The Evaluation of Refractory Linings Thermo-Mechanical Properties

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Abstract

The increasing requirement for high performance furnaces in the metal industries has resulted in the increased use of partially water cooled furnaces that require complex furnace linings. However, with an increasing furnace lining complexity the refractory material expansion becomes a determining factor. The expansion defaults must be calculated to achieve a minimal expansion of the surrounding furnace steel shell whilst in parallel ensuring a leak-proof furnace bottom lining. Foremost, the cooling sections in the side wall or bottom furnace area must be protected against deformation due to an above average refractory expansion. The problems that can arise due to cooling section damage are well established and mainly occur in cooling sections that have their cooling circuit inside the furnace (e.g., refractory deformation can result in cooling water leaking into the furnace). To enable future optimal furnace lining designs that address the technical requirements, a test plant was established at the RHI Refractories Technology Center Leoben, Austria. This work was performed in collaboration with the Christian Doppler Laboratory for Secondary Metallurgy of the Non Ferrous Metals, University of Leoben, Austria. The test plant has been operational since November 2004 and should provide important information for lining concept designs.

1 Introduction

During refractory lining design it has been shown that the load carrying capacity of effective in service constructions do not equate with the results of conventional computing methods. Typically, the static calculations predict larger demands than actually occur in practice.

This is principally due to the complex behaviour of the different materials used in the total furnace construction. Therefore, refractory lining design still remains a civil engineering concern and extensive static proofs are rarely provided. The construction of a furnace lining concept cannot be performed without in service experiences and because the material behavioural characteristics are very difficult to calculate, the theoretical and in service results must be analysed in parallel. Furthermore, to perform static refractory design analysis the following issues must be taken into consideration:

- The walls consist of several layers and each layer must fulfil different requirements including refractoriness, thermal insulation, chemical resistance, and load-carrying capacity.
- The materials are exposed to stresses and strains, primarily multi-axial.
- Thermal shock occurs due to the process conditions.
- The temperatures are high (over 1250 °C).
- There are fluctuating temperatures due to rapid vessel heating.
- The lining is often provided with a system of expansion joints to minimize large deformations due to the temperature load.
- The refractory materials do not deform in a linear manner under large compression stresses.

The rate of temperature change is one reason the refractory lining is stressed and the greater the rate of temperature change the higher the resulting stresses. Furthermore, the fluctuating temperature conditions subject the refractory to higher tensions than the stationary temperature conditions that occur some hours after the heating up phase. Therefore, the heat-up rate must be selected such that during the heating process the compression stresses at the hot side do not cause spalling and that the tensile stresses at the refractory cold side do not result in excessive cracking. Therefore, for each refractory design - depending on the materials used - one maximal heat up velocity is specified for each temperature range [1].

This article focuses on the thermo-mechanical behaviour of magnesia chromite bricks, principally the prereacted MCr 60/40 brick type used in non ferrous industry reactors. However, whilst the operating temperatures in the non ferrous industries are relatively low the operational demands on the refractory lining are mainly high.

These demands on the lining are primarily chemical effects (e.g., reactions between the brick and the melt, slag, and gas) and thermo-mechanical issues (e.g., temperature changes, brick expansion, and brickwork tensions). In the first section of this paper an overview of the analysis of a prereacted MCr 60/40 test piece (50 mm in diameter and 50 mm in height) using standardized methods to determine the refractory characteristics of this brick are described, whilst the second section focuses on the brick's performance in the context of a lining concept. To simulate the brick's behaviour in a lining, a biaxial hot testing press was developed at the RHI Refractories Technology Center Leoben.

2 Overview

2.1 Magnesia-chromite bricks

Sintered magnesia, natural chrome ore, and sintered or fused magnesia chromite-co-clinker are the base materials for magnesia chromite brick production. The in service brick characteristics are hot erosion resistance (due to the brick's corrosion behaviour, hot strengths, and porosity) as well as the absorption of stresses that are caused by the fluctuating temperature conditions. Magnesia chromite bricks are very resistant against corrosion of different basicities. For certain applications, to protect the bricks from hydration (causing the brick to crack and collapse) and foreign matter infiltrations they are after-soaked in a magnesium sulphate solution.

Magnesia chromite bricks are used when magnesia bricks are not appropriate due to the thermal shock stresses and when magnesia carbon and carbon containing magnesia bricks are not suitable because of carbon burn out or the effects of low basicity slag. The principal application area for magnesia chromite bricks is in non ferrous industry reactors (e.g., PS converters, flash furnaces, anode furnaces, and holding furnaces). Furthermore, they are also employed in the iron and steel industry (e.g., AOD converter, ladles, and electric arc furnaces), and in the cement and refractory industries. However, a disadvantage of these bricks is that under certain conditions hexavalent chrome can form, which is an environmental pollutant. At high oxygen partial pressure and temperatures greater than 1000 °C chrome oxidation can occur to form hexavalent chrome; furthermore, in the presence of alkali oxide and occasionally CaO, the CrO_3 reacts to form K_2CrO_4. However, whilst these conditions do not prevail to any great extent in metallurgical reactors, they can occur in cement, lime, and glass industry furnaces.

The chemical analyses of fired magnesia chromite, chromite, and picrochromite bricks are listed in Table 1 [2, 3]. Further details relating to these refractory materials are available in the literature.

Product group	MgO	Cr_2O_3	Al_2O_3	Fe_2O_3	CaO	SiO_2
	[wt.%]					
MCr 85/15	70-82	4-11	3-8	4-11	0.5-3	0.2-4
MCr 60/40	48-70	12-23	4-15	5-16	0.4-3	0.3-5
e.g. silicate-bonded	48-70	12-22	5-15	5-14	0.4-3	2-5
direct-bonded	50-68	14-23	4-13	5-16	0.5-2	0.3-2.5
prereacted	58-62	18-20	5-7	10-14	1.1-1.8	0.4-0.7
MCr 35/60	30-50	20-36	8-23	8-16	0.5-1	1.7-6
chromite	15-32	25-50	10-28	9-20	0.3-1.5	2-6
picrochromite	17-20	78-82	0.2-0.5	0.4-0.7	0.2-0.6	0.1-0.3

Table 1: Chemical analysis of fired magnesia chromite, chromite, and picrochromite brick types

Comparative analysis indicated that the prereacted MCr 60/40 brick (MgO 60%, Cr_2O_3 19%, Fe_2O_3 13.5%, Al_2O_3 6%, CaO 1.3%, and SiO_2 0.5%) is a high-burned magnesia chromite brick, a brick type characterized by an extremely low SiO_2-content, a low porosity, a very high thermo-shock resistance, and an improved slag resistance.

2.2 Thermo-Mechanical Properties

2.2.1 Refractories under Load

The refractories under load test determines the refractory material´s softening behaviour at increasing temperatures under a constant load. The softening behaviour is affected by the refractory test material weight, the crystal distribution in the structure, the crystal morphology, the quantity and apparent viscosity of the melting phases that form, as well as the porosity. The analysis was performed with a test piece 50 mm in diameter and 50 mm in height. Figure 1 illustrates the test results for the prereacted MCr 60/40.

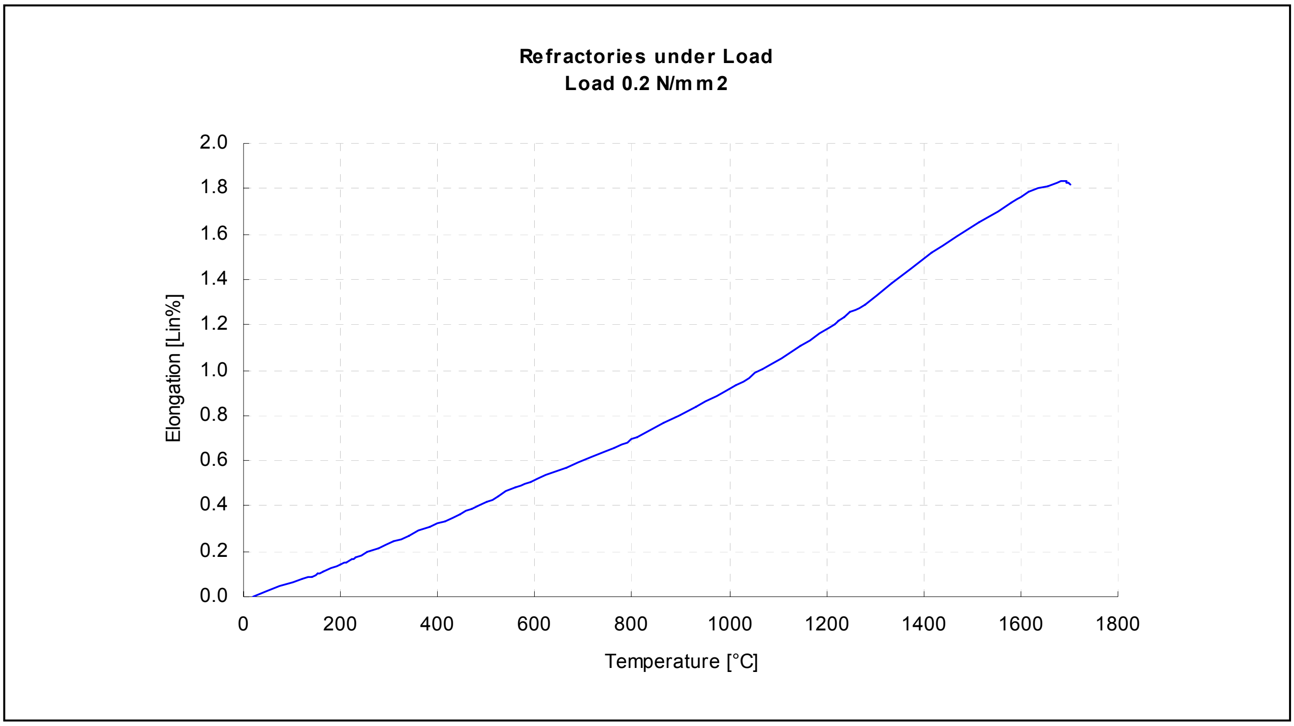

Figure 1: Refractories under load curve for the prereacted MCr 60/40

2.2.2 Thermal Expansion under Load

The time-dependent deformation at a constant temperature and load can be determined by the thermal expansion under load test. This analysis is performed over a long time period, typically 25 hours. Figure 2 illustrates the results of this analysis for the prereacted MCr 60/40.

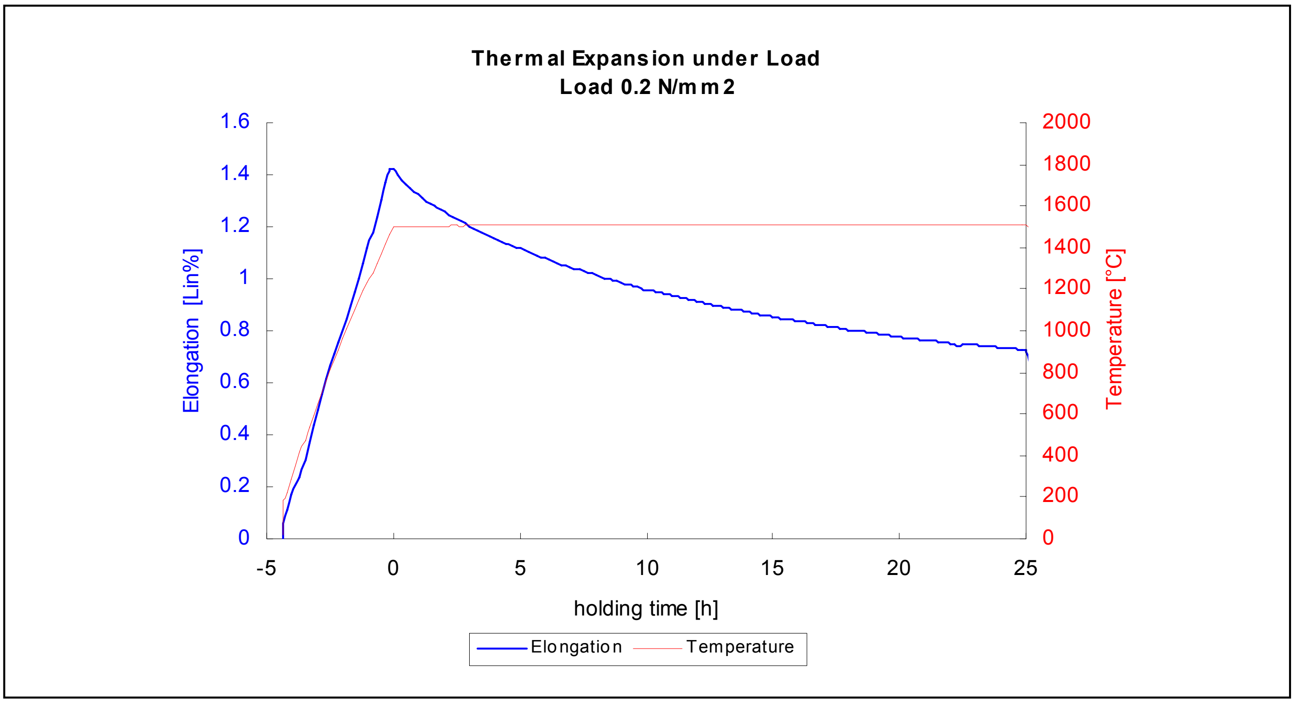

Figure 2: Creep curve for the prereacted MCr 60/40

2.2.3 Deformation-steered Hot Crushing Strength

In contrast to the strength-regulated hot crushing strength test, the deformation-regulated hot crushing strength test enables the maximum possible load, which results from a constantly applied increasing deformation, to be determined for a test sample. With the aid of this test method, the different mechanical in service loads that affect the refractory lining can be simulated. During the heating process tensions develop in a clamped brickwork due to refractory thermal expansion and this results in brick structure damage due to the lack of brick pyro-plasticity [4]. Young´s modulus is the relationship between tension and the reversible deformation. It can be determined from the upward curve gradient and is required for the wedge splitting test (Section 2.2.4). Typically, refractory materials only operate over a very small range of deformabilities and at temperatures where the melting phase results in flexibly; therefore, stress-displacement curves are employed to determine the breaking behaviour.

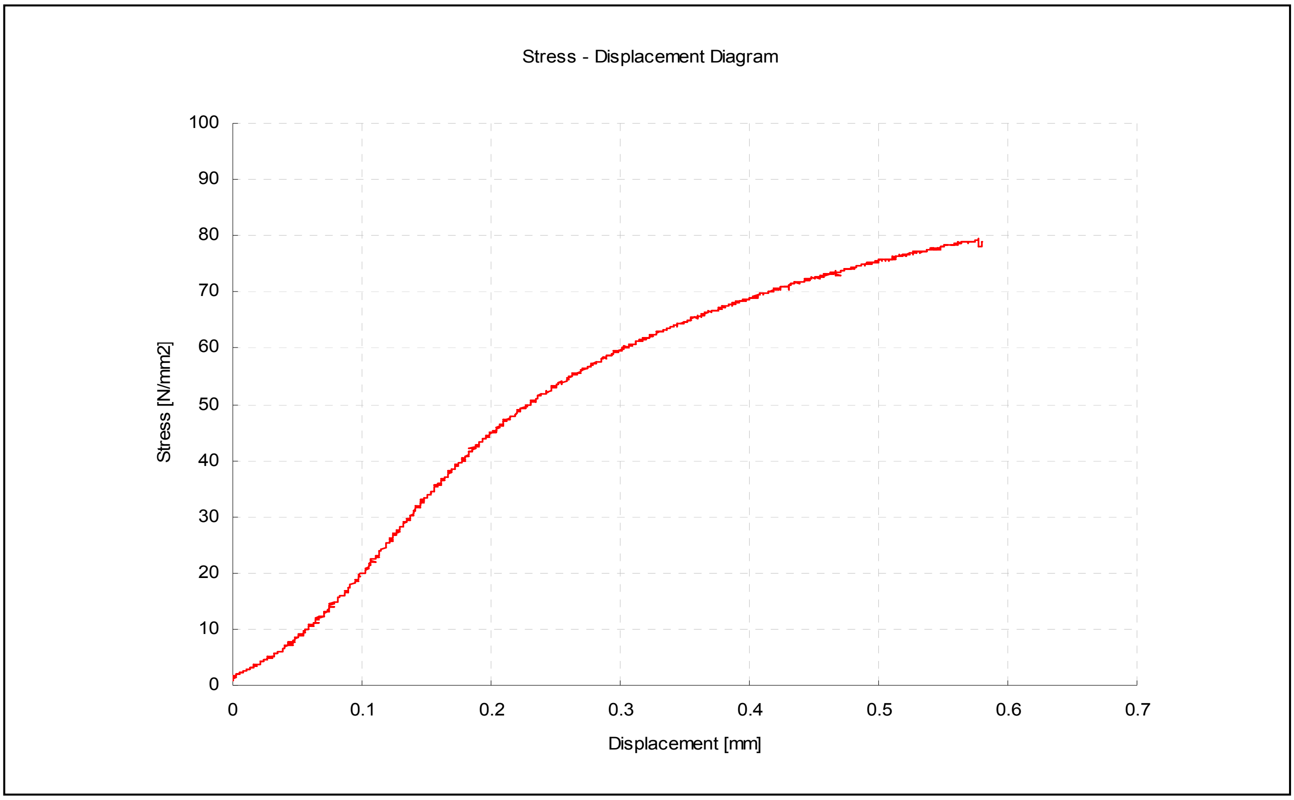

Figure 3: Stress–displacement diagram for the MCr 60/40 prereacted

The stress-displacement analysis was performed at 1250 °C and a load rate of 0.005 mm/s. The results of the test are detailed in Figure 3.

2.2.4 Wedge Splitting Test

Fracture mechanical analysis enabled the durability of magnesia and magnesia chromite bricks under conditions of thermo-mechanical stress to be estimated with a high degree of accuracy. The shape of the load-displacement curve illustrates whether a material exhibits flexible or brittle properties (Figure 4) [5].

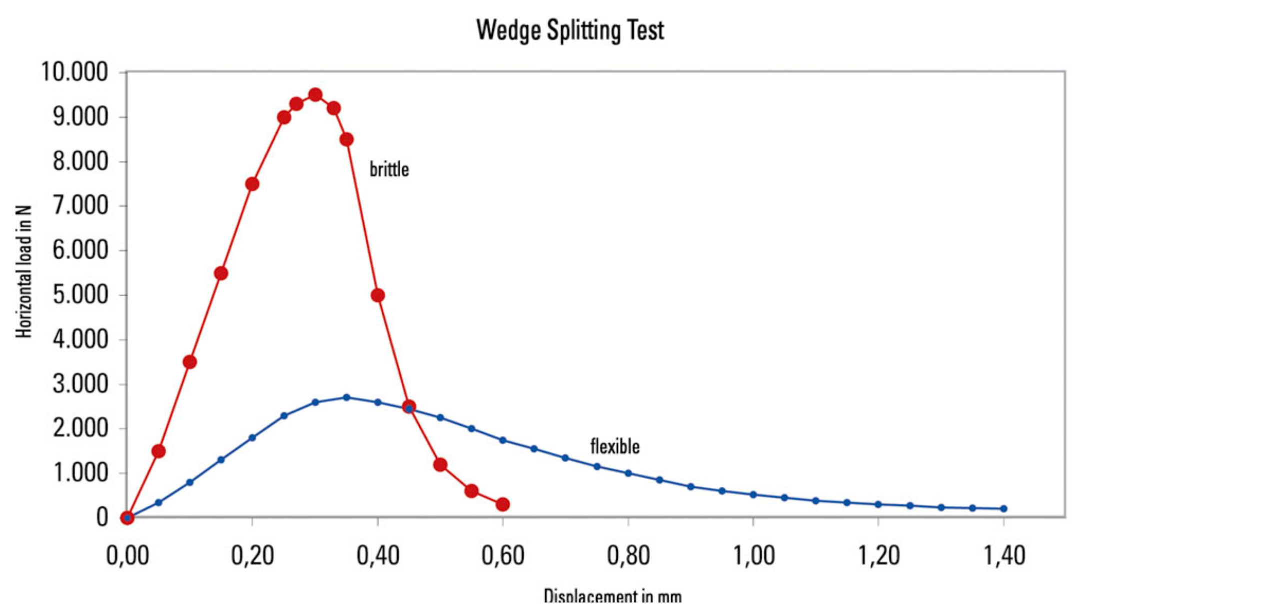

Figure 4: Typical load-displacement graph for the wedge splitting test indicating flexible or brittle material properties

One fracture mechanical parameter determined was the specific fracture energy. One unique advantage of the wedge splitting test is that it enables fracture mechanical parameters to be determined at temperatures up to 1500 °C. This is important because under normal operating conditions crack formation tends to occur at high temperatures and experience indicates that the affected materials reach the greatest brittleness level within the temperature range of 1100–1250 °C. Typically, the bricks aquire their flexible structure during the cooling phase of the brick burning process because innumerable micro-cracks in the bricks structure are initiated during this time. After the bricks have been installed in a reactor the micro-cracks can close during the heating, causing an embrittlement of the structure. The results of the wedge splitting test, performed at 1250 °C, are detailed in Figure 5 for the prereacted MCr 60/40.

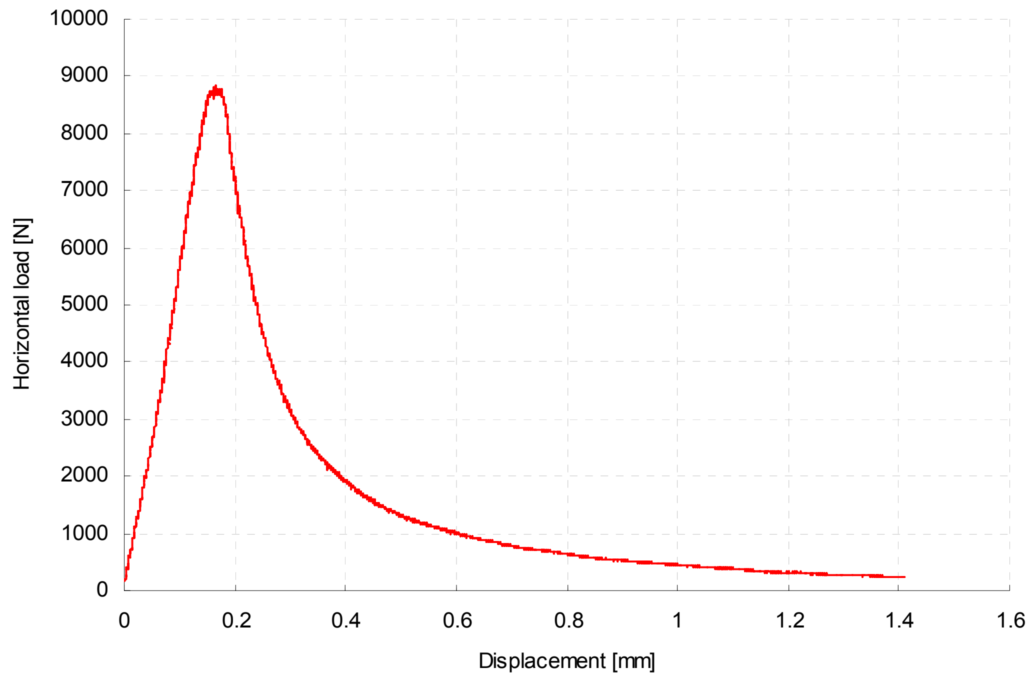

Figure 5: Wedge splitting test for the prereacted MCr 60/40, performed at 1250 °C

A comparison of Figure 4 and Figure 5 indicated that the prereacted MCr 60/40 is in the brittle brick category. In contrast, the MCr 85/15 brick is an example of a more ductile brick type. In addition to the described testing methods there are also other important refractory material evaluations including hot modulus of rupture, cold crushing strength, thermal shock resistance, heat conductivity, and cold modulus of rupture. From these tests significant refractory material characteristics can also be determined. However, in the analysis of the prereacted MCr 60/40 the described testing methods were the most relevant for the extended analysis using the biaxial hot testing press.

3 Thermal Expansion and Reheat Change

To plan a furnace lining a knowledge of the thermal expansion (lin %) and the reheat changes of the different refractory materials to be used is imperative because the expansion must be compensated for in the lining design. The most important factor in the expansion calculation is the temperature dependent expansion coefficient, termed α (1/K). This can be determined with the aid of the refractories under load test and the results of the prereacted MCr 60/40 are illustrated in Figure 1. If the thermal expansion is not taken into consideration or incorrect allowances are made it can have significant effects on the furnace steel casing. Figure 6 illustrates the damage that occurred when insufficient expansion compensation was included in a lining design.

Figure 6: Flash furnace exhaust gas shaft

Frequently, after heating to high temperatures and following the cooling down phase, length variations in the bricks remain, which are termed after-expansion or after-shrinkage. These persisting effects must be differentiated from the reversible thermal expansion. If a brick exhibits too greater after-shrinkage, the joint size in the lining increases and the lining becomes leaky. In the reverse case, if the after-expansion results in the formation of high compression stresses in the lining these can cause lining destruction. In particular, these factors must be considered in the expansion compensation allowances in refractory lining designs.

4 Biaxial Hot Testing Press

The biaxial hot testing press is employed at the RHI Refractories Technology Center to evaluate refractory brick behaviour in different lining systems. Using the press it is possible to control the calculated required lining expansion compensation or to select conditions such that at a certain heating temperature a force-closure occurs between the lining and the furnace steel shell. A further option is that the behaviour of the actual expansion inserts and mortars as a function of the lining load and temperature can be determined. The effects of the different linings on the expansion behaviour is also investigated at the RHI Refractories Technology Center Leoben. Figure 9 illustrates the overall concept of the biaxial hot testing press.

Figure 9: Biaxial hot testing press

With the aid of the two hydraulic plungers it is possible to load the test lining with up to 100 tonnes or to simulate the steel shell flexibility as a result of the brickwork thermal expansion. Figure 10 depicts a tested lining segment from a slag cleaning furnace. The lining was installed without mortar and with the calculated number of expansion inserts to compensate for the predicted thermal expansion.

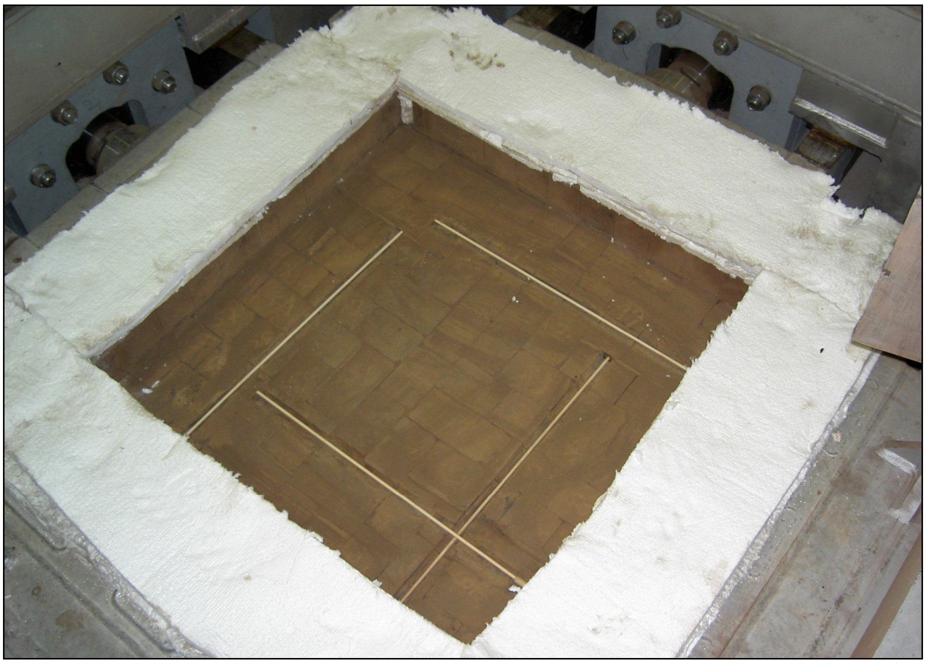

Figure 10: Test lining from a slag cleaning furnace

The lining was heated according to the relevant heating curve for the slag cleaning furnace. The expansion default was calculated to result in force-closure between the lining and the furnace steel when a hot side temperature of 800 °C was reached. In the experimental design the hydraulic plungers were used to simulate the flexible steel shell. In the original furnace, the lining in the vessel should have been self-clamping at 800 °C and should subsequently have been prestressed at the end temperature of 1200 °C (compact lining). A force-closure adjustment at lower temperatures would indicate the calculated expansion compensation was insufficient and would lead to deformation of the furnace shell. Figure 11 illustrates the force-expansion conditions during the heating process.

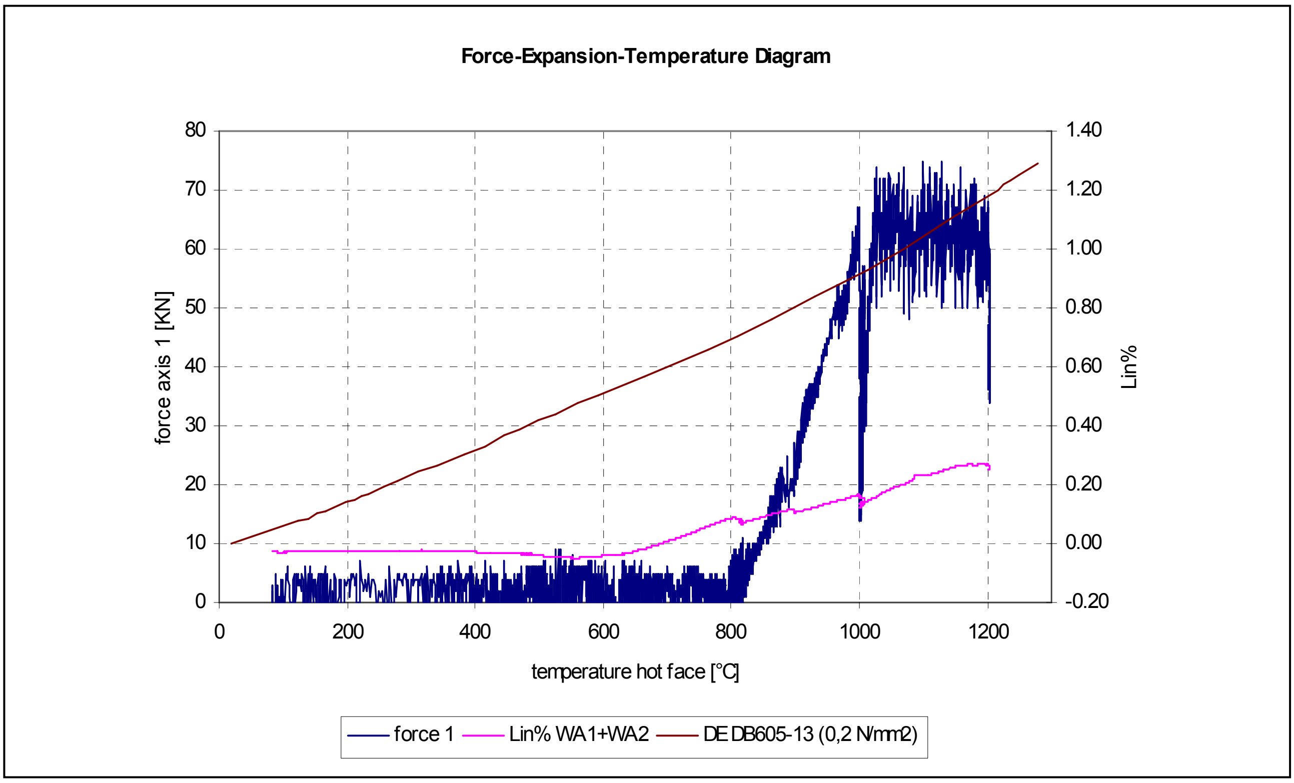

Figure 11: Force and expansion over the hot face temperature

In Figure 11 it is evident that the force closure actually occurred at 800 °C and the calculated expansion default was ideal. The brick expansion was compensated for by the expansion inserts up to a temperature of 700 °C and the inserts completely burnt out at approximately 500-600 °C. Subsequently, the brickwork in the furnace began to clamp itself and form during further heating the desired compact lining with a minimal load on the furnace steel shell.

An important factor in the lining design is the several hours or days holding time at 1000 °C, depending on the reactor size. When the holding time is reached an approximate stationary condition should have been reached, which makes it possible for the lining forces and stresses to be relieved. This particular issue is illustrated in Figure 12.

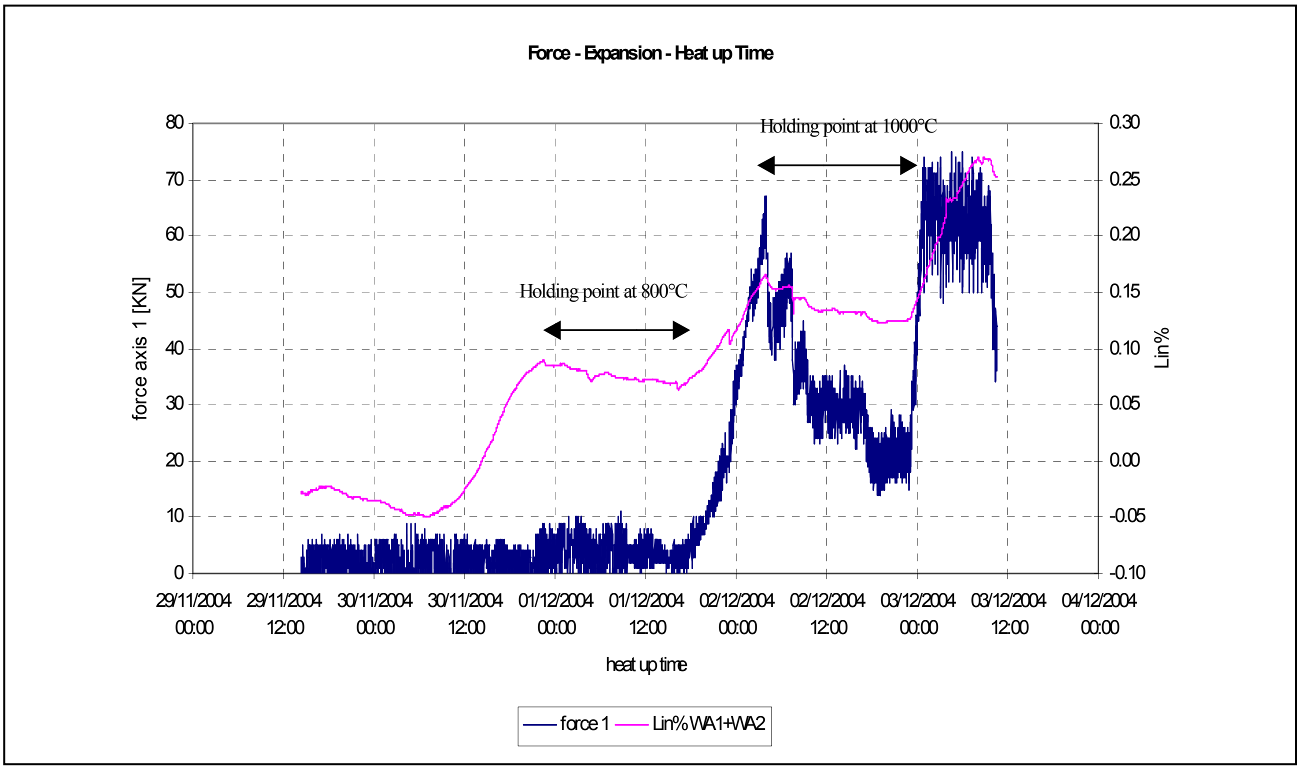

Figure 12: Force and expansion above the heat up time

During the 1000 °C holding period, a decreasing force and an uniformity or a slightly decreasing expansion as a result of the lining set-up is clearly evident.

The results of calculating insufficient or no expansion compensation are described in the following experiment. In this analysis the test lining was cooled down to approximately 750 °C after having reached the heat up end temperature and the brickwork was clamped with the help of the hydraulic plungers (i.e., the refractory material thermal expansion was suppressed). The results of this experiment are detailed Figure 13.

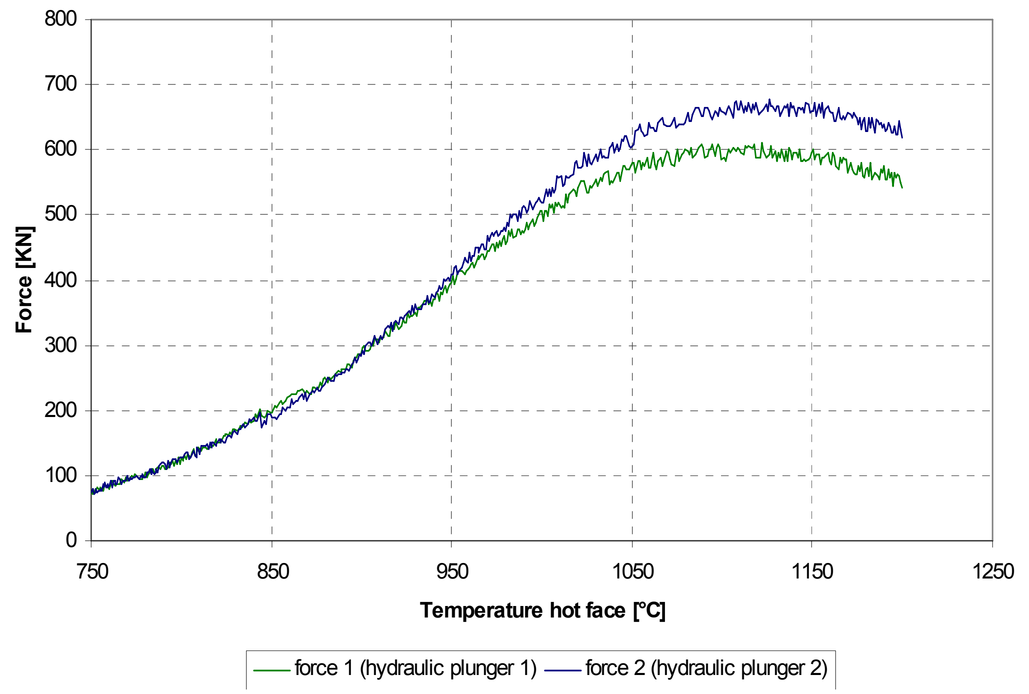

Figure 13: Suppressed expansion

In this case where the thermal expansion was suppressed, the force on the hydraulic plungers increased up until to a temperature of 1100 °C. At this load and temperature the lining showed a relaxation behaviour. In practice this would probably not occur because the furnace steel shell would break before reaching this point [6].

5 Conclusion

A combination of conventional refractory material testing methods and lining system analysis using the biaxial hot testing press will enable lining concepts to be further optimized in terms of their refractory expansion and load behaviour. This project is particularly important because of the increasing furnace complexity requirements, for example the use of furnace cooling elements. To remain competitive in the refractory market it is insufficient to only produce high performance refractory materials because the current trend is to provide a complete installation service. This includes selling, planning and construction, lining installation, customer support during the in service lining lifetime, and the development of new lining concepts and brick types tailored to individual customer requirements.

6 References

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