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PROPERTIES OF TAPHOLE REFRACTORIES AND THEIR EFFECT ON EAF TAPHOLE PERFORMANCE*

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Abstract

In electric arc furnaces, the lifetime of the taphole can be a critical factor in governing productivity and operational costs for the steelmaker. The field performance of tapholes can be investigated by developing a detailed understanding of the key material properties that govern taphole sleeve behaviour in the steelmaking process. In this application, high erosion resistance, oxidation resistance and thermal shock resistance are those key properties, and current taphole sleeve refractory material technology aims to maximize these attributes through formulation and material selection. The improvements in taphole refractory properties are expected to lead to more consistent and stable tapping times with increased taphole lifetime, reducing furnace down time and increasing productivity.

Keywords: Electric Arc Furnace, Refractories, Taphole, Performance, Tapping, High Erosion Resistance, Oxidation Resistance and Thermal Shock Resistance.

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1 INTRODUCTION

1.1 EAF steelmaking and taphole configuration

Over recent years, the use of electric arc furnaces (EAF) for steel production has increased significantly and currently accounts for approximately 30% of worldwide steel production and 40% of steel production in Europe[1]. The increasing emphasis on reducing carbon emissions means that this trend of increasing EAF usage over basic oxygen furnace (BOF) convertors is likely to continue.

EAF's are largely divided into two types, the side-tapping furnace and the bottom-tapping, or eccentric bottom tapping (EBT) furnace. Whilst around 60% of worldwide EAF's are of the EBT type, the performance of the taphole in both designs is critical to the steelmaker's operation. Performing taphole repairs and/or replacements is a time-consuming exercise and minimizing the frequency of these events (and therefore maximizing the availability of the EAF) is desirable. Ideally, the lifetime of the taphole should be matched to other parts of the EAF so that downtime for maintenance is reduced.

Side tapping furnaces have a spout extending from the sidewall through which the molten steel is poured into the ladle. In this configuration, the taphole can be made up of a simple block of refractory containing a pre-drilled hole, or it can be formed by placing high-quality refractory ramming or gunning mix around a metal pipe to create the pouring channel[2]. Fig. 1 shows a schematic example of a side-tapping electric arc furnace with its taphole made up of a set of pressed segments stacked one on top of the other. Generally, these segments are made of high-quality magnesia or magnesia-carbon material.

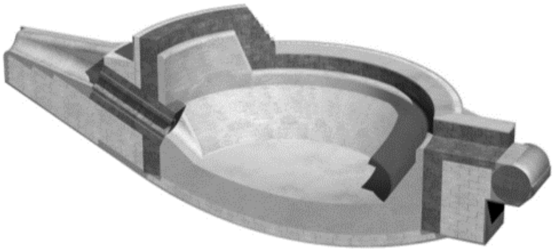

Fig. 1 – Schematic diagram of a side-tapping EAF with its taphole consisting of pressed magnesia carbon segments.

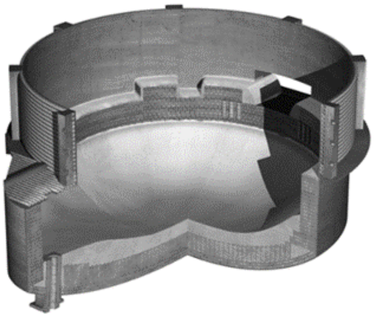

Fig. 2 – Schematic diagram of an eccentric bottom tapping (EBT) EAF with similar taphole construction.

The taphole in a bottom tapping furnace, such as an EBT furnace, goes through the bottom hearth section of the furnace and is often constructed from high-quality dense magnesia or magnesia-carbon segments to form a vertical taphole as shown in the example in Fig. 2. Single-piece sleeves, isostatically formed from high-quality magnesia carbon mix can also be used in either configuration.

In bottom-tapping furnaces, the taphole is often encased within larger rectangular shapes to form a permanent well in the nose of the furnace within which the taphole sleeve refractories can be installed and replaced as needed. Fig. 3 and 4 show close-up diagrams of this type of arrangement.

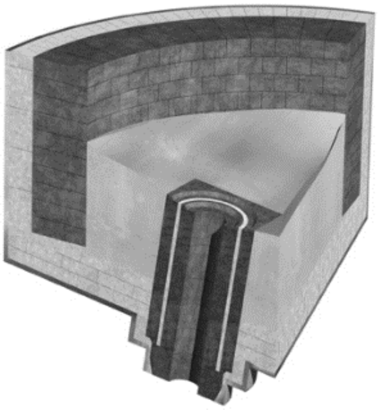

Fig. 3 – diagram of the taphole location within an eccentric bottom tapping electric arc furnace.

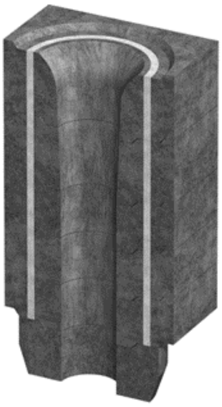

Fig. 4 – diagram of the EBT taphole assembly showing the sleeve segments arranged within the rectangular surround blocks. The segment at the bottom of the assembly is known as the end block.

It can be seen in Fig. 3 that the bottom of the taphole assembly, known as the end block, extends below the shell of the furnace and is therefore exposed to the atmosphere outside the EAF. As such, the material from which the end block is made is required to have excellent oxidation resistance in addition to other attributes essential to the application.

Additionally, the end block is also susceptible to steel/slag build-up around the exit of the bore that requires regular mechanical removal. Therefore, it is not uncommon for the end block to be manufactured from a different material to the sleeve segments, such as alumina-silicon carbide-carbon materials which are generally more tolerant than magnesia carbon materials towards the build-up of steel/slag and its removal.

1.2 Measuring taphole performance

Many steelmakers monitor the performance of the taphole refractories by measuring the time taken to empty the EAF into the ladle, referred to as tapping time or run-out time. When the taphole is new, the tapping time will be longer than when the taphole is older and the bore of the taphole has worn to a larger diameter. The taphole can be earmarked for repair or replacement when the tapping time has been reduced to a predetermined minimum value.

1.3 Repair practice

EBT tapholes can be repaired in situ by inserting a metal tube former of the correct bore diameter into the worn taphole, and the gap between the former and worn refractory filled with magnesia gunning material. A single EAF taphole could be repaired using this method several times before complete replacement.

1.4 Taphole Refractory Materials

The magnesia-carbon materials often used in the working lining of EAF tapholes generally consist of high-purity fused magnesia aggregate with flake graphite (up to 15%wt) and bind together by a continuous bonding phase of phenolic resin and/or pitch derivative. Further additions of metallic antioxidants and/or other matrix-modifying additives can also be made to improve specific properties of the product. Individual segments can be uniaxially pressed and stacked to form the taphole tube or single-piece sleeves can be isostatically pressed. After pressing the pieces are then heat treated to cure the binder before use.Replace this text for your paper content, according to the submission instructions at the Guide for Authors. The document should have twelve (12) pages maximum.
The Introduction includes a brief presentation of the paper, objectives and a literature revision.

2 PERFORMANCE LIMITING FACTORS AND PROPERTIES OF TAPHOLE REFRACTORIES

The main performance limiting factors encountered by EAF tapholes during use can be generally identified as follows:

- ✓ Mechanical erosion at high temperatures by the stream of hot steel;
- ✓ Chemical corrosion by any slag in the stream (e.g. carryover slag from the furnace, oxidizing slag);
- ✓ Oxidation by high oxygen levels in the steel/slag;
- ✓ Oxidation between tapping sequences;
- ✓ Thermomechanical spalling caused by the cyclic heating of the application.

The sections below describe how the formulation design of taphole refractories is tailored to reduce the effect of each of those factors.

2.1 Mechanical erosion:

High-temperature strength is the main contributor to mechanical erosion resistance. Good hot strength can be achieved by careful control of the granulometry of the formulation to optimize density, whilst matrix modifying additives such as metallic antioxidants can strengthen the matrix by in situ formation of carbide and oxide phases during use. However, high-strength materials often combine with high stiffness (high Young's modulus) which could be detrimental to the thermal shock resistance of the material.

Reducing the amount of graphite in the formulation can also enhance strength, however, the graphite has further advantages in terms of corrosion resistance and thermal shock resistance, so a balance must be achieved for optimal performance.

2.2 Corrosion:

The use of high-purity raw materials contributes to the corrosion resistance of taphole refractories by reducing the level and chemistry of impurities that are susceptible to chemical attack by slag that may be present in the taphole. In general, high purity, large crystallite size fused magnesia of 97% purity and higher is generally preferred. High-purity graphite is also beneficial, and its non-wetting properties help to limit the infiltration of liquid phases into the matrix of the refractory.

Decreasing slag infiltration into the refractory can also be achieved by minimizing the apparent porosity of the material by granulometry optimization. Additionally, the use of metallic antioxidants can also contribute to reducing the porosity due to the in-situ formation of reaction phases giving a pore-blocking effect.

2.3 Oxidation by high oxygen levels in the steel:

High oxygen levels in the steel generally lead to high levels of FeO in the slag and can cause loss of the graphite and bond carbon within the refractory, increasing the wear rate according to the following reaction:

$$\mathrm{FeO + C \rightarrow Fe + CO}$$

Again, the use of metallic antioxidants can be helpful, tying up some of the carbon as carbides and limiting its availability for oxidation.

2.4 Oxidation between tapping sequences:

Oxidation between tapping sequences mainly affects the end block, as it is more exposed to the atmosphere than the rest of the taphole assembly, and it is for this reason that this particular segment is often made from a material with higher levels of metallic antioxidant, to further combat the risk of oxidation.

2.5 Thermomechanical spalling (thermal shock)

Thermal shock resistance is an important property for materials used in taphole applications where there is a cyclic and rapid substantial change of temperature. Reducing the refractory material's susceptibility to thermal shock can be achieved by optimizing its key thermomechanical properties, although carbon-containing refractories by their nature generally have very good thermal shock resistance.

The thermo-mechanical energy released during thermal shock may be sufficient to completely shatter the item or may produce less severe damage such as surface cracking, in which some strength is retained. In this respect, Hasselman's thermal shock theory attempts to relate material properties to resistance to catastrophic failure[3,4].

Therefore, a thermal shock resistance parameter, R"" specifically conceived for materials possessing high strength or short cracks, and situations where the fracture is of a catastrophic nature, can be defined by:

$$R'''' = \frac{E\gamma_{wof}}{\sigma_f^2(1-\nu)}$$

Where:
γ_{wof} = work of fracture
σf = fracture stress
E = modulus of elasticity
v = Poisson's ratio
α = thermal expansion coefficient

For long initial crack length situations in low-strength bodies, or situations in which stable or quasistatic crack growth occurs, Hasselman defined the thermal stress crack stability parameter R_{st}:

$$R_{st} = \sqrt{\frac{\gamma_{wof}}{E\alpha^2}}$$

Where:
α = thermal expansion coefficient

For either R"" or R_{st}, maximizing the respective value increases the refractory material's ability to resist thermal shock damage and the most common way to maximize R"" and R_{st} in the design of refractory materials involves the increase of the work of fracture, **γ_{wof}** [5].

Thermal shock resistance is also highly dependent on thermal expansion and low thermal expansion behavior is considered beneficial in this respect. Magnesium oxide has a relatively high thermal expansion compared to most other refractory oxides such as aluminum oxide, however, the graphite contained in magnesia carbon taphole materials serves to reduce the thermal expansion of the bulk material by providing flexible discontinuities in what would otherwise be a continuous and dense ceramic structure.

Furthermore, the graphite content helps to reduce the modulus of elasticity while increasing strain to failure and thermal conductivity.

3 POST-MORTEM EXAMINATION OF USED EAF TAPHOLES

Recent trials of existing taphole materials in EBT taphole applications have been carried out and used samples have been returned from the field, examples of which are shown below in Fig. 5.

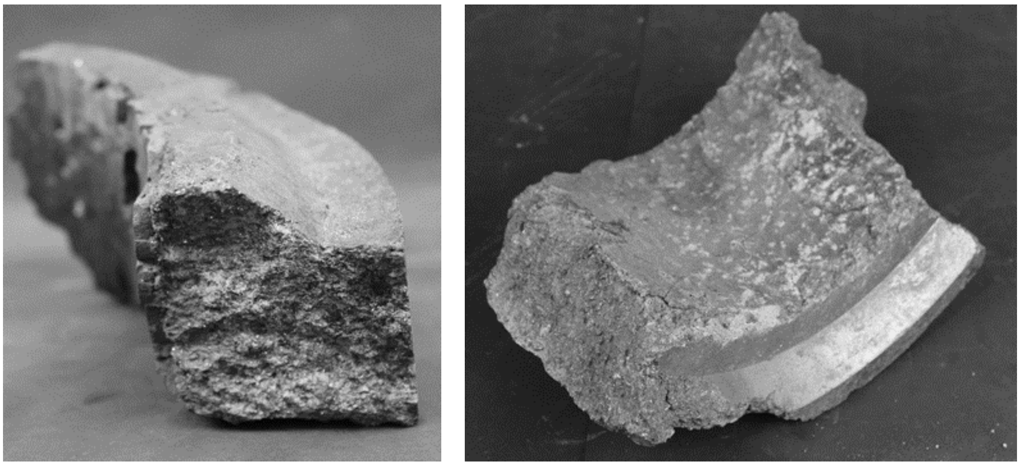

Fig. 5 – Examples of used taphole samples received from the field for examination. It can be difficult to obtain suitable samples after use, and their structural integrity can be compromised due to the destructive nature of the extraction process, which in turn can limit properties analysis to just a few techniques (e.g. chemical analysis, crystallographic analysis, microstructural analysis, etc.).

Examination of the hot faces of samples such as these using optical and electron microscopy can be carried out, the latter of which can also be used to obtain qualitative information on the composition of any slag present and any resulting reaction phases with the refractory, as seen in the electron microscopy image shown in Fig. 6.

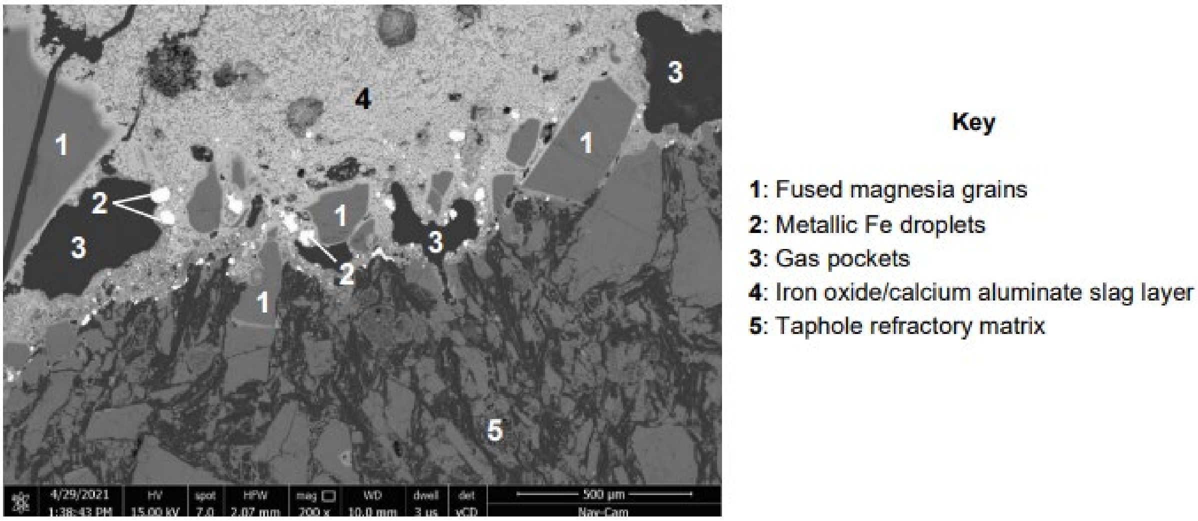

Fig. 6 – Backscattered electron image of the hot face of a magnesia-carbon EBT taphole segment. The visible slag (4) was high in FeO contributing to the carbothermic reduction of some of the refractory carbon, evidenced in the form of droplets of metallic Fe (2) and pockets of CO gas (3).

Whilst this type of examination can be very useful, it is worth noting that there are limitations associated with the post-service examination of used samples in this way. For example, only evidence left from the last few taps will be present, as that from previous heats will inevitably have been worn away.

Additionally, it is also possible that any corrosion that has taken place, such as the oxidation observed in Fig. 6 could effectively mask any evidence of other wear mechanisms that may have been present, e.g., mechanical erosion and/or damage due to thermomechanical spalling. It is also therefore very difficult to determine which of all the wear mechanisms have been the most dominant in determining the performance of a particular taphole sample.

4 EXPERIMENTS AND DISCUSSION

4.1 Measurement of refractory material properties

Literature review and practical experience have indicated that improved thermomechanical properties of EAF taphole materials whilst maintaining the excellent erosion, corrosion, and oxidation resistance required of the application are desired. Accurate measurement of these properties is therefore of fundamental importance in evaluating refractory materials for this critical application.

The modulus of rupture test is carried out in a sealed furnace (Isoheat) purged with argon gas. This test is based on ISO 5014 and consists of the loading of 150x25x25mm bars in a 3-point bending arrangement at a rate of 0.15MPa/s to failure. Samples are heated at a steady rate to 1400°C and left to soak for 30 minutes before testing commences.

The work of fracture, γ_{wof} of any refractory specimen can be measured using an adapted 3-point bend test. Sample bars of dimensions 100x30x15mm with a machined V-shaped notch in the center (see Fig. 7) are loaded by a universal testing machine (Tinius Olsen 5ST) with a controllable load speed (0.05mm/min) to control the rate of crack propagation.

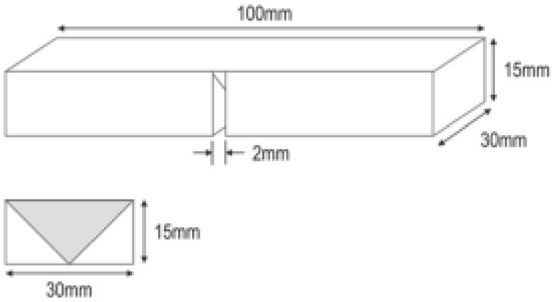

Fig. 7 – Schematic diagram to show the sample arrangement for the work of fracture tests carried out at the Barlborough R&D center.

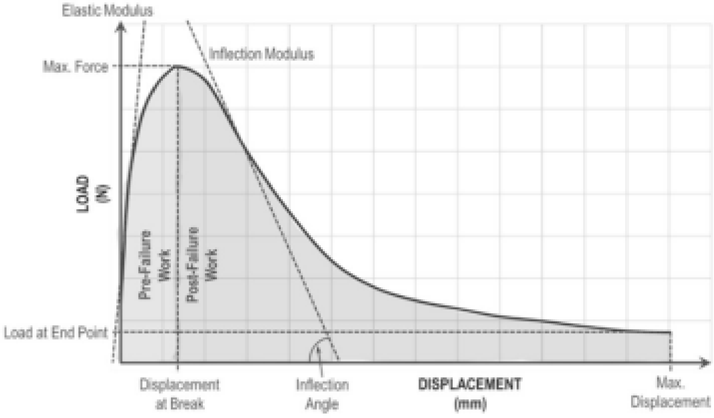

Fig. 8 – An example of the information available from a load-displacement curve obtained from the work-of-fracture test. The total area under the curve (shaded) is used to calculate the work-of-fracture.

The total area under the resulting load-displacement curve (i.e. the shaded area in Fig. 8) is used to calculate the total work-of-fracture. Additionally, the work done before peak load (crack initiation) can be calculated as a fraction of the total work done, so that the energy required to initiate the crack can be compared to the work done to propagate the crack. Ideally, the work required for crack initiation should be lower than that required for crack propagation to give good resistance to thermal shock damage, as it takes less work to form new cracks than to propagate an existing crack to failure[6].

Current work-of-fracture measurements are undertaken at room temperature in the cured state and, in order to assess the effect of any in-situ reactions, after firing at 1400°C for 2 hours in a saggar box filled with coke.

Elastic modulus (Young's modulus) measurements can be made at ambient and high temperatures using the impulse excitation method. The non-destructive nature of this test allows continuous measurement of the same specimen as it is heated in a specially designed furnace (IMCE HT1750).

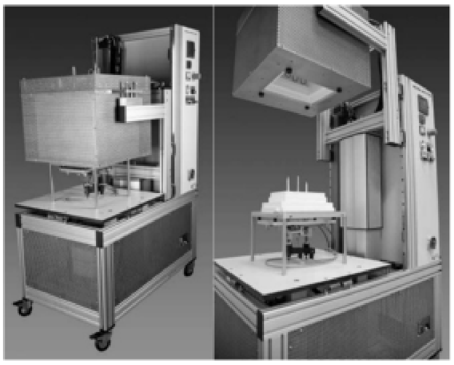

Fig. 9 – Illustration of the IMCE HT1750 impulse excitation equipment used for high-temperature elastic modulus measurement at the Barlborough R&D center.

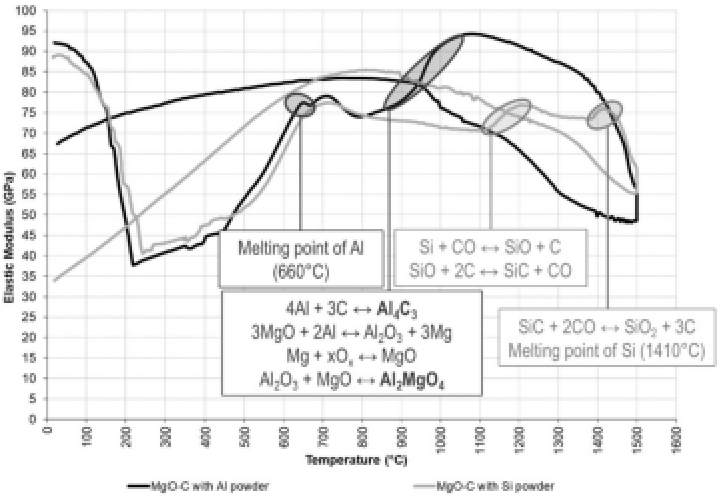

Fig. 10 – An example of two elastic modulus curves obtained from the impulse excitation test. The effect of some of the in-situ reactions on the elastic modulus is indicated.

This test, based on BS ISO 22605:2020, typically uses heating rates of 2°C/min up to 1500°C in an argon atmosphere and elastic modulus measurements are taken at a frequency of every 2 minutes during the heating, dwell, and cooling periods of the test. Standard specimen dimensions are 140x50x30mm.

A vertical dilatometer instrument (Linseis) is used to measure the thermal expansion of 30mm long, 12mm diameter specimens up to 1600°C in an argon atmosphere.

This test also uses a 2°C/min heating and cooling rate with a short dwell of 2 minutes at 1600°C.

The rotary slag test is the standard test used to evaluate and compare slag corrosion resistance (BS 1902 : Section 5.13). In this test samples are arranged in a cylindrical barrel, which is then rotated horizontally whilst being heated with an oxy-propane burner to a target temperature of 1600-1700°C (Fig. 11). The test is run for 2 consecutive days (6 hours/day) and every 30 minutes, old slag is poured out and replaced with fresh slag to avoid the possibility of the slag reaching saturation.

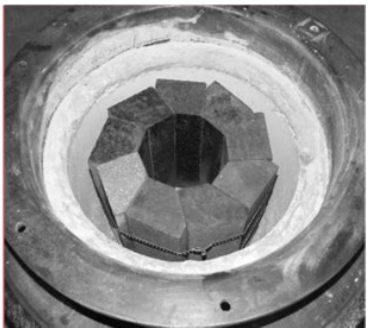

Fig. 11 – Samples arranged in a cylindrical barrel, which is then rotated horizontally whilst being heated with an oxy-propane burner to a target temperature of 1600-1700°C.

Fig. 12 – The test is run for 2 consecutive days (6 hours/day). Every 30 minutes, old slag is poured out and replaced with fresh slag.

After testing is completed, the barrel is allowed to cool and dismantled. Each sample is then sectioned along its length and the thickness is measured and compared to the original thickness, and average wear in mm and wear rate in mm/hr is calculated.

Oxidation resistance is measured by a thermogravimetric method using a furnace adapted with a thermally isolated balance. Samples consisting of 50mm3 cubes of the test material are placed on the balance support within the furnace and heated at

1°C/min to 1000°C in air with a soak time of 10 hours. The change in mass of the sample is recorded along with the furnace temperature allowing the weight change to be recorded as a function of temperature and/or a function of time.

4.2 New generation of taphole refractories

Measurement of the key thermomechanical properties such as those described above has facilitated the evaluation of existing refractory materials and enabled the development of products with improved thermomechanical properties whilst maintaining the excellent erosion, corrosion, and oxidation resistance required of the application.

The use of special matrix modifying additives has helped to achieve this objective, resulting in an increase in the flexibility of the material (reduced Young’s modulus), increased work-of-fracture that would satisfy R"" and Rst, along with reduced thermal expansion. This enhancement allows further modifications of the matrix with strengthening additives such as metallic antioxidants, without significant compromise of the thermomechanical properties.

Additionally, an alternative proprietary binder system that offers enhanced attributes compared to conventional binder systems has also been developed. This binder system has given significant reductions in elastic modulus and thermal expansion characteristics over conventional binders used in magnesia-carbon refractory materials.

The improved knowledge of fundamental principles, equipment design, and process conditions gained from the extensive research and characterizations undertaken have led to further enhancement of thermomechanical properties over standard refractories used in taphole applications. When the properties of the refractory materials described above are optimized, it is possible to develop taphole refractory materials that possess good hot strength, high work-of-fracture, low elastic modulus and low thermal expansion, as displayed below in Fig 13 and 14:

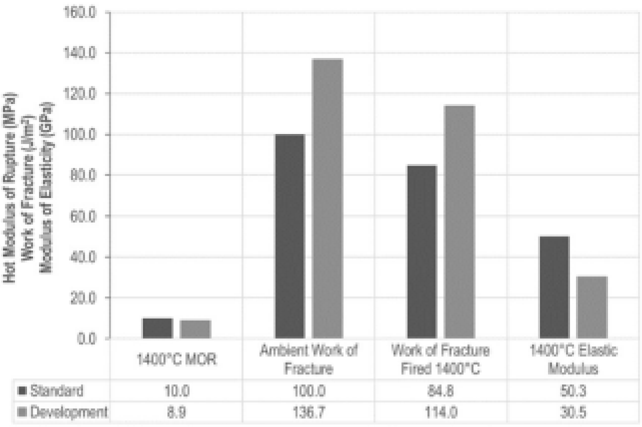

Fig. 13 – Comparison of the thermomechanical properties of a standard taphole material and a recent development, showing improvements in work of fracture and elastic modulus, whilst maintaining comparable hot strength.

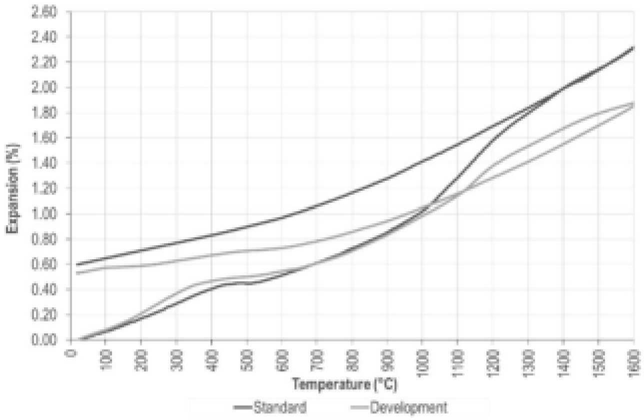

Fig. 14 – Comparison of thermal expansion curves of a standard taphole material with the development material. Significantly reduced expansion is observed above 1000°C due to the combination of improved binder and matrix-modifying additives.

5 CONCLUSIONS

The performance of the electric arc furnace taphole is a very significant factor for the electric steelmaker and can influence the output and efficiency of steel production. Continuous improvement of taphole refractories used in this application is therefore of particular importance.

With recent advances in taphole refractory technology and the tangible benefits gained from the utilization of formulation variations and the use of novel raw materials, increases in the taphole lifetime have been realized. However, Vesuvius is continuing development work to further improve the performance of their Supermag taphole product range, with a view to reducing the number of taphole repairs and replacements required to maintain the operation of any EAF.

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