Effects of dry joints on compressive behaviour of refractory linings

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Abstract

To support optimisation of refractory masonry structures compressibility of dry joints of magnesia-carbon and magnesia-chromite bricks have been investigated. Laboratory scale tests, field measurements and finite element modelling have been performed. Measurements done in wide temperature range have shown that the exponential form of the joint closure curve results from gradual closure of initially non parallel surfaces. The stress needed to close the joint was found to be proportional to the material stiffness. Temperature influences the joint closure by changing the stiffness of material and by reducing the initial joint gap due to thermal dilatation.

1. Introduction

Dry joints are an important factor in thermo-mechanical behaviour of refractory linings[1]. Although it is known that under compression the stiffness of the refractory lining will decrease with increasing amount of joints[2,3]. Little has been reported on the effects of the material behaviour and the brick geometry in the process of dry joint closure.

This paper presents results of an in-depth analysis of the process of dry joint closure. The investigation was conducted in three parts. Firstly, the joint condition in the newly relined BOF converters and RH-degassers was measured. Secondly, compressive joint closure tests in wide temperature range were performed in the laboratory. Magnesia carbon (MaC) and magnesia-chromite (MCh) bricks were investigated. Also, the planarity of the brick surfaces was measured. In the third part the role of individual factors in the process of joint closure was analysed using thermo-mechanical FEM analysis. The results of the investigation were to be used in computer models of refractory linings.

2. Joints in installations.

Joints in newly relined installations were measured using a joint filler (**fig. 1**). The device consists of several plates of different thickness. The joint thickness is determined by inserting the plates into the joint. Several snorkels and two new converters were measured. Mainly hot face joints were assessed. In the converter wall and in top courses of snorkel vertical joints were assessed along the whole joint length. The converter bottom seems to be very tight (**table 1**). The bottom has curved form and the gravity helps pressing the bricks to each other. In the wall significant variation, both in width and shape of the joints, was observed. In the converter the vertical joints were thicker than horizontal joints. In the snorkels joints were almost similar in both directions. The off-set structure of the horizontal joint and resulting friction is held responsible for increasing the thickness of the horizontal snorkel joints. Shapes of vertical wall joints (**fig. 2**) can be classified into three types. The first type is joint opening due to non plan-parallelism of the brick faces forming the joint (joints 1-1, 2-2, 3-3, 4-4 in **fig. 2**). The brick distortions responsible for non parallelism can take e.g. forms of banana or parallelograms. The second type (6-6 **fig. 2**) is formed by the bricks not put tightly together, either by mistake or due to distortions of the shell. The third type is formed by parallel surfaces with small scale surface roughness (5-5 **fig. 2**). The joints of the first type seem to be most frequent. The brick distortions responsible for

Table 1 Initial joint thickness [mm]

	Vertical joint	Horizontal joint
BOF wall	0.3+/-0.15	0.15+/-0.1
BOF bottom	<0.1	<0.1
Snorkel	0.22+/-0.18	0.26+/-0.15

Table 2 Dimensional tolerances [mm] (shown as +/-d from respective dimension)

	MaC			MCh		
	L	W	H	L	W	H
Supplier A	1	1	0.5	2	1	1.5
Supplier B	NA	NA	NA	3.5	NA	0.5

L-length, H-height, W-width (taper)

Fig. 1 Joint filler in a joint of RH-degasser snorkel.

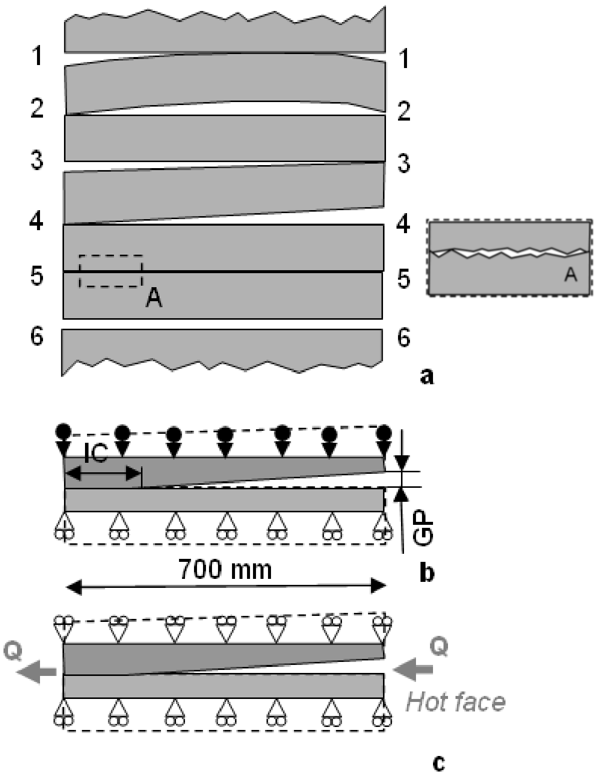

Fig. 2 Possible joint types (a) and FEM model of the joint 4-4 (b, c). The models simulate (b) external displacement loads, (c) own thermal loads.

the joint opening of a fraction of mm can easily be accommodated in the tolerances of several mm accepted by the brick suppliers (**table 2**).

3. Laboratory tests

The process of joint closure was measured indirectly by compressing samples with and without joints and by direct optical measurements (Digital Correlation Image, DIC). In samples the joint faces were formed by the original brick surfaces orthogonal to the direction of the brick pressing. The sample surfaces that contact the pistons of the testing machine were plan-parallel polished. The length of the tested joints varied between 50 and 120 mm. Direct optical measurements were performed only at room temperature. The detailed description of the testing procedure and results are given in [4].

Commercially available resin bonded MaC quality with anti-oxidants was tested. **Fig. 3** shows a comparison of the joint closure obtained by direct and indirect methods. Note that for the direct method the results showed were obtained by making the average of the local measurements over the entire length of the joint. The two methods show a good result correlation. Due to roughness, shape variation and non parallelism of faces, the joint thickness is not constant. The joint closure curve has an exponential form. In the beginning intensive joint displacements develop at relatively low stresses. The joint compacts and the contacting faces must be gradually approaching each other. With progressive loading, reaction to the compaction increases. At a certain stress level the joint appears to be closed completely as the closure curve aligns itself parallel to the compressive stress axis. At room temperature the full closure is expected to happen at joint compaction of approximately 0.3 mm (**fig. 4**). This happens under stresses that are approximately 70-80 % of the brick strength.

Temperature seems to have strong influence on the joint closure (**fig. 4**). The heating-up increases the resistance to joint closure and reduces the full closure displacement. Thermal expansion is the most probable explanation of the latter effect. Thermal displacement corresponding to a specimen height of 100 mm represents approximately 1 mm per 1000 °C of temperature growth. Even temperature increase of 300 °C is enough to produce thermal displacement equal to the full joint closure displacement measured at room temperature.

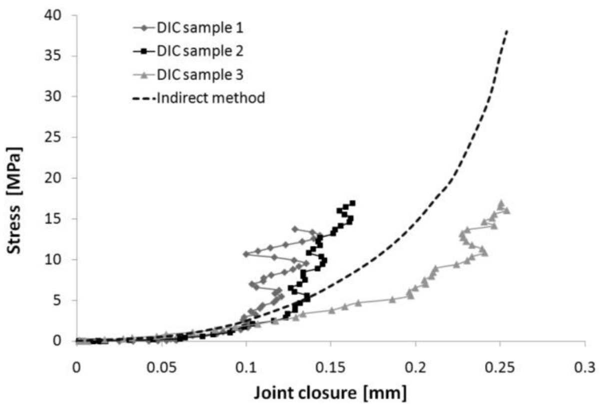

Fig. 3 Comparison of joint closure for the indirect and direct methods at room temperature (MaC, three samples for DIC method, average curve for indirect method).

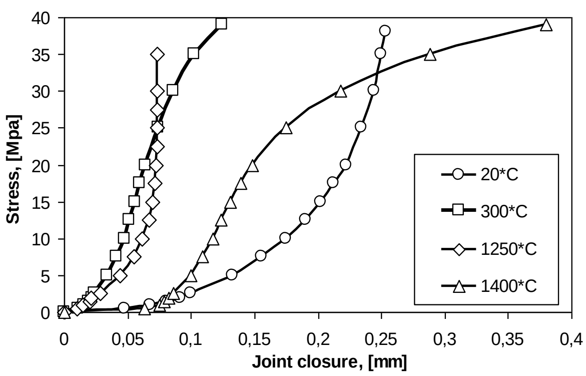

Fig. 4 Joint closure curves of MaC.

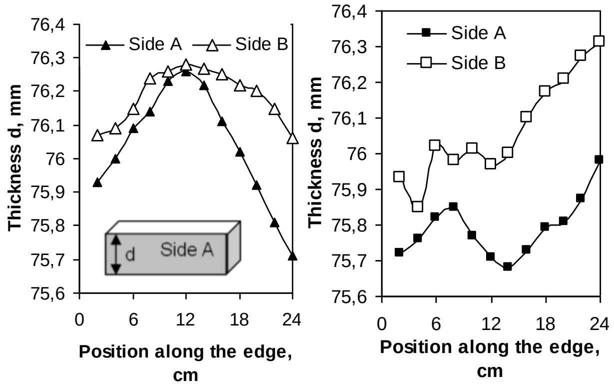

Fig. 5 Typical brick thickness variation for two magnesia-chromite bricks. Sides A and B are opposite each other.

Of course not all of the sample thermal growth is directed into the joint, but even a part of it is able to significantly reduce the joint closure displacements. Another important factor is the variation of material stiffness with temperature. Also the "softening" that is seen in some exponential curves at higher compressive stresses is explained by high temperature material softening and resulting local plastic strain [4].

The joint closure displacement of several decimals of mm determined in the lab tests agrees well with measurements of brick thickness (**fig. 5**). Brick thickness variation along the brick length can take different shapes, which will result in non parallelism of joint surfaces. E.g. one end of the brick can be thicker than the other (**fig. 5.a**), the middle section is thicker than the edges (**fig. 5.b**). Over the length of 50 mm the brick thickness can easily vary some 0.2-0.3 mm.

4. FEM analysis

Computer FEM analysis was used to investigate influence of individual factors on the process of joint closure. In the refractory structure the joint closure can happen either under external loads or due to own thermal expansion of the bricks. The external forces can be the result of either the expansion of neighbouring parts or the mechanical forces, such as gravity of lining, bath pressure etc. Depending on the loading the joint closure can either take place along the whole joint length (**fig. 2.b**) or locally, when only a part of the joint is closed. The latter is expected to be a predominant mechanism during the thermal loading (**fig. 2.c**). Laboratory tests of joint closure involved both the external loads and the temperature effects. In FEM modelling the two effects were investigated separately.

The joint closure under external forces was simulated using the geometry of a converter brick **fig. 2.b**. The varied geometry factors were the initial contact area (IC) and the maximal joint gap (GP). The geometry of the joint was also quantified by the value of the average joint thickness (AJ). The variation of the geometric parameters was within limits obtained from the laboratory and the field measurements. Linear elastic brick behaviour was assumed. Young's modulus of the material determines the stress when the joint is closed (**fig. 6.a**). The higher is the material stiffness the higher is the stress needed to close the joint. The final joint closure displacement did not depend on the material

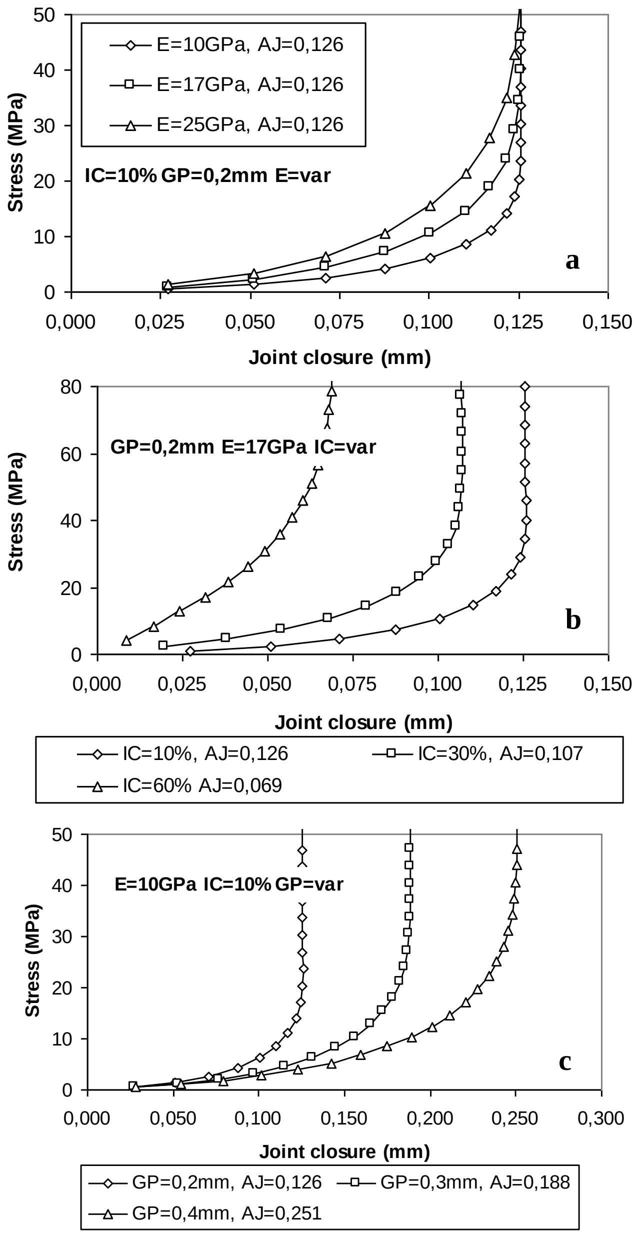

Fig. 6 Joint closure curves calculated by the model of fig. 2b. The effects of brick stiffness (a), initial contact area between the bricks (b), initial contact gap (c).

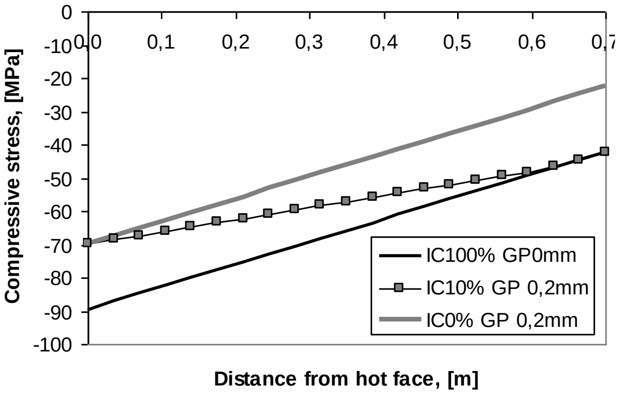

Fig. 7 Stress perpendicular to the joint surface in the model of fig. 2.c. Hot face temperature is 850 °C.

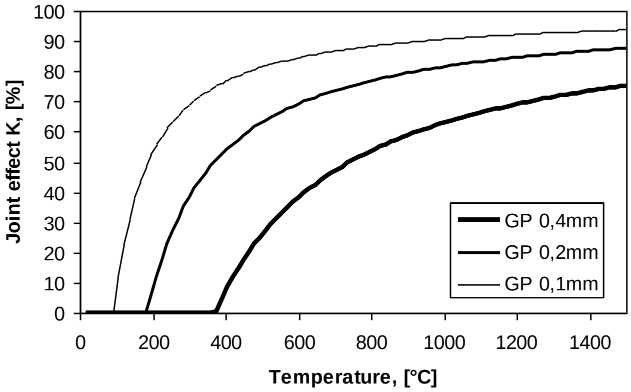

Fig. 8 Reduction of the stress due to joint closure (IC=10%). Stress near the hot face is presented.

stiffness. With constant joint gap, increasing the initial contact area increases the joint stiffness, that is joint closure occurred at higher stresses (**fig. 6.b**). Bigger joint gaps had higher values of the joint closure displacement (**fig. 6.c**). In all cases the final joint closure displacement was found to be equal to the average joint thickness (AJ).

Model with stationary thermal gradients simulated the thermal joint closure (**fig. 2.c**). Linear elastic material behaviour with E=10 GPa, CTE=10^{-6} 1/K and the conductivity of 10 W/m/K was simulated. The cold end heat transfer accounted for the thermal effects of the back-up converter lining. The stress reduction due to the presence of the joint intensifies with increase of gap (GP) and the reduction of the area of initial contact (IC) – **fig. 7, 8**. Depending on the temperature the presence of the joint of 0.2 mm between 100 mm thick bricks the stresses can be reduced by some 50 % (**fig. 8**). The joint effect K is calculated as a ratio between the stresses in the model with the joint of given geometry and the stress predicted to develop in the model with the perfect joint (IC=100%, GP=0mm). The analysed 2D models do not account for non parallelism of joint face perpendicular to the plane of the model. Due to this 3D effect the exponential nature of the joint closure is expected for the local thermal joint closure, as in the proven case of the joint closure due to external loads.

5. Conclusions

With focus on magnesia-carbon and magnesia-chromite bricks, the process of compressive closure of dry joints has been investigated. Measurements in newly re-lined installations, laboratory tests and FEM modelling have been performed. It has been shown that the presence of joints can reduce the stresses in the lining by up to 50%. The joint gap responsible for the stress reduction is mainly determined by non parallelism of the contacting brick surfaces. In most cases the gap of some 0.1-0.3 mm can be expected. The compressive joint gap closure is characterized by the exponential curve. The stress needed to close the joint is founded to be proportional to the material stiffness. In many cases the complete joint closure takes place at some 80% of the brick uni-axial compressive strength. Temperature influences the joint closure in two ways. Firstly, the temperature influences material stiffness. Secondly, thermal expansion seems to be responsible for lower joint closure displacements detected when high and room temperature test results were compared. The analysis of the study will be used in computer models of refractory linings.

Acknowledgements

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