

SHINAGAWA TECHNICAL REPORT

自己修復耐火物

～究極の微構造強靱化メカニズム～

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報文／REPORT

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Self-Healing Microstructure: The Utmost Refractory Toughness Mechanism

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要 旨

耐火物は、熔融金属を出し入れする混鉄車や取鍋のように、稼働サイクル中に温度変化に頻繁にさらされる。このような激しい熱衝撃に対処する最も一般的な手法は、カーボン原料を導入して耐火物の熱伝導率を高め、高温側と低温側の温度勾配を小さくすることである。一方、耐火物中へのカーボン原料の導入は、熱衝撃による損傷に強くなる利点をもたらす反面、熱伝導率が高くなることで、稼働中の熱損失が大きくなるという問題が生じる。本研究では、最も過酷な使用条件に対応できる人工的な微細構造から着想を得て、カーボン原料やその含有量を変化させることなく、自己修復特性を有する $\text{Al}_2\text{O}_3\text{-SiC-C}$ れんが(以下ASCれんが)を見いだすことを目的に、革新的な手法を検討した。新たに開発したれんがにおいては、加熱冷却により発生した亀裂の修復に成功し、繰り返し加熱冷却試験後にはさらに丈夫な材料となった。物理的特性や耐酸化性、高温特性、耐食性などの他の特性も良好な結果を示し、実炉試験結果もまた、加熱冷却サイクルにさらされる耐火物の役割を完全に変えることができる、自己修復技術の誕生を示唆している。

Abstract

Refractories are often exposed to thermal variations during their operational cycle, such as in torpedo cars and iron ladles, where molten metal is loaded and unloaded. Dealing with that aggressive thermal shock is not straightforward and the most common approach for these materials is to optimize the carbon sources, increasing the thermal conductivity of the bricks and reducing the thermal gradient between the hot and cold faces. If, on one hand, the material becomes more resistant to thermal shock damages, on the other hand, its higher conductivity imposes a negative consequence: higher thermal loss during operation. In this work, inspired by intelligent microstructures with the ability to adapt to the most severe environmental conditions, an innovative approach was evaluated, aiming at obtaining an $\text{Al}_2\text{O}_3\text{-SiC-C}$ brick formulation designed to present a self-healing behavior, without variation in the carbon sources or content. The new developed structure successfully regenerated the cracks initiated during thermal cycles, resulting in an even tougher material after thermal shock tests. Other properties such as mechanical resistance, oxidation, hot mechanical properties and corrosion resistance also showed promising results, pointing out the birth of a smart self-healing technology, able to completely change the role of refractories in thermal cyclic operations proven by field tests.

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1. 緒言

製鋼プロセスは、脱炭素の未来に向けた移行段階にあり、さまざまな取り組みが検討されている¹⁾。そのほとんどは20年以内に本格的に実用化されると期待されているが、すでに製鉄工程では、燃料の転換や新原料の追加といった対策が実施されている。さらに鉄鋼メーカーは、高炉操業以外の工程におけるエネルギー損失とCO₂排出を削減する方法を模索している²⁾。

耐火物ライニングは、炉内の熱を維持し、温度低下を抑制する直接的な役割を担っている。しかしながら混鉄車や取鍋のように、非常に苛酷な温度変化に耐えなければならない炉においては、このような役割を果たすことが困難な場合もある。熱衝撃による損傷を低減する一般的な手法は、主に黒鉛を配合することで熱伝導率を向上させ、熱応力を低減することである。一方で黒鉛の配合は熱伝導率を高め、炉壁からの熱伝導によってより多くのエネルギーを失う結果をもたらすため、鉄鋼メーカーのサステナビリティの観点からは望ましくない³⁾。

すなわち黒鉛の配合量を抑制しつつ、加熱冷却の繰り返しによる亀裂の発生を回避するのは難しく、解決には従来とは異なる視点が必要である。そこで今回着目したのは、稼働中に発生した亀裂を自己修復するという考え方である。

自己修復メカニズムは、ポリマー分野において広く探求されており、例えば、硬化剤を含む小さなカプセルが材料の構造中に組み込まれており⁴⁾、亀裂がこれらのカプセルに達するとカプセルが破壊され、基材と活性化した硬化剤との間で硬化反応が起こり、亀裂部位の完全な封鎖が促進される。同様に建築用コンクリートの分野においても、バイオミネラライゼーション能力を持った新たなコンクリートが開発されている。これらの材料にはバクテリアが導入されており、バクテリアが代謝的に鉱物を生成することで、コンクリートの亀裂や損傷を修復するのを助けている⁵⁾。

このような自己修復メカニズムは良く知られており、効率的に機能することが証明されているが、依然として室温条件に限定されている。鉄鋼製造プロセスで必要とされる高温条件下では、自己修復メカニズムを機能させるために組み込まれる通常の成分は機能しない。したがって、本研究の主な目的は、耐火物に適した全く新しい高温自己修復メカニズムを開発することであり、これによって今までにない優れた靱性メカニズムを生み出すことにある。

1. Introduction

The steel production chain has been going through a transition process towards a decarbonized future, where a large variety of actions are under consideration¹⁾. Although most of them are predicted to be fully implemented before no less than two decades, others are already in place in the ironmaking sector, involving both the use of different fuel mixes and the addition of new metallic charges. Additionally, steel producers have been looking for opportunities to reduce energy losses and CO₂ emissions in process beyond the blast furnace operations²⁾.

The refractory lining is directly responsible to keep the heat inside the equipment and prevent any metal temperature drop. Nonetheless, in some cases, such role becomes challenging as the refractory material must also withstand very aggressive thermal cycles, as in the case of torpedo cars and hot metal ladles. A classical approach to reduce thermal damage is by adding carbon sources, mainly graphite, in the refractories' structure so that the heat is easily transferred through the material and a lower thermal stress is generated. As a side-effect, however, more energy is lost by thermal conductivity by the refractory walls, which is undesirable for the sustainability commitments of steel producers³⁾.

In this scenario, where avoiding the cracks generated by thermal cycles are not straightforward, a different perspective is needed and the right question to be asked is: what if we could recover such cracks during operation?

Self-healing mechanisms are quite largely explored in the polymers field, where, for instance, small capsules containing a setting agent are included in the materials structure⁴⁾. When a crack reaches them, the capsules are broken and a hardening reaction takes place between the base material and the additive which is now available, promoting the complete sealing of the crack area. Likewise, a new class of concretes for building construction was also developed with biomineralization ability. In these materials, bacteria are introduced so that they can metabolically produce minerals to help repair cracks and damage to the concrete⁵⁾.

Although those self-healing mechanisms are well-known and proved to work efficiently, they are still

Table 1 ACS brick formulations evaluated in this work, in mass%. SRB REF is the Shinagawa reference brick in the market. SRB HEALBORN stands for the newly developed SELF-HEALING technology

RAW-MATERIAL	SRB REF	SRB HEALBORN
Coarse Al_2O_3	55.0 %	55.0 %
Fine Al_2O_3	13.0 %	13.0 %
$\text{SiC} + \text{C}$	13.0 %	13.0 %
Binder	4.0 %	4.0 %
Anti-oxidants	2.0 %	2.0 %
Self-healing additives	–	5.0 %

2. 材料と実験方法

混鉄車のライニング材料として一般的なASCれんがにおいて、新しい自己修復メカニズムの導入を検討した。生物による修復挙動を再現すべく、通常のASCれんがに新たな微細構造を導入し、発生した亀裂と効果的に相互作用して、それを修復できるようにした。これは、人間の細胞組織が新しい細胞組織を形成して傷を治癒する様子に似ている。このような修復を可能とする修復剤として2種類の無機添加剤をASCれんがの配合に追加し、Table 1に示すような独自の自己修復配合(SRB HEALBORN)を得た。比較の基準となるASCれんが(SRB REF)は、既存製品から選択した。

2.1 自己修復評価

自己修復メカニズムの存在を観察するために、両方の配合を対象に繰り返し加熱冷却試験を実施した。試験には1450℃で5時間、還元雰囲気中で焼成した直方体形状(160mm×40mm×40mm)の試料を供した。繰り返し加熱冷却試験の各サイクルは、室温(30℃)に置いた試料をあらかじめ1200℃に予熱した炉に挿入して急加熱を実施、30分後に炉から取り出した後、室温に30分間放置して冷却するものであり、この工程を16回繰り返し、2サイクルごとに試料の弾性率を測定した。

また、自己修復配合(SRB HEALBORN)の試料における修復された亀裂の存在を特定する目的で、走査型電子顕微鏡(SEM)による組織観察を実施した。比較のために通常のASCれんが(SRB REF)の調査も併せて実施した。

limited to room temperature conditions. At very high temperatures, such as the ones contemplated during the steel process operations, the usual components incorporated to induce self-healing mechanisms in those materials are no longer functional. The main purpose of this work was, then, to investigate and develop an entirely novel high temperature self-recovery mechanism, based on nature-like phenomena adapted to refractory structures, giving birth to the utmost toughness mechanism ever seen.

2. Materials and Methods

The introduction of the new self-healing mechanism was evaluated in an Al_2O_3 - SiC - C brick, frequently used as the torpedo car lining material. In order to mimic the healing behavior of living creatures, the regular ACS microstructure was reengineered in such a way that it could smartly interact with the just-generated crack and seal it, just like the human tissue heals a fresh wound with the formation of a new tissue layer. For this purpose, a combination of two non-organic recovery agents was added to the torpedo car formulation, as shown in Table 1, resulting in the SRB HEALBORN formulation. The reference ACS recipe (SRB REF) was selected due to its benchmarking performance in the market.

2.1 Self-healing evaluation

For a better observation of the presence of eventual self-healing mechanisms, cyclic thermal shock tests were conducted for both formulations, using three prismatic samples (160 mm × 40 mm × 40 mm) of each composition, pre-fired at 1450 °C for 5 h at reducing conditions. Each cycle started with placing the samples originally at room temperature (30 °C) into a pre-heated furnace (1200 °C), leading to an aggressive heating shock. After leaving them there for 30 minutes, the cycle ended by returning the pieces to room temperature for more 30 minutes, inducing a cooling stress. This step was repeated sixteen times and, for every two cycles, the modulus of rupture (MOE) of the samples were measured to follow any variation in the material's structure along the test.

Once the recovering benefits could be proved, a scanning electron microstructural (SEM) analysis was performed to identify the presence of healed cracks in the damaged samples of the SRB HEALBORN composition. The cracks in the SRB REF material

2. 2 各種性能評価

自己修復特性以前に重要なことは、耐火物の微細構造に自己修復メカニズムを導入しても、他の特性が損なわれず、元々の混鉄車用れんがの優れた性能が維持されることである。そこで、二つの配合 (SRB REFおよびSRB HEALBORN) について、以下の試験を行って各種特性を評価した。

見掛け気孔率および見掛け比重

ASTM規格C380に従い、灯油中でアルキメデス法により評価を行った。

強度試験

直方体試料(160mm×40mm×40mm)を用いて三点曲げ試験および圧縮強度試験(ASTM C583)を実施した。

侵食試験

回転ドラム法により、高炉スラグ80%と鉄屑20%の混合物を侵食剤として用いて行った。試験時間は2時間、途中1時間経過後に侵食剤を入れ替えた。

耐酸化性試験

立方体試料(50mm×50mm×50mm)を1000℃に予熱した炉内に置き、酸化雰囲気下で加熱した。6時間または24時間後に取り出し、冷却後に切断し、切断面における酸化領域を測定した。

熱間曲げ強さ

1450℃、還元雰囲気下で、直方体試料(160mm×25mm×25mm)を用いて三点曲げ試験(ASTM C583)を実施した。

上記のすべての試験において、1000℃または1450℃で5時間、還元雰囲気下で焼成した資料を用いた。

耐火物のラボ評価は重要であるが、実際の操業条件に適したものであるかは、実炉試験を行って確認する必要がある。そのため、当社のSRB HEALBORNれんがを、ブラジル国内の製鉄所において、溶鉄鍋の最も重要な部位である底部の湯当たり部に試験適用し、剥離の有無、使用後の残存厚み、損耗速度について調査を行った。

今回は実炉試験を溶鉄鍋で実施したが、この設備は混鉄車と使用条件が似通っており、かつ、使用期間が短くデータ収集が迅速に行えるメリットがある。

3. 結果と考察

繰り返し加熱冷却試験で得られた結果をFig.1に示す。基準試料(SRB REF)は16回の加熱冷却サイクル後も良好

were also investigated for comparisons.

2. 2 Performance evaluation

One of the project assumptions is that the introduction of a self-healing mechanism in the refractory's microstructure would not damage any of the other properties and, therefore, compromise the well-known performance of Shinagawa's bricks for torpedo car. The following properties were then evaluated for the two formulations (SRB REF and SRB HEALBORN):

- Open porosity and apparent density: evaluated by using the Archimedes technique in kerosene, following the ASTM Standard C380;
- Modulus of rupture: carried out under three-point bending tests and compressive strength (ASTMC 583) using prismatic samples (160 mm × 40 mm × 40 mm);
- Corrosion tests: conducted in a rotary furnace, in a two-cycle process, where a mix of blast-furnace slag and pig iron was used (80 % slag + 20 % pig iron);
- Oxidation resistance tests: carried out according to the following procedure → cubic samples of 50 × 50 × 50 mm were placed inside a pre-fired furnace at 1000 °C, under oxidizing atmosphere, so they could go through an aggressive oxidation process. They were withdrawn after 6h or 24h and, after cooling down, they were cut, and the cross-sections were used for measuring the oxidized layer.
- Hot modulus of rupture: carried out under three-point bending tests (ASTMC 583) at 1450 °C and reducing atmosphere using prismatic samples (160 mm x 25 mm x 25 mm).

For all the above-mentioned tests, samples were previously fired at 1000 °C or 1450 °C, for 5 h, at reducing atmosphere.

Laboratory validation of refractory materials is of great importance, but only after field tests the material can be validated due to the specific operating conditions. For this reason, Shinagawa's brick SRB HEALBORN was tested in the most critical region of an iron ladle (impact region on bottom) in a Brazilian steel industry and the following parameters were monitored during the campaign:

- Presence of spalling;
- Residual thickness after the campaign;
- Wear rate.

な性能を示した。最初の2回の加熱冷却後に、弾性率が約15%低下しており、これは構造中に軽微な損傷が形成されたことを示しているが、その後それ以上の弾性率の低下は見られなかった。すなわち、SRB REFは熱衝撃による損傷に十分耐えるように設計されており、安定した性能を示すものであった。

新たに開発された配合 (SRB HEALBORN) も同様の初期挙動を示し、構造中に微亀裂が生成したと考えられる。しかし、その後は単にそれ以上の損傷を抑制するだけでなく、その優れた微細構造は新たな亀裂と相互作用し、加熱冷却を繰り返すごとに徐々にそれらを封じ込め、最終的な弾性率は元の損傷のないレベルに完全に回復するという、驚くべき結果が得られた。

試験後、SRB REFおよびSRB HEALBORNの試料における亀裂の状況を比較するために、微構造観察を行った。SRB REFの SEM画像をFig.2 (a) に示す。粗粒とマトリックスの間に亀裂が生成しているが、適切な粒度構成と熱的特性により、亀裂は進展することなく停止し、前述のグラフで示されるように、繰り返し加熱冷却を受けても安定した

The test was carried out on an iron ladle as this equipment has very similar demands to the torpedo car and allows faster data collection due to the shorter campaign.

3. Results and Discussion

The results obtained during the cyclical thermal shock tests are shown in Fig. 1. It is possible to observe that the reference material (SRB REF) confirmed its denomination as the benchmarking product, with a very good performance after 16 thermal cycles. A small decrease in the Modulus of Elasticity is perceived after the two first cycles (~15 %), indicating the formation of minor damage in the structure, with no further deterioration, which, in other words, means that the SRB REF composition was well designed to sustain the initial thermal shock damage and guarantee a stable performance. The newly developed formulation (SRB HEALBORN) also presented the same initial behavior, with the generation of thermal cracks in its microstructure. Nonetheless, better than just suppressing the damage propagation along the test, its smart microstructure was able to interact with the new cracks and progressively seal them as further thermal cycles were applied to the samples. As the test was concluded, the last MOE measurement presented an amazing result: its value was entirely recovered to the level of the original, non-damaged structure.

After the test, the samples of SRB REF and SRB HEALBORN were collected and used for a microstructural evaluation in order to identify and compare the cracks situation at both materials. Fig. 2 (a) shows the SEM image obtained for the SRB REF material using topographic effects, where it is easy to point out the generated crack between a

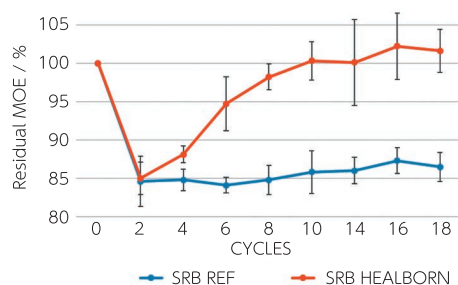


Fig. 1 Residual Moduli of Elasticity (MOE) as a function of thermal shock cycles for SRB REF and SRB HEALBORN formulations.

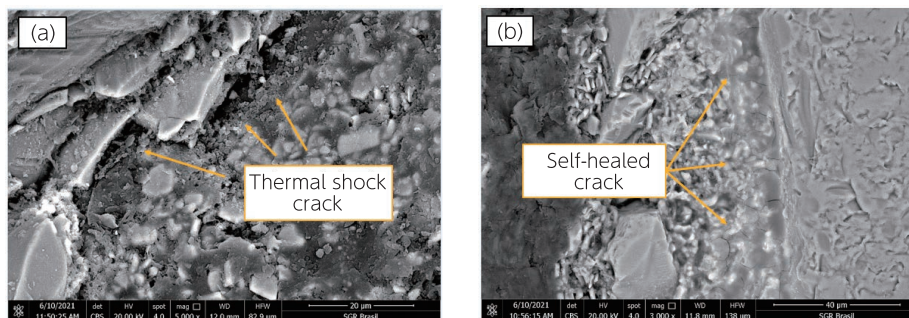


Fig. 2 Micrograph of (a) SRB REF and (b) SRB HEALBORN samples, obtained by SEM after sixteen thermal shock cycles.

状態を維持した。SRB HEALBORNの微構造 (Fig.2 (b)) においても、マトリックスと粗粒との間に同様の亀裂パターンが観察されたが、最も重要な違いは、生成したこの亀裂がその後の繰り返し加熱冷却中に自己修復剤が微構造内で活性化され、進展する亀裂と相互作用することで形成された新しい相によって修復されている点である。この革新的なメカニズムは、微構造を元の状態に修復する役割を果たす。

このメカニズムの適用により、熱衝撃による損傷に対して高い抵抗性を持つ新しいタイプのASCレンガの提供が可能となる。新しいメカニズムの導入が予期しない不具合を生じないかを確認するため、他の重要な物理的および化学的特性を検証した。Fig.3, 4, 5および6は、それぞれ、1000℃および1450℃で、還元雰囲気中で5時間加熱した両試料の見掛け比重、見掛け気孔率、冷間曲げ強さおよび圧縮強さを示す。

レンガのマトリックスの組成の違い、およびその結果として高温で形成される新しい相の構造に起因して、両者は1450℃加熱後の比重と気孔率においてわずかな違いを示した。しかし、このような違いにもかかわらず、新しい自

coarse grain and the matrix. Due to a well-designed grain size distribution and proper thermal properties, the crack was successfully deflected and stopped, enabling a stable behavior along the thermal cycles, as seen in the previous graph. In the microstructure of the SRB HEALBORN material (Fig. 2 (b)), one may also observe the same crack pattern between the matrix and coarse grains. The main and most important difference is that such crack is visually sealed with a new phase that was formed during the following thermal cycles by the activation of the self-healing agents in the microstructure when they interacted with the propagating crack.

This innovative smart mechanism was responsible to restore the microstructure original condition and, therefore, could be used to implement a new series of $\text{Al}_2\text{O}_3\text{-SiC-C}$ bricks virtually immune to thermal cyclic damages. For that, it is also important to verify other important physical and chemical properties in order to check whether the introduction of such a new structure could lead to a non-expected side-effect. Fig. 3, 4, 5 and 6 present, respectively, the

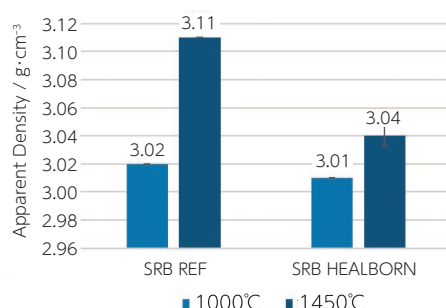


Fig. 3 Apparent density of SRB REF and SRB HEALBORN samples after firing at 1000 °C and 1450 °C.

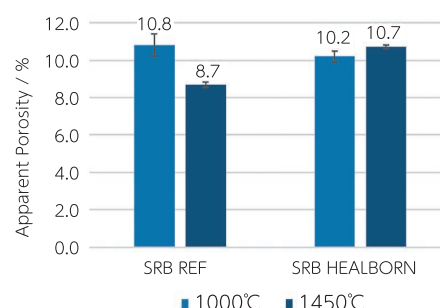


Fig. 4 Apparent porosity of SRB REF and SRB HEALBORN samples after firing at 1000 °C and 1450 °C.

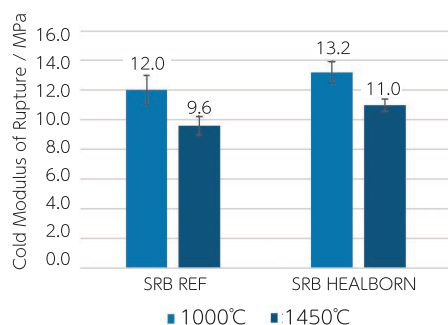


Fig. 5 Modulus of rupture of SRB REF and SRB HEALBORN samples after firing at 1000 °C and 1450 °C.

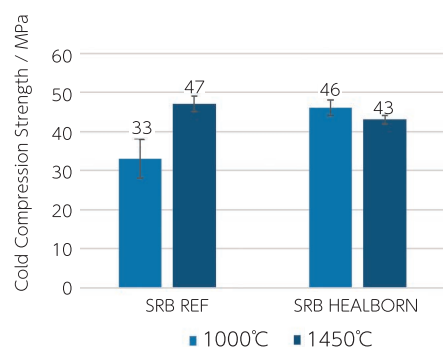


Fig. 6 Compressive strength of SRB REF and SRB HEALBORN samples after firing at 1000 °C and 1450 °C.

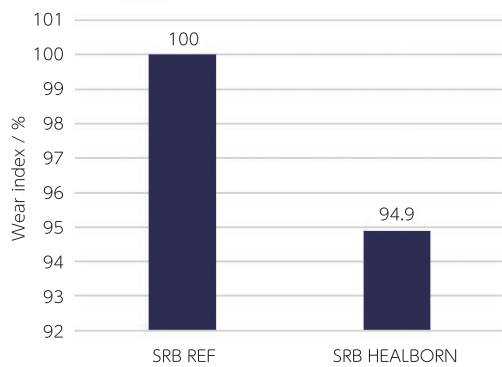


Fig. 7 Corrosion wear index of SRB REF and SRB HEALBORN samples.

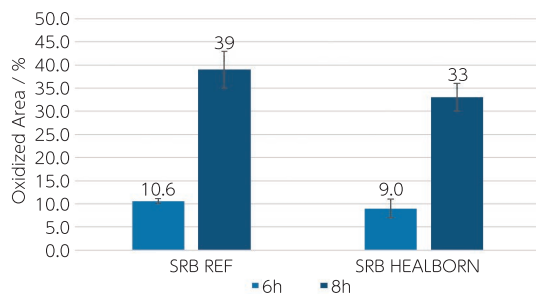


Fig. 9 Oxidation resistance results after 6 h and 24 h for SRB REF and SRB HEALBORN samples.

己修復材料の曲げ強さ (MOR) および圧縮強さは、基準となる試料に匹敵するレベルであることは重要であり、しっかりと結合した組織を有していることが示されている。

自己修復メカニズムを導入したSRB HEALBORN材は、基本的な物理特性をほぼ維持した上で、耐食性の向上も認められた (Fig.7, Fig.8)。耐火物の侵食は、材料内の空隙や欠陥を通じて金属やスラグが浸透することによって生じるため、亀裂を封鎖する機能が金属やスラグの浸透経路を遮断し、れんが内部での化学的溶損の抑制に寄与したものと考えられる。

酸化試験結果をFig.9に示す。自己修復剤の添加はSRB HEALBORN材料の耐酸化性には影響せず、実際には亀裂を封鎖する機能が酸化をわずかに抑制した可能性が考えられる。また、再生能力を持つ材料における一般的な懸念は、自己修復剤が高温の物理的特性に与える影響であるが、Fig.10に示すように、自己修復剤の添加は材料の熱間強度に悪影響を及ぼさなかった。



Fig. 8 Cross-section of SRB REF and SRB HEALBORN samples after the corrosion test.

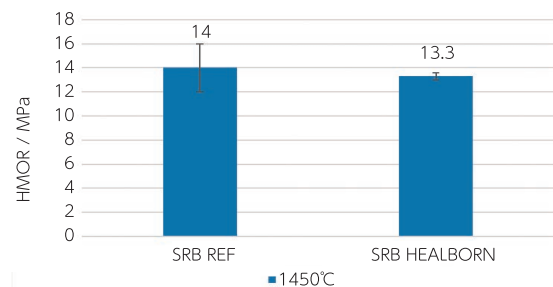


Fig. 10 Hot modulus of rupture index at 1450 °C for SRB REF and SRB HEALBORN samples.

apparent density, apparent porosity, cold modulus of rupture and compressive strength for both materials after firing at 1000 °C and 1450 °C for 5 h at reducing atmosphere.

Due to the difference composition of the brick's matrix and, consequently, to the new phase structures which are formed at high temperatures, the new SRB HEALBORN samples presented slight differences in the density and porosity values after firing at 1450 °C. However, it is relevant to note that, despite of those differences, the new self-healing material presented a cohesive and well bonded structure, as the MOR and compressive strength values were entirely compatible with the benchmarking reference ones.

Besides keeping almost the same values for the basic physical properties, the introduction of the smart self-healing mechanism in the SRB HEALBORN material also led to an improvement of the corrosion

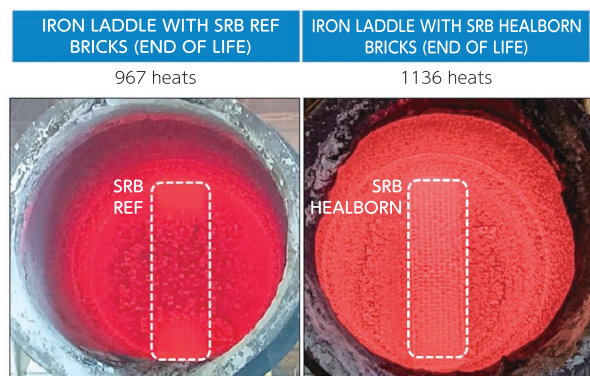


Fig. 11 Visual aspect of the impact region in the SRB REF and SRB HEALBORN campaigns after the end of life.

Table 2 Residual thickness, wear rate, wear and heats number for SRB REF and SRB HEALBORN materials after their respective campaigns

IRON LADLE - IMPACT ZONE (BOTTOM) - SRB REF			
HEATS	RESIDUAL THICKNESS / mm	WEAR RATE / mm·heat ⁻¹	WEAR / mm
967	207	0.096	93
IRON LADLE - IMPACT ZONE (BOTTOM) - SRB SH			
HEATS	RESIDUAL THICKNESS / mm	WEAR RATE / mm·heat ⁻¹	WEAR / mm
1136	213	0.076	87

さらに、溶銑鍋における実炉試験において、SRB HEALBORNレンガの優れた性能が確認された。前回のキャンペーンで使用したSRB REFレンガと比較すると、その違いが明らかである。Fig.11に示すように、SRB HEALBORNレンガは剥離や亀裂、顕著な溶損は認められず、基準材料であるSRB REFレンガと比較して大幅に良好な外観であった。

キャンペーンの終了時に、SRB HEALBORNレンガの残厚を測定し、前回のキャンペーンで使用したSRB REFのデータと比較した。加熱サイクルが多かったにもかかわらず、SRB HEALBORNはより大きな残厚と、より低い損耗速度を示し、その優れた性能を証明した (Table 2)。これらの有望な結果は、SRB HEALBORNが熱衝撃に対して優れた抵抗力を持ち、亀裂や剥離がないことに起因しており、それらの特徴が浸潤や目地損傷を抑制し、損傷を低減したと考えられる。

resistance, as observed in Fig.7 and 8. As the refractory corrosion takes place via the infiltration of metal and slag through voids and defects in the material, a high-temperature sealing system may clearly help to block possible infiltration paths and to prevent chemical dissolution inside the brick.

Fig. 9 presents the measurements of the oxidized area of SRB REF and SRB HEALBORN samples after exposition of 6 h and 24 h in air. Once again, the presence of the self-recovery additives did not affect the material's oxidation resistance and, actually, the smart sealing process could again have helped to slightly decrease the oxidation process for the SRB HEALBORN material.

A common concern when it comes to materials with the ability to regenerate is the effect of regenerating additives on the material's hot mechanical properties. However, as can be seen in Fig. 10, the change in formulation did not have a negative impact on the material's hot mechanical strength.

During the campaign of the iron ladle with SRB HEALBORN bricks in the field trials, the refractory's superior performance was visually observed, especially when compared to SRB REF from the previous campaign. The SRB HEALBORN bricks showed no spalling, visible cracks or pronounced corrosion, as well as a considerably superior and uniform appearance compared to the reference material, as can be seen in Fig. 11.

At the end of the campaign, measurements were taken of the residual thickness of the bricks from the campaign with SRB HEALBORN to compare with the data from the previous campaign with SRB REF. Even though it went through more heating cycles, at the end of the campaign SRB HEALBORN had a greater residual thickness and a lower wear rate, proving its superior performance (Table 2). These promising outputs are the result of SRB HEALBORN's greater resistance to thermal shock and absence of spalling, which result in a lower tendency to infiltration, joint attack and wear.

4. Conclusions

Aiming at reducing the energy losses in the steel manufacturing process while also increasing the lifetime of refractories applied at high thermal cyclical areas, an exclusive smart self-healing structure was

4. 結言

製鋼プロセスにおけるエネルギー損失を削減し、高温の加熱を繰り返し受ける条件で使用する耐火物の寿命を延ばすことを目指して、独自の自己修復メカニズムを開発し、混鉄車用のASCれんがに導入した。この新しいメカニズムは、熱衝撃によって生成する亀裂に迅速に反応し、自己修復剤の働きにより亀裂を完全に封鎖することができた。この作用により材料は元の状態に完全に修復され、弾性率は熱衝撃を受ける前と同等のレベルに戻った。ラボ評価の結果、新たなメカニズムの導入による物理的特性や耐食性、耐酸化性の低下は認められなかったため、実炉においても良好な性能が期待され、実際に実炉試験によってそれが証明された。自己修復れんがは、稼働中に生じた亀裂を修復し、剥離が発生しなかったことで、その優れた性能を証明した。

developed and introduced in an $\text{Al}_2\text{O}_3\text{-SiC-C}$ torpedo car brick composition. The new mechanism was able to interact promptly with the cracks generated during thermal shock processes, activating the self-healing agents, and completely sealing the crack area. This innovative process induced a total recovery of the original structure of the material and its modulus of elasticity returned to values as high as the pre-thermal shock condition. As neither the physical properties nor the resistance to corrosion and oxidation were affected by this new smart structure, a good performance was expected from this nature-inspired toughness mechanism, which was proven by field tests. The self-healing bricks proved their superior performance by recovering the cracks generated during operation and not spalling.

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