Determination of the Thermal Shock Resistance of Refractories

E. Brochen, S. Clasen, E. Dahlem, Chr. Dannert

Industrial high-temperature processes, in which refractories are involved, request flexible temperature control and frequent thermal cycling. For the refractories, the resulting thermal shock is the predominant factor that shortens their service life. R&D on refractories with superior resistance to thermal shock is therefore an ongoing concern for research centres and producers of refractories. Technological testing methods to determine the thermal shock resistance at a laboratory scale significantly support the development of improved refractories. A broad choice of methods is nowadays available which can be chosen according to the thermal shock characteristics and individual specific features. These methods reflect the conditions during service of the refractories to different degrees. New technological trends are testing methods for thermal shock testing under controlled atmosphere and testing methods that allow determination of the crack and failure mechanisms in-situ during thermal cycling. Seven different technological testing methods, which are being used for R&D at Forschungsgemeinschaft Feuerfest e.V./DE, are being described and their suitability and proficiency are being discussed.

1 Introduction

Among the diverse phenomena causing the wear of refractory linings of high temperature process furnaces and vessels, the harsh alteration of temperature at the surface of the linings (thermal shock) is the most likely to lead to premature and uncontrolled wear. The design of many industrial processes in which refractories are involved, like steelmaking or power generation, however requests flexible temperature control and therefore recurrent thermal shocks. Unexpected failures of the refractories due to thermal shock lead to plant stoppages with high costs and waste of time, production, materials and labour. Consequently, refractory suppliers are forced to develop innovative materials with outstanding resistance to thermal shock. Proper evaluation of the thermal shock resistance is therefore a key issue for both producers and users of refractory products. Moreover, the capability to evaluate and compare the thermal shock resistance of refractory products is decisive for the development of innovative products with improved performance.

Ongoing efforts are being made to develop testing methods that enable a proficient assessment of the thermal shock resistance (TSR) of refractory products in the laboratory scale. Due to the high diversity of applications for refractory products and the corresponding diverse thermal shock conditions, no single "ideal" testing method for TSR test has been established. On the contrary, testing methods, conditions and sample shapes for TSR testing are being individually adapted to fit the actual service conditions of the investigated refractory [1]. As a result, a variety of testing methods for TSR are available, starting from standardised testing methods for basic quality control and leading towards highly individual designs for the investigation of innovative refractory products with improved TSR.

A number of customised testing methods for thermal shock resistance, based on different concepts, are being operated at Forschungsgemeinschaft Feuerfest e.V. This paper provides an overview of technological testing methods and their proficiency to assess the TSR as well as describing the underlying concepts.

2 Background

While operating conditions for refractory products vary greatly according to their application (cement production, iron- and steelmaking, glass, nonferrous metals production, petrochemical processing or waste incineration ...), all refractory linings experience at least one heating and cooling sequence. Depending on the rate and frequency at which the heating/cooling sequences take place, extensive thermal stresses arise within the refractory, leading, sooner or later, to the fracture and eventually to the breakdown of the refractory lining. The components of a lining expand and contract by different amounts as the temperature changes. Thermal stresses arise whenever these thermal expansions are restricted, which happens at a macroscopic scale for refractory linings in two major ways:

- External constraints, due to design limitations, by preventing the free thermal

Erwan Brochen, Stephan Clasen,
Emilie Dahlem, Christian Dannert
Forschungsgemeinschaft Feuerfest e.V.
56203 Höhr-Grenzhausen
Germany

Corresponding author: Erwan Brochen
E-mail: brochen@fg-feuerfest.de

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expansion of the refractory components. In practice, the development of external constraint can be minimised by judicious design of the refractory linings, for instance by means of a system of expansion joints.

- Non-uniformity of the temperature field within refractory components induces non-uniform thermal expansion strains. Each volume element in the refractory components tends to expand/contract in a different way from the neighbouring volume element. In a continuous body, such an expansion/contraction generally cannot proceed freely, and thermal stresses are set up, also depicted as "internal constraint".

The extent of the thermal stresses in refractory linings largely depends on the conditions of the processes in which they are involved. Generally speaking, high operating temperatures and large thermal gradients within a lining lead to short lifetime of the lining. Severe conditions, such as the thermal cycling of steel ladles that are filled with molten steel and then cool down again after pouring, induce extensive stresses and damages. While the initiation of cracks due to thermal stresses cannot generally be avoided, refractory products are tolerant to damage and retain their structural integrity up to a certain degree before finally failing.

In spite of significant achievements in understanding the refractory damaging and failure processes as well as in their modelling, the lifetime of refractory products under service conditions cannot be predicted so far. The TSR depends on a large number of factors (material properties, component geometry, heat transfer conditions) [2] that again depend on temperature and time and may even change while the refractory linings are being used. Refractory engineers therefore still have to rely on technological testing methods to properly assess the TSR of refractory products. However, there is neither ideal nor definite testing method to assess the TSR. Even the simplest tests, used for decades, can be improved with modern quantification and instrumentation techniques, and innovative testing methods are constantly being developed. Those testing methods can be classified based on different relevant concepts with specific characteristics, which can be used to determine the suitability of a technological testing method for a given application.

2.1 Ascending versus descending thermal shock

The thermal gradient and accordingly the stress distribution and intensity in a refractory component are significantly affected by the way a thermal shock is being applied. Describing the change of the temperature in the test piece during the thermal shock, the distinction between "ascending" and "descending" thermal shock is intuitive and self-explanatory. Considering a test piece with uniform temperature distribution before a thermal shock, an ascending thermal shock induces firstly important rather local compressive stresses near the surface in contact with the hot medium and moderate tensile stresses in the colder inside part of the test piece, while the opposite occurs during a descending thermal shock. Besides the fact that different populations of defects are thereby being stimulated (surface or volume defects), the strength and accordingly the damaging process of refractories depends strongly on the type of stress (compressive or tensile) and the temperature.

In practice, ascending thermal shocks are usually more severe and decisive for most refractory linings (sudden contact with molten metals, slags or hot aggregates, burner flames ...). Refractory linings experience at least one ascending thermal shock when they are heated up for the first time. Compressive stresses arise near the hot face.

With increasing operating time, the tensile stresses induced in the colder part of the refractory linings increase while a steady state tends to be achieved. During a subsequent cooling, the compressive stresses are progressively removed at the hot face and the state of stress in the refractory linings is overall reduced. Afterwards, tensile stresses may appear on the surface of a lining if its temperature drops below the temperature now evenly spread in the body of the refractory lining.

2.2 Intensity of the thermal shock

Most of the modern refractory products are able to sustain moderate thermal shocks for an acceptable operating time. Severe thermal shocks are however one of main reasons for short lifetime of refractory products in most demanding applications. For a given refractory product operating under specified service or testing conditions, the severity of a thermal shock directly depends on the ratio of heat transfer h [$W \cdot m^{-2} \cdot K^{-1}$] to thermal conductivity λ [$W \cdot m^{-1} \cdot K^{-1}$] and can be quantified using the dimensionless Biot number

$$Bi = \frac{l \cdot h}{\lambda} \quad [-] \qquad (1)$$

where l [m] is the characteristic length of the refractory product (length of the brick or thickness of wall made of refractory monolithic in refractory linings).

If the heat conduction inside of the refractory component is significantly more efficient than the heat flow rate at the component surface ($Bi \ll 1$), only a weak thermal shock occurs, the thermal gradient is low and resulting thermal stresses are low. On the opposite, if the heat conduction is insufficient to efficiently transfer the incoming or extracted amount of heat ($Bi \gg 1$), the temperature near the transfer surface(s) changes rapidly whereas the temperature within the refractory component varies significantly slower (severe thermal shock). A substantial thermal gradient is thus generated and serious damaging is to be expected.

2.3 High temperature versus low temperature thermal shock

The material properties of many refractories are strongly affected by temperature and may even evolve with increasing exposition time at high temperature. Moreover, the behaviour of refractory products can drastically change above 1000 °C, as the ceramic microstructure, which is rather brittle at room temperature, gains in ductility with increasing temperature. Thermal shock testing exclusively below 1000 °C may therefore lead to erroneous assessment of the TSR for refractory products that experience thermal cycling at elevated temperatures, for example in the wear lining of a steel ladle.

2.4 Characterisation method for the resulting damage and the damaging process

The simplest evaluation of the damage induced by thermal shock testing is achieved with optical observations after testing. After one or more thermal shock cycle(s), the number, length and orientation of macro-cracks can roughly be estimated with the naked eye and the damaged microstructure can be characterised using optical or electron microscopy. However, the quality of the evaluation largely depends on the experience of the observer and no quantitative values for comparison with other materials are obtained.

Historically, the earliest attempts to provide quantitative values, especially to compare the TSR performance of different refractory products, were based on the loss of weigh of the test piece after a given number of thermal shock cycles or on the number of cycles before the test piece breaks into two or more large fragments. The measurement of loss of weigh turned out to be quite an inaccurate value and is largely inapplicable to modern refractories with good TSR. The number of thermal cycles that the test piece withstood before it failed, since easy to perform, is still widely used as quantitative measure but tends to be replaced by measurement of the residual mechanical strength of test pieces after a certain number of thermal shock cycles.

With the development of non-destructive testing methods, the Modulus of Elasticity (MoE) or ultrasonic velocity (UV) measured on the same test piece before and after thermal shock provide even more accurate quantitative values for the assessment of the TSR. Damping measurements also offer additional information to better understand the damaging process [3]. However, all methods described above require the test piece to be removed from the testing setup. Although rather well adapted to quantify the damage resulting from thermal shock testing, all the previously described methods provide limited information on the damaging process inside of the material itself during the thermal shock. Basically, the damaging process of refractory products consists of the nucleation of micro-cracking, followed by the growth and coalescence of these cracks. All these processes give rise to specific vibrational and acoustic events. The acquisition and evaluation of these acoustic events using acoustic emission sensors represent a major step forward in the in situ characterisation of thermal shock damaging. Microphones are being preferred to vibration sensors as they do not need physical contact with a test piece. If vibrations are to be measured, Laser Doppler Vibrometers (LDV) offer promising perspectives for contactless measurement. These systems are able to assess the damage of test pieces during the thermal shock testing up to high temperature and without removing the test piece from the testing setup, providing a direct insight into the damaging process.

3 Technological testing methods

3.1 Testing according to standards

Description

Standardised tests use rather simple methods to apply a thermal shock to refractory test pieces, either by means of water quenching (DIN 51068) or by air quenching (EN 993-11 and ASTM-C-1171). The European standard EN 993-11 describes two similar procedures A and B that apply to the determination of the thermal shock resistance of dense shape refractory products, although the second procedure (B) is also applicable to monolithics. In both cases, test pieces are heated up to 950 °C, then blow with compressed air, which corresponds to one thermal shock cycle.

The number of thermal shock cycles that a test piece is able to endure without failing after applying 0,3 MPa bending stress (maximum 30 cycles) serves as a measure of TSR for procedure A. In procedure B, the modulus of rupture (MoR) and/or ultrasonic velocity (UV) in test pieces submitted to five thermal shock cycles is compared to the MoR of undamaged test pieces or the UV measured on tested test piece before thermal shock cycles. The higher the residual strength and/or residual UV is, the better the TSR.

ASTM-C-1171 describes a very similar testing procedure to the procedure B of the EN 993-11, however test pieces are smaller (25 mm × 25 mm × 150 mm) and are being heated to 1200 °C instead of 950 °C. Once again, the residual MoR or Modulus of Elasticity (MoE) is the measure of the TSR.

DIN 51068 differs by applying water quenching to a cylindrical test piece (50 mm × 50 mm). The heating temperature (950 °C) and the evaluation of the TSR are, however, similar to the procedure A of EN 993-11. Thermal shock cycles are repeated until the test piece breaks into two or more large fragments and the number of cycles represents the TSR (Fig. 1).

Fig. 1 Cylindrical test piece after thermal shock testing according to DIN 51068

3.1.1 Application/suitability

The TSR testing standards are widely used for quality control of established refractory products. A comparison of the TSR performance of different products can be achieved without extensive effort or specific know-how. Criteria may be set up, such as a minimum number of thermal cycles to be withstood or the smallest strength/ultrasonic velocity to be retained after a given number of thermal cycles.

3.1.2 Proficiency

Especially with water quenching, good heat transfer and effective thermal shock are achieved. However, a descending thermal shock is applied in a temperature range that may differ from typical refractory applications. These tests allow a relative comparison of the thermal stress behaviour of the tested products under the thermal shock conditions given in the standards [4]. Transfer of test results achieved with standardised methods to explain the behaviour of refractory linings of industrial furnaces and vessels needs to be treated with caution.

3.2 Koltermann test

3.2.1 Description

Following the testing procedure proposed by M. Koltermann [6], a prismatic test piece (35 mm × 35 mm × 200 mm) is being heated up to a temperature of 1350 °C in an electric furnace and, after a holding time, placed onto a water-cooled plate for

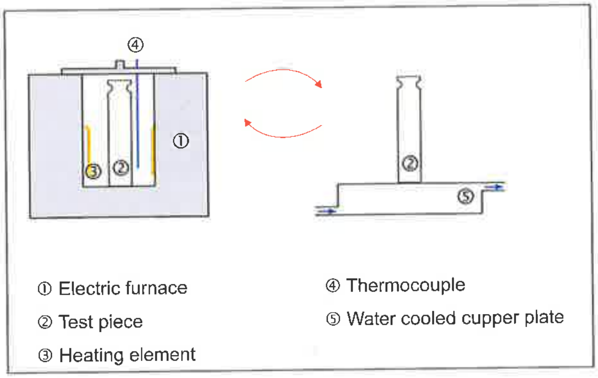

Fig. 2 Koltermann test

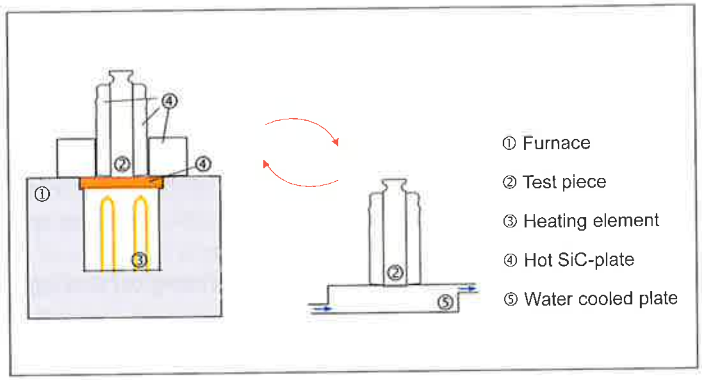

Fig. 3 Improved Koltermann test [7]

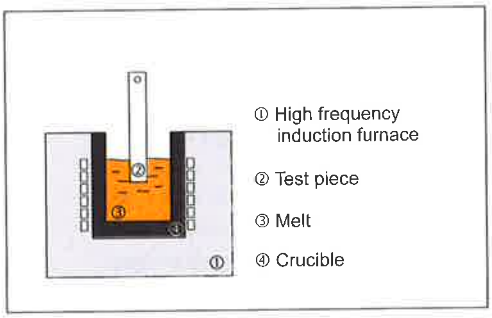

Fig. 4 Melt immersion test

quenching. This thermal cycling is repeated until it fails. The number of thermal cycles that a test piece endures without breaking is being used as the measure of TSR.

3.2.2 Application/suitability

While, just like with the standardised testing methods, a descending thermal shocks is being applied, the cooling process of the Koltermann method promotes quasi one-dimensional heat flow, roughly similar to the heat flow observed in refractory linings in service. A directional temperature gradient is induced in the test piece, resulting in a thermal stress distribution significantly more matching the stress distribution within refractory linings in service. In order to further enhance the agreement with service conditions and promote one-dimensional heat flow during the testing procedure, the size of the test piece can be extended, the lateral sides of the test piece thermally insulated and the test piece heated up only from its base, for instance by means of the contact with a hot SiC plate (Fig. 3).

3.2.3 Proficiency

The Koltermann test and its derivatives represent an improvement to the standardised testing methods and are still simple to implement. Focusing on one-dimensional heat flow increases the similarity to the conditions in service. Measurement of residual ultrasonic velocity of test pieces after thermal cycling may also easily be applied to characterise the extent of the thermal shock induced damaging. The time-dependent temperature distribution of the test piece can be measured with the aid of thermocouples fixed on the surface of the test piece. Additionally, acoustic events induced by the damaging process may be easily monitored using microphones. Based on this data, analytical or numerical models are used to calculate the stress distribution inside of the test piece and its time-dependent evolution. Correlations between the stress distribution and the acoustic emissions enable the analysis of the damaging process during thermal cycling in more detail.

3.3 Melt immersion test

3.3.1 Description

Test pieces are at least partially immersed into a melt (e.g. pig iron, steel, aluminium) [5] that is produced, for example, in a high-frequency induction furnace (Fig. 4). After a defined period of immersion, the test piece is withdrawn to cool down in air (natural convection or assisted). This procedure is repeated to a predefined number of cycles or until the test piece fails. The number cycles or the number of cycles sustained until failure is taken as a measure for the thermal shock resistance.

3.3.2 Application/suitability

Melt immersion tests apply ascending thermal shocks that are similar in intensity to those that refractory linings in metallurgical vessels experience in service. With some adjustments to the setup, tests can be carried out under controlled oxygen-free atmosphere. The method offers practical relevance for refractories that are used in direct contact with steel or pig iron melt and implements effective heat transfer due to the intensive contact of the liquid melt and the test piece. However, melt immersion tests are as such expensive and relative laborious.

3.3.3 Proficiency

Besides triggering extensive thermal stress within the test piece, melt immersion tests are intrinsically combined with corrosion phenomena, thereby enhancing the relevance of the method to mimic the damaging processes occurring in metallurgical vessels. The generation of cracks due to thermal stress is expected to promote the infiltration of the test piece by the melt and therefore to accelerate the corrosion process, which in turn intensifies cracks propagation.

3.4 Open-flame burners

3.4.1 Description

In order to produce ascending thermal shocks, the use of open flame burners as heat source is regularly reported [9, 10] and provides more efficient heat transfer into the test piece compared to a cold test piece that is simply placed into a hot furnace. Many different configurations were developed and even an ASTM testing standard (ribbon thermal shock test) was established in the U.S. However due to difficulties to obtain reproducible testing conditions between laboratories, the use of the ASTM standard declined and the standard was finally withdrawn in 2005 [10].

Fig. 5 Thermal shock testing method using open-flame burners.

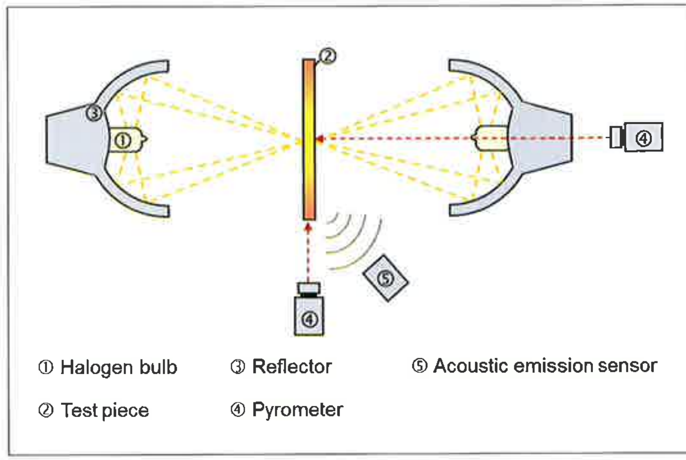

Fig. 6 Disc irradiation method

3.4.2 Application/suitability

The use of open-flame burners offer flexibility in the choice of the geometry and size of the test pieces and of the testing conditions. Thermal shock tests involving open-flame burners are therefore particularly suitable for quality control of complex refractory products in a given laboratory where test results simply need to be comparable to each other. For research and development, test pieces can be easily instrumented with thermocouples to monitor the temperature distribution during thermal cycling.

3.4.3 Proficiency

Depending on the requirements (for instance quality control) or the degree of instrumentation of the test piece, thermal shock tests using open-flame burners offer an interesting alternative to the standardised methods, as they produce ascending thermal shocks that are more similar to typical service conditions of refractories. The behaviour of refractory linings in industrial furnaces using open-flame burners as heat source or during the pre-heating of vessels for the steel industry is soundly depicted. The moderate heat transfer into the test pieces that is achieved with burners does however not allow reproducing the most severe thermal shock conditions, such as the filling of a steel ladle with molten steel.

3.5 Disc irradiation method

3.5.1 Description

The disc irradiation method was first developed in the 1980s in order to determine the critical thermal shock stress intensity factor of technical ceramics under ascending thermal shock conditions [11]. Since then, the test principle and test piece geometry were further developed to investigate the specific behaviour of refractory products under thermal loading. Disc-shaped test pieces (diameter of about 75 mm and thickness of at least 5 mm) are irradiated centrally on both sides using focused halogen lamps (Fig. 6). During the thermal shock process, the temperatures in the middle and at the edge of the test piece are measured by pyrometers. The intensity of the thermal shocks can be adjusted by changing the power of the halogen lamps so that the resulting temperature difference between the edge and the centre of the test piece is reduced or increased.

Within a few seconds, a circular temperature field is generated in the test piece. Temperatures higher than 1000 °C are measured at the centre of the test piece while the edge of the test piece remains significantly cooler (Fig. 7). The temperature difference depends on the thermal conductivity of the tested material and is usually greater than 500 °C in the first stage of the thermal shock. The heating-up regime causes a higher thermal expansion at the heated centre of the test piece compared to its edge, inducing a stress gradient in the test piece. Tangential and radial compressive stresses in the centre of the test piece are progressively substituted by tangential tensile stresses towards the edge region of the test piece. This stresses ultimately induce the fracture of the test piece, which is typically initiated at the edge and propagated towards to the centre.

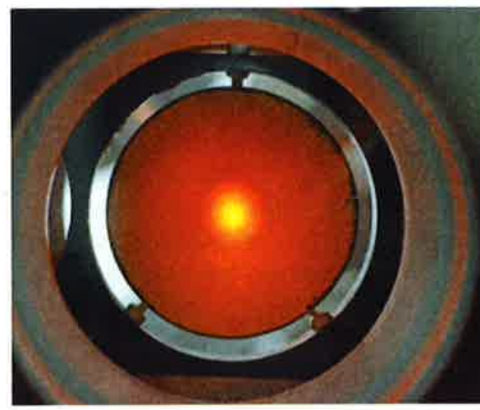

Fig. 7 Test piece immediately after halogen irradiation heating

3.5.2 Application/suitability

Halogen irradiation is an effective and versatile way to heat up test pieces reproducibly and the testing conditions are easily controlled and monitored. Coupled with a well-defined geometry of the test pieces, the stress field inside of the test pieces can be conveniently modelled using FEM. Thermal shock tests may in such a setup also be performed under controlled oxygen-free atmosphere, in order to investigate refractory materials sensitive to oxidation.

3.5.3 Proficiency

With an appropriate in situ damaging detection, for instance microphones or a Laser Doppler Vibrometer, the disk irradiation method is highly suitable to investigate the fracture process taking place within refractory test pieces during thermal shock. Using in situ detection of the acoustic emission during cracking, the modes of active damage in the stressed test piece (damage

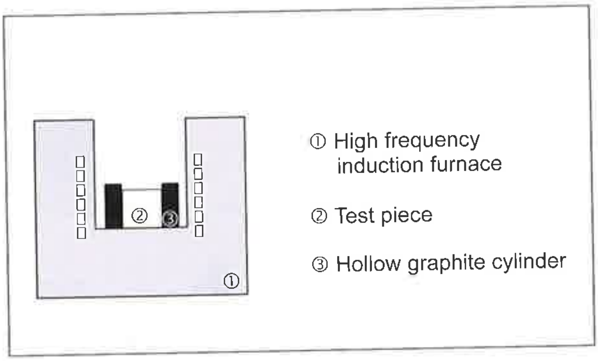

Fig. 8 High frequency induction irradiation method

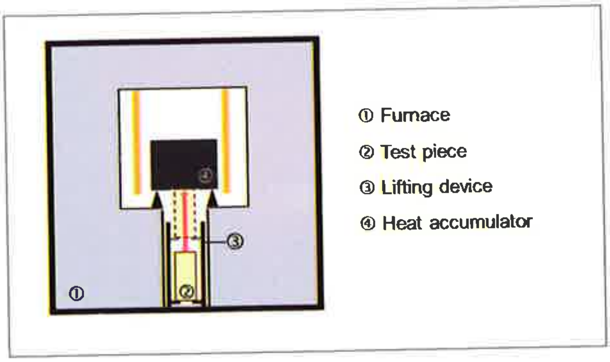

Fig. 9 High temperature cycling method developed by Forschungsgemeinschaft Feuerfest e.V.

mechanisms) can be detected during the thermal shock procedure.

3.6High frequency induction irradiation method

3.6.1 Description

The high frequency induction irradiation method is a versatile method to apply ascending thermal shocks. A hollow graphite cylinder (outside diameter for example 75 mm, inside diameter 54 mm, height 50 mm), coupling with magnetic field, is heated up in a high frequency induction furnace. The hollow graphite cylinder is made to glow within seconds and intensively irradiates the outside of a cylindrical test piece (50 mm × 50 mm) placed in its centre (Fig. 8). After a given dwelling time or after reaching a specified temperature, the test piece is cooled down in the induction furnace with the heating turned off or removed to cool in air outside of the induction furnace. Such cycles are repeated easily.

The heating rate of the hollow graphite cylinder, and accordingly of the test piece, can be adjusted via control of alternating current flowing through the induction coil. Depending on the heating rate and on the thermal conductivity of the material being tested, extremely high temperature gradients inside of the test piece are achieved.

3.6.2 Application/suitability

Highly efficient heat transfer is observed between the glowing hollow graphite cylinder and the test piece, almost comparable to the heat transfer occurring at the surface of refractory products in contact with molten metal. The high frequency induction irradiation method proves to be a convenient alternative to melt immersion tests in order to mimic rapid heating processes, but without the overlaying influence of corrosion effects. This is most advantageous when merely the TSR of products is to be investigated. The intensity of the thermal shock can be regulated by applying different heating rates. Applying a low heating rate at first furthermore enables a smooth pre-heating of the test piece to a pre-defined temperature. Thermal shock cycles are then being initiated towards even higher temperatures, closer to the temperature ranges experienced by linings for the steel production.

3.6.3 Proficiency

Thanks to the simultaneous measurement of the thermal gradient (using thermocouples in the test piece) and detection of the resulting crack events (using a Laser Doppler Vibrometer is easily possible as the sample is neither acoustically nor mechanically manipulated) the method delivers direct information about the damage process during the thermal shock itself. It delivers reliable and reproducible results and allows evaluation of TSR and a sound comparison of refractory products.

3.7 High temperature cycling method

3.7.1 Description

In order to perform thermal cycling between elevated temperatures, experimental furnaces with two chambers set to different temperatures are described in the literature [12]. The test samples are moved from one chamber to the other and are thus being thermally cycled between two specified high temperatures. However, only very mild heat transfer is achieved under these testing conditions, leading to limited thermal damages of the test pieces.

Forschungsgemeinschaft Feuerfest e.V. develops an alternative method with a moving test piece carrier (Fig. 9). The test piece is initially maintained at about 1000 °C in the "cold zone" of a furnace. For a thermal shock cycle, the sample is elevated and moved into contact with a hot ceramic piece (heat accumulator) that is situated in the "hot zone" of the furnace (up to 1700 °C). Due to the high heat capacity of the heat accumulator, a strong heat transfer into the test piece is induced when the test piece touches the surface of the heat accumulator. Additionally, the lateral sides of the sample are thermally insulated in such a way that the induced heat flow is almost unidirectional (similar to the improved Koltermann method). Therefore, the high temperature cycling method induces a directional temperature gradient in the test piece similar to the one observed for refractory lining in service e.g. in a steel vessel. After a given time in contact with the heat accumulator or having reaching the steady state (thermal equilibrium within the test piece), the test piece is moved back to the colder zone of the furnace to cool down. Thermal cycles can be repeated easily.

3.7.2 Application/suitability

The method is specifically being developed to achieve thermal shock cycling in a temperature range relevant for refractory linings from metallurgical vessels. In other words, the temperature gradients and, even more so, the temperature dependent material properties of the test piece should be rather close to the operating state of the investigated products. The testing procedure is fully automated and allows therefore performing large amount of thermal cycles without extensive

Tab. 1 Characteristics and specific features of technological testing methods for thermal shock resistance of refractories

Method	Thermal Shock Characteristics				Specific Features
	Ascending/ Descending Thermal Shock	Intensity	Thermal Cycling Range[1]	Characterisation of the Damage induced by Thermal Shock	
Testing according to standards	Descending	Moderate to severe	Low temperature	Exclusively after testing	Widely accepted
Koltermann test	Descending and/or ascending with some design modifications	Moderate	Low temperature	After testing, in-situ possible	Inducing one-directional thermal gradient
Melt immersion test	Ascending	Severe	temperature	After testing	Coupled with corrosion process, controlled atmosphere
Open-flame burners	Ascending	Moderate	Low temperature	After testing	Versatile, large test pieces of almost any shape
Disc irradiation method	Ascending	Moderate to severe	Low temperature	In-situ	Clearly defined thermal gradient, controlled atmosphere
High frequency induction irradiation method	Ascending	Moderate to severe	Low to high temperature	After testing and in situ	Highly efficient heat transfer
High temperature cycling method	Ascending, descending		High temperature	After testing and in situ	Operating at temperatures typical for thermal shock cycling in service, controlled atmosphere

[1] Range in which the temperature at the surface of the test piece is alternated: below 1000 °C = low temperature; above 1000 °C = high temperature

effort. Thereby, even refractory products with improved TSR are brought to their limits.

3.7.3 Proficiency

The residual ultrasonic velocity or residual strength are easily performed on the test piece after cycling to quantify the extent of the thermal damaging. The testing device is designed to allow the in situ measurement of the acoustic emissions issued during the damaging process at high temperature, using a Laser Doppler Vibrometer. Along with the measurement of the thermal gradient, thanks to thermocouples placed directly on the surface of the test piece, extended data is provided on the damaging processes during cycling between high temperatures.

4 Conclusion

A broad choice of technological testing methods to determine the thermal shock resistance of refractories is available and a method can be chosen according to its complexity, the type of information required and its closeness to the conditions during service of the refractories. The methods are defined by at least four characteristics that facilitate choosing the appropriate method for a given environment (Tab. 1).

Innovative technological testing methods for thermal shock under controlled atmosphere, e.g. for testing of refractories containing carbon, and methods that allow determination of the crack mechanisms in situ during thermal cycling are currently being developed. Damaging processes give rise to specific acoustic and vibrational events during thermal shocks, which can be acquired and evaluated using acoustic emission sensors. Microphones as well as vibration sensors are being utilised. Laser Doppler Vibrometers (LDV) also offer promising perspectives for in situ measurement of vibrational events without interfering with the test pieces. All these systems can be used to assess the damage of test pieces during the thermal shock testing at the testing temperature, providing a direct insight into the damaging process.

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