1260°C are not available on the market, the lining of the non-oxidising furnace, until 2006, consisted of insulating bricks.

This lining, however, has two main disadvantages; it has a relatively short life and therefore a negative effect on the availability and the lining is under suspicion of contributing from time to time to soiling of the steel strip. A project was set up to find a conventional refractory lining for the non-oxidising furnace of the galvanising line with an increased life time and with no negative effects on the steel strip.

REQUIREMENTS

The non-oxidising furnace of the galvanising line operates under normal conditions at temperatures between 1200°C and 1350°C. In case of an unexpected production stop nitrogen is injected into the furnace to cool the furnace as quickly as possible. This is done to protect the strip from overheating and breakage. In that case cooling rates of more than 50°C/min are not unusual (an example of such a short cooling cycle is shown in figure 1). Beside this extreme temperature regime, the other main requirements for the new NOF lining are: long life (no intermediate repairs during three years), no negative influence from the lining on the quality of the steel strip, comparable heating and cooling curves as for the original lining with insulation bricks. Because of the limited time between the study and the relining of the NOF only “standard” materials available on the market could be considered.

Based on the fact that the lining is not exposed to erosion and mechanical damage and given the above thermal regime it is assumed that thermal related stresses are the main cause of lining failure. In general the parameters from the Hasselman’s equations are used in such cases to select the optimal materials for a lining with high thermal stresses. Materials with high strength, high flexibility, high thermal conductivity and/or low expansion are preferred. However, the problem with this approach is that it only compares the thermal shock resistance of different materials at some specific temperatures and that it is still unclear at which temperature the highest stresses really occur. It also doesn’t take into account the design aspects of the furnace like the effect of expansion allowances and mortars. Therefore generally this method is too simplistic, because it doesn’t explain the shape of the cracks within the lining nor does it give sufficient information to select a lining design without partly using the trail & error method. An alternative method to overcome these problems is thermal mechanical finite element computer modelling (FEM). FEM has been used to analyse the problem the NOF section of the galvanising line. FEM has helped to identify properties which can help select a suitable alternative material and design. It is also used to give useful information about cooling and heating curves for the furnace.

ANALYSIS OF THE EXISTING LINING

The existing lining in the NOF section of the galvanising line in IJmuiden is based on lightweight insulation bricks. After use, the lining is typically cracked on the hot face (figure 3a). Apart from these larger cracks, small cracks within the brick can be observed (figure 4). The crumbling of the degraded insulation bricks may cause material to fall onto the floor and/or stick on the strip and thus soil the steel strip. A 3-D FEM model of half a wall section has been used to analyse the effect of expansion allowance and variation in material characteristics (figure 2a). A smaller, more detailed model has been used to predict stresses in the brick and the effect of the mortar joint (figure 2b). The models have been validated with thermocouple measurements inside the furnace, thermocouple measurements inside the lining and infrared measurements of the furnace shell.

Using the FEM model, it was found that maximum stresses develop in the lining due to rapid cooling of the hot face during production stops. Stress calculations have been made for the short-term cooling cycle and are discussed in this paper. The results are given in table 1 (column: Insulation brick class 28)). A stress/strength ratio can be calculated. This ratio is obtained by relating the highest calculated stress predicted by the model to the material strength. Based on the strength of the brick of 1 N/mm^2 and a maximum calculated stress of 0.9 N/mm^2 this gives a ratio of 0.9, which would mean theoretically this lining should have just sufficient strength to resist the thermal cycles. However the problem with "standard" FEM modelling is the fact that the properties of the materials are assumed the same for all the bricks within the lining. It is generally known, that within the production of refractories a lot of variables have an effect on the quality of each individual brick or several bricks, like small variations in raw material distribution (caused by weighing in, mixing, filling of the mould), variations in press pressure and in baking temperature (temperature differences in the furnace). If this is taken into account it means there is a variation in characteristics of the bricks in the lining. This is modelled by varying randomly, within the spread in material properties, the Young's modulus of the bricks in the lining, resulting in the damage distribution as is shown in figure 3b. The typical vertical cracks in the model are a good representation of the cracks found in the real furnace (figure 3a). To avoid this kind of cracks the strength of the bricks has to be significantly higher than the stresses occurring in the process. Other typical cracks that can be found in the furnace seem to be generated by the mortar joints (figure 4a). In figure 4b the results of the detailed model are shown. From the stress distribution it can be seen that the stresses are concentrated near the vertical mortar joint. The used mortar is much stiffer than the insulation bricks. Therefore the vertical mortar joint acts like a stress concentrator. Areas of tensile and shear stresses develop at the joint.

ALTERNATIVE SOLUTIONS

Optimisation of the lining can be done by adjusting the quality or the design. Because of the limited time available before the next relining of the NOF furnace, three materials were selected out of three main material groups with short delivery times and/or availability within Corus. The first material is a clay-bonded bauxite based ramming mix which has been used in this kind of installation in the past with relatively acceptable success (longer life compared to the insulation bricks). The second material is a fired andalusite brick, which is known for its thermal cycling properties based on the usage in steel ladles, hot metal ladles and in heating furnaces. The third material is a low cement mullite based castable, which is being applied for applications with a lot of thermal cycles. A selection of the characteristics of the 3 materials is given in table 2.

The results of the FEM modelling with the 3 alternative materials are given in table 1. While the stresses for the insulation brick lining are much lower than for the other solutions, the much lower strength results in still a high stress/strength ratio. The stress/strength ratios for the ramming material and the andalusite brick are lower than for the insulation brick. The lower ratio for the ramming mix is in line with the fact that in the past this material was used successfully (life) in the hot face lining of the NOF. In case of the ramming material, the higher stresses are compensated by much a higher strength and therefore in a lower stress/strength ratio. The combination of characteristics of the fired andalusite bricks, i.e. low thermal expansion, high strength, relatively good flexibility and higher conductivity, results in low stress/strength ratio. The higher stress/strength ratio for the low cement mullite based castable can be explained by the higher thermal expansion and lower flexibility compared to the andalusite brick. Based on the above results it is recommended to go for a fired andalusite based lining to reduce the crack generation in the lining. The fact that only three materials have been considered may imply that further optimisation could be possible. Using the FEM model it will be relative easy to select better alternative materials.

A second possibility to minimise stresses in the lining is to alter the design in such a way that less stress will develop. One option is to reduce the width of the bricks. In the existing lining the width is 305 mm (with a lining thickness of the hot face of 305 mm, and a height of the brick of 76 mm).

Using the detailed model for a single fired andalusite brick, the stresses in the lining have been modelled for different widths of the bricks. The results are given in table 3. Changing the width of the brick has significant effect on the stress/strength ratio, because of the lower stresses generated in the lining. The stress/strength result of the fired andalusite with a width of 115 mm is only 3% (!) of the stress/strength ratio of the original insulating brick lining with a width of 305 mm.

EFFECT ON COOLING AND HEATING

Using a dense brick in the hot face of the lining instead of an insulation brick will have an effect on the heating and cooling cycles of the furnace. Therefore three situations have been analysed; heating up of the lining, cooling down to 800°C and cooling down to 50°C.

To have an as low as possible downtime, the heating up of the furnace should be fast. The heating up rate is mainly limited by avoiding thermal cracks. For heating rates between 200°C/h and 600°C/h the model predicts stress/strength ratios for fired andalusite bricks lower than for insulating bricks.

The cooling time between 1300°C to 800°C is important in case of strip breakage outside the NOF section. The hot face has to be cooled as quickly as possible. This takes for the andalusite lining twice as much time as for the lining based on class 28 insulation bricks (figure 5).

In case a person has to enter the NOF section, the furnace lining has to be cooled down to 50°C over the

whole thickness of the lining (figure 5). This is reached quicker for the fired andalusite lining (72 hours), because of the higher conductivity, than for the insulating bricked lining (86 hours).
Further optimisation should be possible if more materials than the selected three are taken into consideration.

CONCLUSIONS

Thermo-mechanical finite element computer modelling is an efficient tool to optimise a furnace lining. One can avoid cracking of the lining and improve the heating and cooling cycles.
Insulation bricks are sensitive to thermal cracking because of the low strength and low thermal conductivity. A fired andalusite brick is an excellent alternative material to increase lining life, however the higher density (higher heat capacity) has a negative effect on the cooling time for the hot face from 1300°C to 800°C. A complete cooling down as well as the heating up is better for the fired andalusite based lining.
Considering the fact that only three materials have been considered, further optimisation of the lining is still possible to optimise the balance between stress/strength ratios and cooling/heating requirements. Also different lining concepts (thinner hot face layer) could be considered to optimise the heating and the cooling of the furnace even further.

Tab. 1: Effect of the variation in material (-properties) on the stresses in the lining of the NOF

Hot face material	Insulation brick class 28	Clay bonded ramming mix	Castable	Andalusite brick
Maximum calculated stress [MPa]	1,0	3,1	24,5	5,7
Temp. at time and point of max. stress [°C]	783	811	1042	867
Strength at max. stress temperature [MPa]	1,1	5	23	22
Stress/strength ratio [-]	0,9	0,6	>1	0,3

Tab. 2: Material properties of selected materials for the hot face of the NOF zone.

	Class 28 insulation brick	Clay bonded bauxite ramming mix	Fired andalusite based brick	Mullite based low cement Castable
Bending strength (N/mm^2)				
20°C	1,2	2,2	17,7	16
800°C	1,0	5,3	22,4	21
1200°C	1,2	4,5	12,2	21
V-modus (GPa)				
20°C	1,03	1,65	15,8	14,9
800°C	0,67	3,67	6,8	22,85
1200°C	0,14	0,2	2	5,4
Thermal expansion (1/K e^{-6})	7,6	5,8	5,7	7,1
Heat conductivity (W/mK)				
250°C	0,38	1,67	2,59	2,41
750°C	0,42	1,36	2,45	2,10
1250°C	0,52	1,55	2,45	2,35

Tab. 3: Effect of the width of the fired andalusite brick on the stresses in the lining of the NOF

Hot face material	Fired andalusite brick			
Short cycle, width of the brick	305	230	150	115
Maximum calculated stress [MPa]	5,7	1,7	1,0	0,8
Maximum stress temperature [°C]	867	1020	944	1059
Strength at max. stress temperature [MPa]	22	22	22	22
Stress/strength ratio [-]	0,3	0,08	0,05	0,03

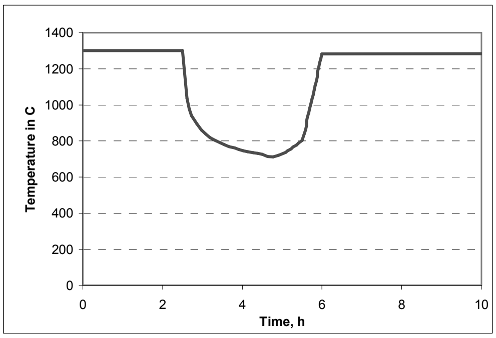


Fig 1: Short cooling cycle in case of strip breakage.

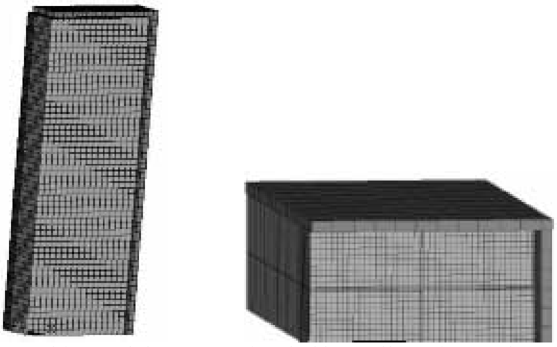
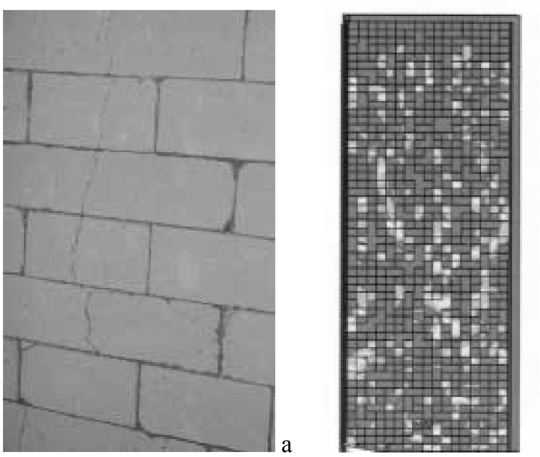


Fig 2: a) big model representing half a wall section and expansion allowances, b) small model representing 3 bricks with mortar joint and expansion allowance.



a b

Fig. 3: Damage predicted by the model (b) and observed during autopsy (a). In (b) the damage is presented in form of plastic strain distribution – elements with colours other than dark gray are cracked, dark gray elements have no damage.

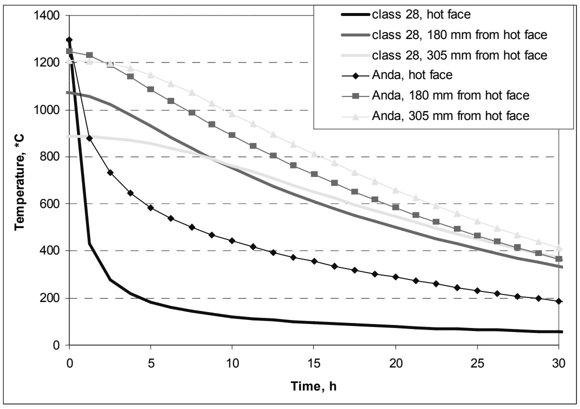


Fig. 5: Cooling curves for linings based on class 28 insulation bricks and on fired andalusite bricks.

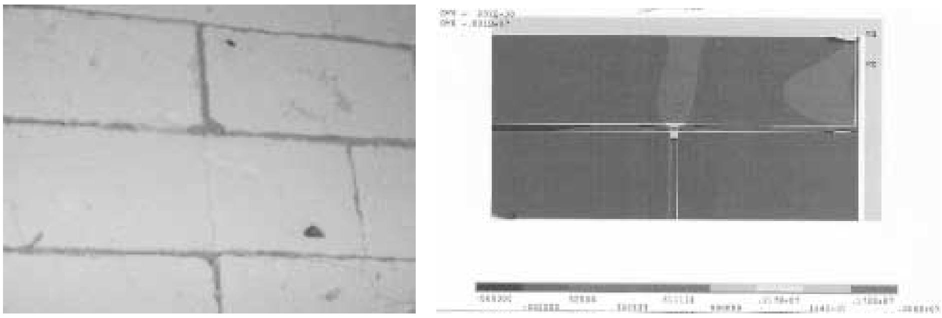


Fig. 4: Typical cracks on the hot face of the brick in the length of the mortar joint.