

SHINAGAWA TECHNICAL REPORT

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for BOF Bottom Blowing Tuyere Bricks

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品川技報

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要 旨

転炉底吹き用羽口の中で、Multi-hole plug (MHP) は細管集合型に分類される。使用後のMHPには稼働面に平行な亀裂が見られる場合があり、この亀裂から剥離損傷が起きると考えられる。MHPの更なる耐用性向上を実現するためには実機で見られる亀裂剥離の低減が必要であるが、従来の浸漬法などの試験方法では実機を再現する評価が困難であった。今回、MHPのスポーリング評価方法の検討を行い、一体構造物として評価可能な試験方法を開発した。

Abstract

The Multi-Hole Plug (MHP), a type of a bottom blowing tuyere brick used for BOF steel making, contains many slender pipes which are closely aligned in a MgO-C brick. When we observe used MHP bricks, we often recognize they have cracks parallel to the hot faces, which suggests that if we could suppress the cracking, the performance of MHP bricks would be improved. Conventional thermal spalling test methods such as a dipping test into molten metal were not suitable for evaluating the MHP bricks because cracking usually occurs along the direction of the pipes. We developed a new spalling test method using a panel of spalling test equipment in which restraint against MHP monoblock and partial cooling of the core brick of an MHP were introduced. We conducted computer aided FEM analysis and estimated when the cracking occurred in the new spalling test procedure.

1. 緒言

転炉の上底吹き精錬において、底吹き羽口からのガス吹きによる強攪拌は非常に重要な役割を果たしている。羽口にはいくつかの方式があり、MgO-Cレンガ内に多数のSUS細管を埋設したMulti-hole plug (MHP; Fig. 1) は、大流量から

1. Introduction

Strong molten-metal agitation by gas-blowing from bottom tuyeres has an important role in the BOF steel making process. The Multi-Hole Plug (MHP), a type of a bottom blowing tuyere brick, contains many slender stainless

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小流量までの広範囲のガス流量の調整が可能である点が特徴である¹⁾。また、ガスの吐出位置を一定範囲に広げることで、ガス吹きに伴う熱応力が羽口中心に集中することを防ぎ、安定した耐用を実現している。

しかし、実機使用後のMHPを回収して観察すると、れんが内に稼働面と平行な亀裂が観察される場合がある (Fig. 2)。吹錬中のMHPは溶鋼による稼働面の加熱とSUS細管のガス冷却によって、れんが内部に大きな温度勾配が生じている。また、出鋼後はガス冷却によってMHPの稼働面も急速に冷却される。使用後品に認められる稼働面と平行な亀裂は、このような温度勾配と温度変動によって生じた熱スポーリングと考えられる。さらに、稼働中の残厚測定の変移から、MHPではある頻度で亀裂からの剥離損傷が発生していると考えられる。そのため、MHPのさらなる耐用性向上を図るためには、れんが内に生じる亀裂・剥離の低減が必要である。

MHPの場合、埋設されたSUS細管の存在や芯体とブロックから構成される構造体としての特徴から、熱衝撃による亀裂の発生や伸展の様式がMgO-Cれんが単体での状態とは異なる。そこでSUS細管を埋設した構造体として耐スポーリング性を評価する方法を検討した。

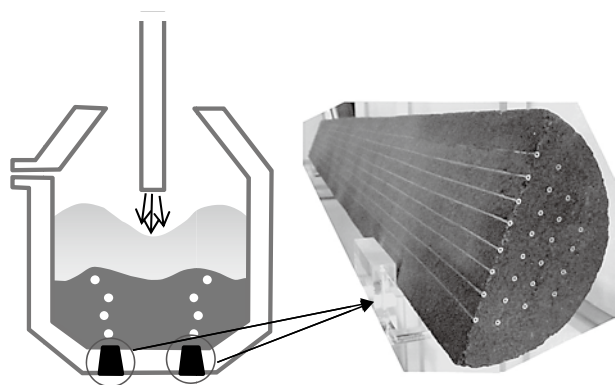


Fig. 1 Outline of MHP for BOF.

steel pipes (approximately 2mm I.D.) which are closely aligned in a MgO-C brick (Fig. 1). MHP is characterized by its superior controllability of gas blowing rate for a wide range from small to large quantities¹⁾. In addition, MHP has the advantage of having more stable and superior performance than other tuyere bricks because the thermal stress caused by gas blowing is dispersed to certain areas by many slender pipes, which suppress the strong focusing of thermal stress around the center of the brick as in other tuyere bricks.

However, when we observe used MHP bricks, cracks are often recognizable parallel to the hot faces (Fig. 2). During the refining, MHP bricks have steep temperature gradient in the body due to the combined effects of heating from the molten metal to the hot face and cooling by the blowing gas through the pipes. Furthermore, the hot face of the MHP will be cooled rapidly after tapping since gas keeps flowing through the pipes. Such a thermal gradient and fluctuation probably cause the cracking parallel to the hot face as observed in the used MHP bricks. In fact, we think the MHP bricks peel off occasionally from the parallel cracks during the

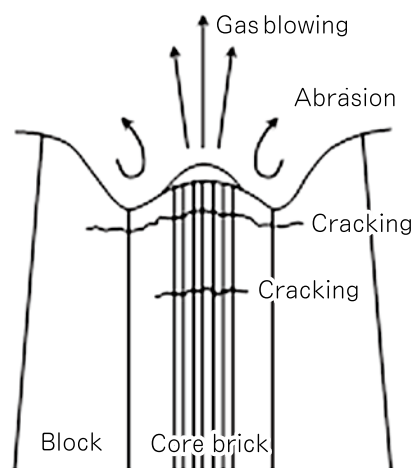


Fig. 2 Wear mechanism of MHP tuyere bricks.

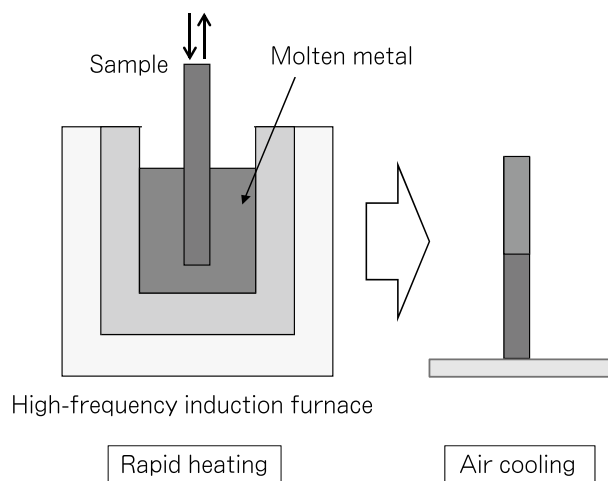


Fig. 3 Molten metal dipping spalling test.

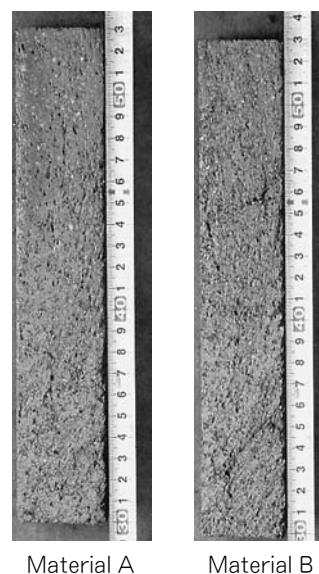


Fig. 4 Cut sections of MgO-C brick samples after molten metal dipping spalling test.

2. スポーリング試験方法の検討

2.1 芯体のみの溶銑浸漬スポーリング試験

MgO-Cレンガの亀裂、剥離の評価方法としては高周波誘導炉を用いた溶銑浸漬による急熱急冷²⁾が一般的である (Fig. 3)。曲げ強度/弾性率比の異なる2種のMgO-C材について単体試料を作製して試験すると、Fig. 4に示すように亀裂の発生状況に違いが認められる。SUS細管を埋設したMHP試料についても同じ手法でスポーリング試験を試みた。

SUS細管を6本含んだ40×40×230mm形状のMgO-Cレンガ試料を作製し、Fig. 3と同様な手順で溶銑に浸漬した後の外観をFig. 5に示す。SUS細管を埋設した試料では細管に沿うように亀裂が発生した。SUS細管とMgO-Cレンガの境界は亀裂が生じやすい組織的な弱所であるが、実機の使用後ではこのような亀裂はほとんど認められず、細管方向と垂直な（稼働面と平行な）方向の亀裂がよく観察される。これは、実機の耐火物ライニングでは周囲のレンガからの拘束によって境界に沿った亀裂の発生が抑制されているため、と考えられる。また、MHPはガスを導入する中心部分（芯体）と周囲のブロック部分が同時成形で一体化された大型形状で使用されるのが一般的であ

campaign according to the measured of residual thickness data of the MHP bricks. Thus, it is necessary to suppress cracking or spalling in order to improve the performance of MHP bricks.

The mechanism of crack generation and propagation of MHP bricks is different from that of simple bricks because MHP bricks are composed of MgO-C material and stainless steel pipes, and, also the MHP in this study is a monoblock type composed of a core brick part and surrounding block part co-molded into a monoblock shape. We examined how to evaluate the spalling resistance of such monoblock MHP bricks in the laboratory.

2. Examination of Thermal Spalling Test Method

2.1 Spalling test of core brick by dipping into molten metal

A molten metal dipping test using a high-frequency induction furnace (Fig. 3) is widely used to evaluate the spalling resistance of MgO-C bricks.²⁾ Fig. 4 shows the results of the

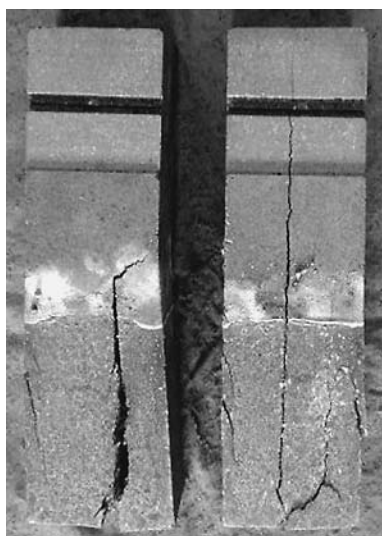


Fig. 5 Appearance of MgO-C brick samples containing stainless pipes in the body after molten metal dipping spalling test.

る。したがって、MHPのスポーリング試験は構造体として評価することが重要と考える。

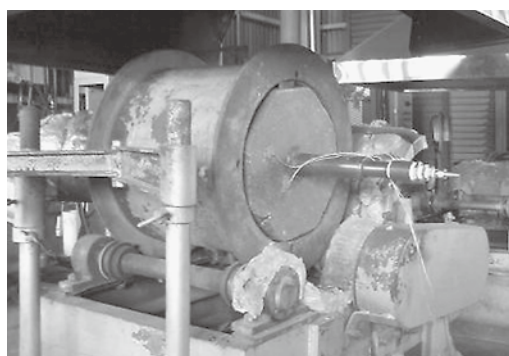
2. 2 MHP一体構造体のバーナー加熱

スポーリング試験

実機製品同様にSUS細管埋設部分（芯体）と周囲のブロックの一体構造体を作製し、回転ドラム侵食試験装置を活用してバーナー加熱スポーリング試験の予察実験を行った。試験装置の概要をFig. 6に示す。試料は実製品と同じ工程で作製し、8角柱形状に切断してドラム内に設置した。ドラムと試料との間にはわずかな隙間があり、鉄皮による拘束は効いていない。実機操業時のガス吹き

spalling test for two kinds of MgO-C materials with different ratios of MOR (modulus of rupture) / MOE (modulus of elasticity). The result clearly demonstrated the difference in the spalling resistance of materials. We tried to evaluate the MHP core brick samples which contain pipes by the same dipping spalling test.

We prepared samples with dimensions of $40 \times 40 \times 230 \text{ mm}$, each of which contained 6 stainless steel pipes. Fig. 5 shows the appearance of the samples after the dipping test conducted by the procedure shown in Fig. 3. Some cracks occurred along the direction of the pipes. We think the boundary between the pipes and MgO-C materials is a vulnerable area for cracking. However, this type of cracking is rarely observed in the used MHP bricks. Instead, the cracks perpendicular to the pipes (i.e. parallel to the hot face) are often observed. We think that the cracking along the boundary between the pipes and MgO-C materials must be suppressed by the restraint force of the surrounding bricks in the actual lining. In addition, MHP tuyeres are generally used as a large monoblock structure composed of the core brick part with the pipes and supporting block part, which is co-molded into a monoblock shape. Therefore, we thought it important to consider such special conditions for evaluating



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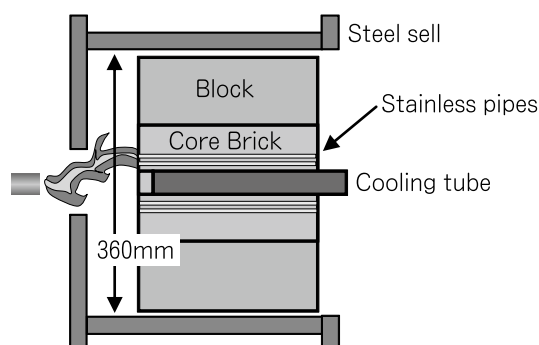


Fig. 6 Burner-heating drum spalling test for the MHP monoblock with water cooling tube.

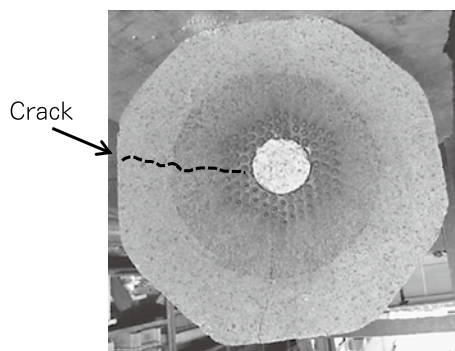


Fig. 7 Appearance of hot face of the MHP monoblock after the burner-heating drum spalling test.

による中心部の冷却を模擬するため、中心部分に孔を開けて冷却管を設置し、そこへ循環水を通した。炉体は回転させずに固定したままで酸素-プロパンバーナーを用いて片面を加熱し、冷却は自然放冷で行った。

試験後試料の加熱面をFig. 7に示す。試験後の試料には実機の使用後にみられるような加熱面に対して平行方向の亀裂は発生せず、溶銑浸漬スポーリング試験同様のSUS細管に沿う方向の亀裂が発生するのみであった。

この試験方法においても、ブロックと一体化することで、細管に沿って芯体に亀裂が発生することを抑制する拘束力がある程度は生じていると推測される。しかし、亀裂は一体構造体の全体に渡って生じた。このことから、稼働面と平行な亀裂を生じるためには周囲の耐火物ライニングからの拘束力も必要であることが分かった。

2. 3 れんが張りパネル中でのMHP一体構造体のバーナー加熱スポーリング試験

実機と同様な亀裂を再現するために、MHP一体構造体について拘束条件下でのスポーリング試験方法を開発した。

2. 3. 1 試験装置

重油バーナー加熱のパネルスポーリング装置を改造して試験炉を作製した。Fig. 8にその概要を示す。本装置の特徴は、1)大型のMHP一体構造体(400×390mm)を設置できる、2)1500℃までの加

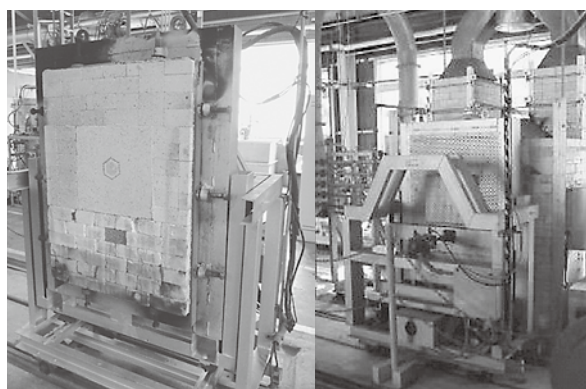
the spalling resistance of MHP bricks.

2. 2 Burner-heating spalling test of MHP monoblock samples

We prepared an MHP monoblock sample which was composed of the core brick and surrounding block part which was the same as the actual MHP products, and then, we conducted a preliminary burner-heating spalling test using rotary drum corrosion test equipment. Fig. 6 shows an outline of the burner-heating spalling test. The sample brick was made in the same manner as manufacturing actual products. Then, it was cut into an octagonal prism shape for setting in the drum as a test sample. There was a slight gap between the sample and the drum, so, the restraint around the sample brick was not effective. In order to simulate the cooling effect of the blowing gas, we made a hole in the center of the core brick and inserted a cooling unit with a water circulation system. We heated the hot face of the sample using an oxygen-propane burner without rotating the drum, and then, cooled down the drum in the ambient air.

The appearance of the sample after the test is shown in Fig. 7. There were no cracks parallel to the hot face but a crack in the same direction of pipes similar to the molten metal dipping test were found.

We felt certain that the restraining force would prevent the core brick cracking along the direction of pipes because the sample was a monoblock in which the surrounding block part could restrain the core brick. However, a longitudinal crack occurred along the whole length of the monoblock. We realized that, in order to produce cracking parallel to the hot face, we needed to simulate further restraining force against the MHP monoblock sample, that is, the force from the refractory lining bricks around the MHP monoblock.



Heating side

Back side

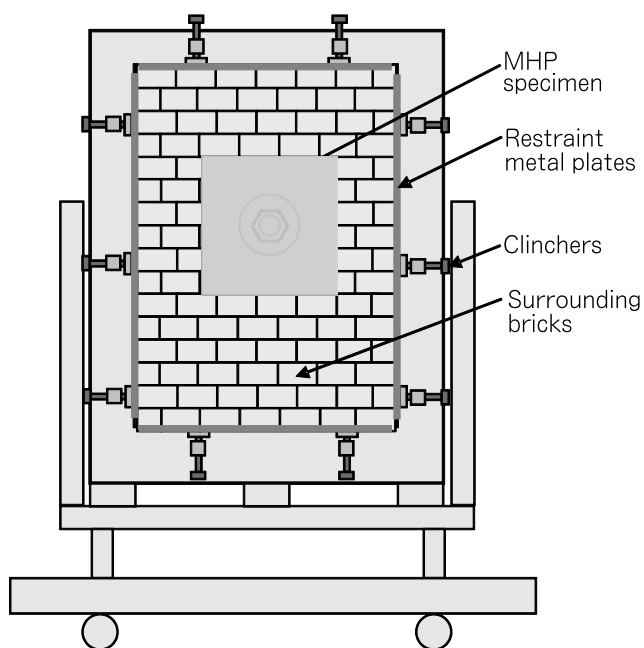


Fig. 8 New panel spalling apparatus for testing restrained MHP monoblock samples.

熱および保持が可能、3)周囲のれんがをボルト締めすることで試料を上下左右に拘束できる、4)試料台を左右にスライドさせて加熱冷却の繰り返しができる、5)冷却を水冷、空冷、自然放冷の3種類から選択可能、である。

2. 3. 2 実験条件

Table 1に示すように、3種のMHP一体構造体を新しいパネル式スポーリング試験に用いた。試料No. 1, No. 2はSUS細管本数が同じで、MgO-C材料が異なる (A, B)。この材料A, Bはそれ自体の耐熱スポーリング性が異なる。試料No. 3はMgO-C材料はNo. 2と同じであるが、芯体の冷却

Table 1 Configurations of the MHP monoblock samples

Sample No.	MgO-C material	Number of pipes
1	A	30
2	B	30
3	B	90

2. 3 Burner-heating spalling test of MHP monoblocks under restraining conditions

In order to reproduce cracking similar to actual usage, we have developed a new spalling test method for the MHP monoblock under restraining condition.

2. 3. 1 Testing equipment

We remodeled panel spalling test equipment with a heavy-oil burner-heating unit. Fig. 8 shows the outline of the new test equipment. This equipment has the following characteristics; 1) a large MHP monoblock sample (390×400×400mm) can be set in the panel, 2) the maximum heating temperature is 1500℃, 3) the MHP sample can be restrained both horizontally and vertically by constraining the panel bricks by bolting, 4) both rapid heating and cooling can be repeated by moving the sample panel from the heating position to the cooling position, 5) three types of cooling methods (water-cooling, air-cooling, and natural cooling) are possible.

2. 3. 2 Experimental procedure

As shown in Table 1, three kinds of MHP monoblock samples were used for the new panel spalling test. Samples No. 1 and 2 contained the same number of stainless pipes (30pcs) but different MgO-C materials (A, B), which had different thermal spalling resistances. As for the sample No. 3, the MgO-C material was the same as that used for No. 2, but the number of stainless pipes was increased to 90pcs in order

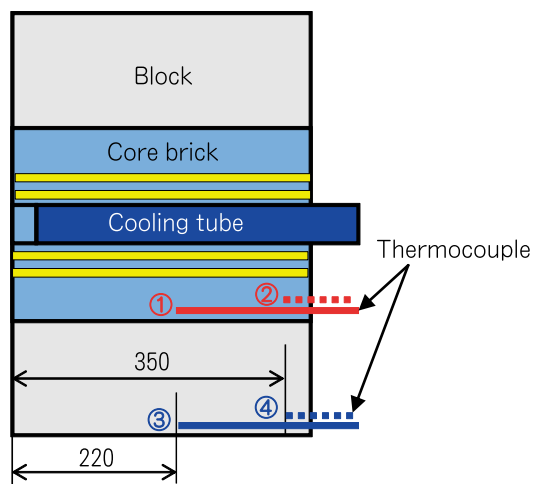


Fig. 9 Point of temperature measurement in MHP monoblock sample.

効果を高めるためSUS細管本数を増やしてある。

試料は実機製品と同じ工程で製造された。但し、試料の中央部には冷却管が入るため、あらかじめ中央部を避けてパイプを配列した。成形された一体化母材は高さ390×幅400×奥行き400mmの形状に切断し、中心部に冷却管設置用の貫通孔(φ60)を孔あけした。孔と冷却管との隙間には鉄粉を充填した。試験中の試料内温度を測定するため、加熱面より約220mmと約350mmの位置に熱電対を設置した (Fig. 9)。

試験試料の拘束は、周囲に並型形状のれんがを設置し、その周囲を押さえ金物とボルト締めにて拘束する方法で行った (Fig. 8)。参考のため、予察実験において均等に拘束することを十分に考慮せずに実験を行った時の炉内面の状態を Fig. 10に示す。回転ドラムを用いた場合 (Fig. 7)と同様に、SUS細管に沿う方向の亀裂が発生し、加熱面に平行な亀裂は発生しなかった。実機と同様な亀裂を再現するためには、強い拘束力が必要ではないが、試料が細管に沿った方向に開くのを防止するために全周を均一に拘束することが重要である。

温度条件は次の通りである。試料は昇温速度 $4.7^{\circ}\text{C} \cdot \text{min}^{-1}$ で炉内温度1500℃まで加熱して60分間保持の後、冷却位置にスライドして自然放冷した。

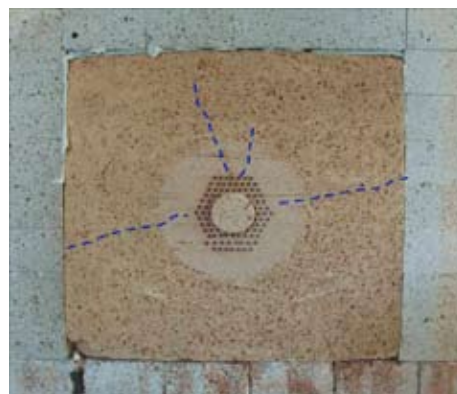


Fig. 10 Appearance of hot face of the MHP monoblock after burner-heating panel spalling test without restraint.

to increase the cooling effect on the core brick.

The sample bricks were made in the same manner as when manufacturing actual products. However, we did not place pipes in the central area of the core bricks in order to retain room for inserting a cooling tube. Each sample brick was cut to the shape of H390×W400×L400mm, then, a 60mm I.D. hole was drilled in the center of the core brick. The hot face end of the hole was plugged with MgO-C brick. The gap between the hole and the cooling tube was filled with iron powder. Thermocouples were installed approximately at 220 and 350mm away from the hot face to measure the brick temperatures (Fig. 9).

Rectangular bricks were installed around the MHP sample and the whole lining was restrained by bolting four metal plates surrounding the lining from four directions through a rigid frame as shown in Fig. 8. For a reference, the hot face of an MHP monoblock sample after the preliminary test was conducted without careful consideration on giving even restraint is shown in Fig. 10. Like the results of the rotary drum spalling test shown in Fig. 7, cracking occurred only in the direction along the pipes but no

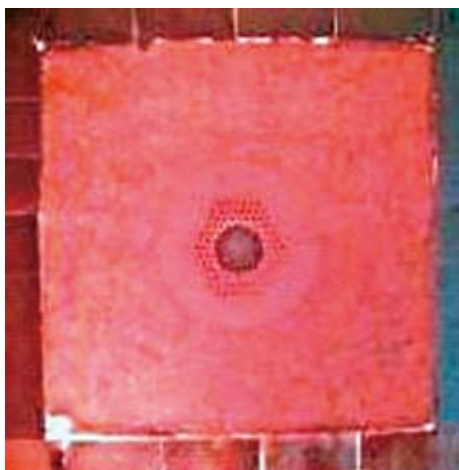


Fig. 11 Appearance of hot face of the MHP monoblock soon after burner-heating.

20分後、再び加熱位置に戻してバーナー加熱を行った。炉内温度1500℃にて60分間保持した後、再び冷却位置にスライドして常温まで自然放冷した。試料が常温まで低下してから、切断面における亀裂発生状況を確認し、耐熱スポーリング性を評価した。

2. 3. 3 試験結果および考察

冷却中のMHPブロックの加熱面の外観をFig. 11に示す。赤熱した加熱面のなかでSUS細管を埋設した中心部分のみが暗くなっており、冷却の効果が確認できた。

実験中の測温は毎回実施したが、再現性は良好であった。試料No. 2の測温結果をFig. 12に示す。炉内温度が1500℃に達し定常状態のとき、芯体外周部もブロック外周部も加熱面から約220mmの位置では550℃程度、約350mmの位置では450℃程度であった。なお、冷却時の試料は炉正面から外れた位置にあるため、加熱面はFig. 12の炉内温度よりも低い温度まで低下している。サーモカメラで観察した結果、冷却位置で20分自然冷却後に加熱面の温度は約500℃に低下していることを確認した。

試験後試料の加熱面および切断面をFig. 13に示す。拘束なしの片面加熱試験で発生したSUS細

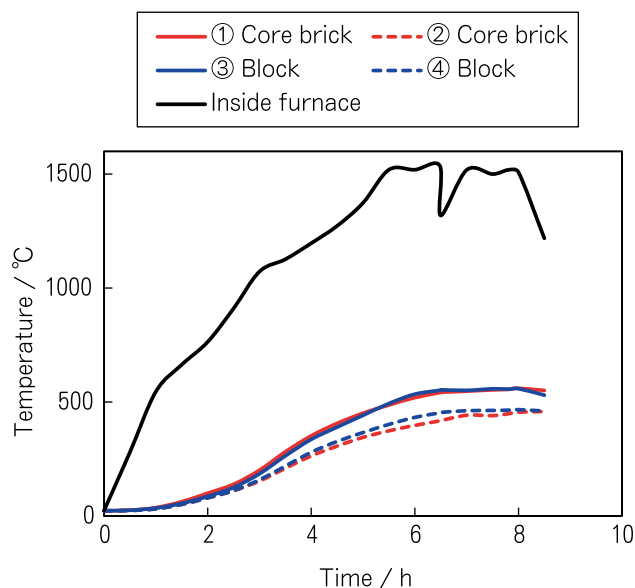


Fig. 12 Results of temperature measurement.

cracking parallel to the hot face occurred. This result suggests that an even restraining force around the MHP sample would have been required to prevent cracking along the pipes although a large restraining force might not been necessary to reproduce cracking similar that in actual usage.

The heating and cooling procedures of the new test method were as follows. The sample was gradually heated to 1500℃ at a rate of $4.7^{\circ}\text{C} \cdot \text{min}^{-1}$ and was kept at that temperature for 60 minutes. Then, the sample was moved from the heating position to the cooling position and was cooled naturally. After 20 minutes of cooling, the sample was moved back to the heating position and was heated rapidly up to 1500℃. After keeping the sample at 1500℃ for 60min, it was moved again to the cooling position. After cooling down to room temperature, we observed the appearance and cut face of the sample in order to evaluate the spalling resistance.

2. 3. 3 Results and discussion

The hot face of an MHP monoblock sample

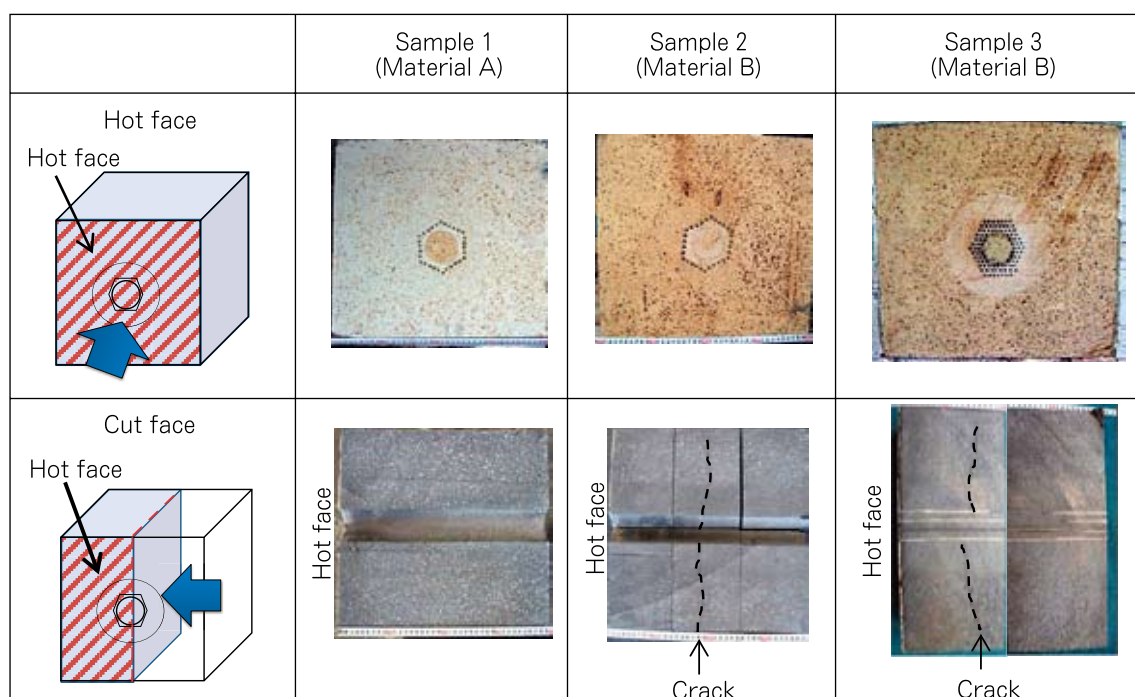


Fig. 13 Appearance and cut sections of the MHP monoblock after the burner-heating panel spalling test.

管に沿った亀裂は認められなかったため、周囲れんがによる拘束は効果があったと判断される。試料No.1（材質A）ではブロックと芯体との境界でわずかな肌分けが発生した以外には亀裂は認められなかった。試料No.2,3（材質B）では加熱面に対して平行方向の亀裂が認められた。この亀裂の位置は、SUS細管が30本の試料No.2では加熱面から約180mmであり、SUS細管を90本に増やした試料No.3では加熱面から約150mmであった。

したがって、本試験方法での冷却能の違いは亀裂の発生位置に影響し、亀裂の発生の有無はれんがが材質に依存している。試料No.2,3で認められた加熱面と平行方向の亀裂は実際の使用後れんがで観察される亀裂を再現しており、SUS細管を含んだ一体構造物としての評価が可能となった。

3. 構造解析

MHP一体構造物を用いた新しいパネル式スポーリング試験について、構造解析により亀裂の発生機構を検討した。

during the cooling stage of the test is shown in Fig. 11. Because a dark spot in the central area of the core brick surface was observed while other areas were red, we thought the effect of the cooling unit worked as expected.

Temperature measurement was conducted in every test and the results were reproducible. Fig. 12 shows the result for temperature measurements of sample No.2. When the furnace temperature reached 1500℃ and was being maintained, temperature of the core brick and surrounding block were both about 550℃ at 220mm from the hot face and about 450℃ at 350mm from the hot face. During cooling, the temperature of the hot face of the sample became far lower than that of the furnace temperature which is shown as “Inside furnace” in Fig. 12, because the sample was located away from the front of the furnace. Thermal camera observation revealed that the hot face of the sample was cooled down to about 500℃ after 20 minutes natural cooling in the cooling position.

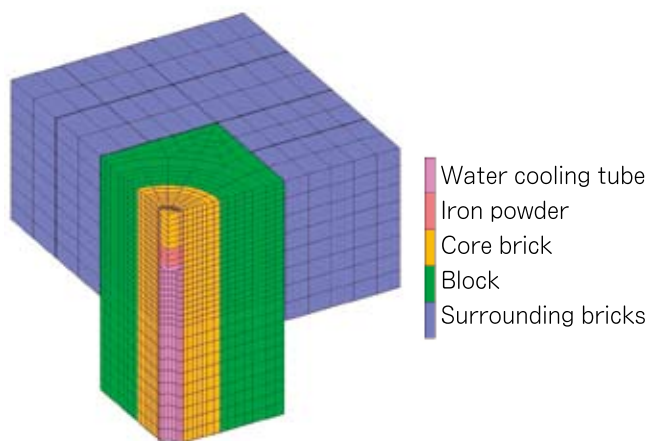


Fig. 14 Model for FEM calculation.

3. 1 解析モデル

解析モデルをFig. 14に示す。3次元の対称モデルを用い、有限要素法を適用した。解析モデルは中心部より、(1)水冷管、(2)鉄粉、(3)芯体、(4)ブロック、(5)周囲れんが、の5層から構成される。(3)の芯体と(4)のブロックがMHP一体構造体を構成している。周囲れんがはMHP一体構造体の熱膨張に対して固定されており、ある程度の拘束力が生じている。

3. 2 境界条件

加熱面の雰囲気温度はスポーリング試験の測温結果に基づき、Fig. 15に示す温度条件とした。伝熱解析は、水冷温度を30℃、炉内の雰囲気温度を1500℃とした。また、ブロックと周囲れんが間の伝熱は、炉内面側の拘束部分でのみ生じるように設定した。計算に用いるMgO-Cれんがの熱間特性については、成形母材を試料形状に加工した際の切り捨て部から試料を作成して測定した。

3. 3 結果と考察

試料No. 2 (材質B) について、1500℃保持中の試料内部の温度分布計算結果をFig. 16に示す。中心に埋設された冷却管によって冷却されているため、加熱面から等しい位置で比較すると、ブロック外側から芯体の中心に向かって次第に温度が低下している。実験中の測温位置において、実測値と計算値の差は10℃以内であり、温度分布は再現

Fig. 13 shows the appearance of the hot face and the cut face of MHP monoblock samples after the new panel spalling test. Because cracking along the pipes which was always observed in the past experiments without moderate restraining force was not observed in this test, we thought the restraining force was effective in preventing such cracking. No cracks were observed in sample No. 1 (material A) except for a negligible separation between the core brick and surrounding block. Cracks parallel to the hot face were observed in the material B samples (No. 2 and 3). The crack locations were about 180mm away from the hot face in sample No. 2 with the 30 pipes and about 150mm away in sample No. 3 with the 90 pipes.

From these results, we thought the different cooling effect probably affected the location of the cracking, and the tendency for crack generation depended on the brick materials in these tests. The cracks observed in samples No. 2 and 3 were similar to the cracks observed in the used MHP monoblocks from actual BOFs. Thus, we thought the new spalling test method utilizing restraining conditions was a useful method for evaluating thermal spalling resistance of the MHP monoblocks.

3. Computer Aided Structural Analysis

We performed computer aided structural analysis on the new panel spalling test in order to study the cracking mechanism of the MHP monoblock samples.

3. 1 Analytical model

An analytical model for calculation is shown in Fig. 14. We applied finite element modeling (FEM) with a three dimensional symmetrical model. The analytical model consisted of five layers from the center to the outside in the order as follows; (1) water cooling tube, (2) iron powder, (3) core brick part, (4) block part and

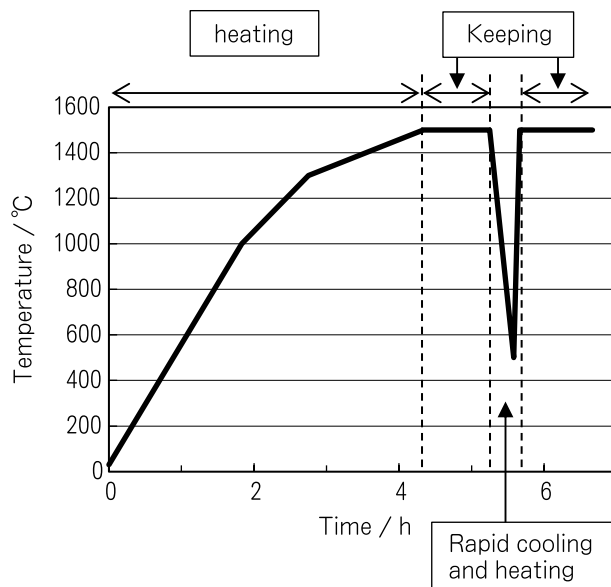


Fig. 15 Calculation conditions for atmosphere temperature at the hot face.

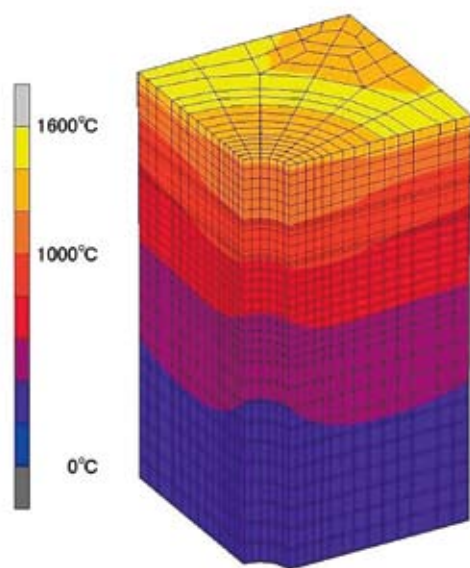


Fig. 16 Calculated temperature distribution of the MHP monoblock (material B) at 1500°C.

できた。

試料No. 2の1500°C保持中の試料内部の応力分布をFig. 17に示す。芯体中心付近（SUS細管埋設部に相当）の加熱面から100～200mmの範囲において、加熱面に対して垂直方向に強い引張応力が生じた。また、最大応力の発生位置と向きは加熱過程を通じてほぼ同じであった。このように構造

(5) surrounding bricks. A joint was not applied to the boundary between the core brick part and block part because they were in monoblock configuration. The surrounding bricks were considered not to move even when the MHP monoblock expanded so that a restraining force could be generated on the MHP monoblock.

3. 2 Boundary conditions

Based on the temperature measurements during the test, the temperature conditions shown in Fig. 15 were applied to the calculation. For the heat flow analysis, the temperature of the cooling water was assumed to be 30°C with an atmosphere temperature of 1500°C in the furnace. Thermal conduction between the MHP monoblock and surrounding bricks was assumed to take place only in the area on the hot face side where the restraint force was generated in the calculation. We measured the hot temperature properties required for the calculation, using the residual part of each monoblock sample.

3. 3 Results and discussion

The calculated temperature distribution in MHP monoblock sample No. 2 (material B) during the 1500°C keeping is shown in Fig. 16. The temperature gradually declined from the outside to the central zone in the monoblock because the center of the core brick was cooled by the cooling unit. Because the difference between the measured and calculated temperature was below 10°C, we thought the assumptions regarding the boundary conditions were reasonable.

The calculated stress distribution of the same sample at the same timing is shown in Fig. 17. Strong tensional stress in the perpendicular direction to the hot face was recognized in the area between 100 and 200mm from the hot face of the core brick. The location and the direction of the maximum stress were almost consistent during the entire heating process. Thus, the

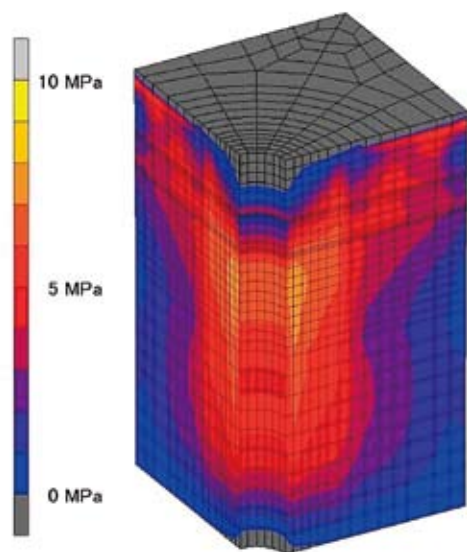


Fig. 17 Calculated stress distribution of the MHP monoblock (material B) at 1500°C.

解析の結果は、加熱面から100～200mm位置の中央部で、加熱面に平行な亀裂が発生しやすいことを示している。これはスポーリング試験後の亀裂発生状況と一致している。

次に、加熱面から120mmの芯体中心付近の温度および応力の履歴をFig. 18に示す。試験開始後、温度上昇に伴って緩やかに応力が増加し、約660°Cで最大6.5MPaの応力に達した。この温度は、不焼成レジンボンドMgO-Cれんがが、レジンボンドの消滅とカーボンボンドの未発達によって、最も強度低下している温度域である。次に1500°Cで保持が始まると温度上昇率が小さくなり、応力値はやや低下した。その後、急冷によって引張応力は急激に減少したが、その後の急加熱に伴い7.0MPaまで急激に増加した。再び温度を保持すると応力値は低下した。

計算結果から、最初の昇温時に加熱面と冷却管の温度差かられんが内に亀裂が発生する可能性が高く、加えて急冷後の急加熱による熱衝撃が亀裂を助長させているものと考ええる。

実機の操業では、MHP羽口は出鋼後にガス冷却により急冷され、待機後の受鋼時に冷却状態から急加熱されることを繰り返す。このような熱履歴

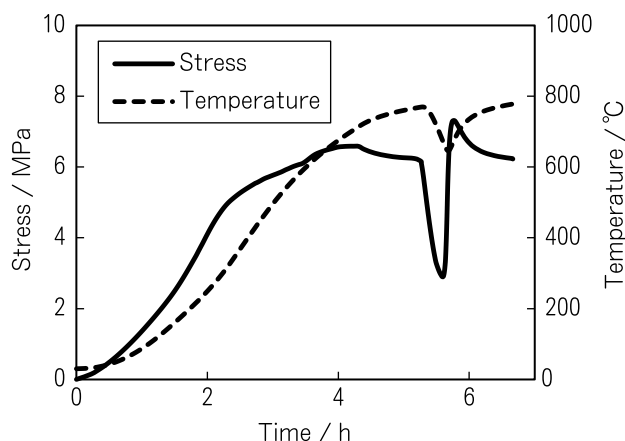


Fig. 18 Transition of calculated temperature and stress at 120mm away from hot face of core brick.

calculation results revealed crack generation parallel to the hot face could occur in the area between 100 and 200mm from the hot face of the core brick. We thought this result was consistent with the actual cracking situation observed in the new spalling test.

The transition of the calculated temperature and stress at the position 120mm away from the hot face in the core brick is shown in Fig. 18. The stress increased gradually with the temperature and reached approximately 6.5MPa when the temperature was about 660°C. This temperature was in the range where unburned resin-bonded MgO-C bricks show the lowest hot strength value because the resin bonding disappears but carbon bonding is still immature. After the start of 1500°C keeping, the rate of temperature rise became slow and the stress showed a slight decrease. When the sample was cooled, the tensional stress once decreased rapidly, then, again increased quickly to approximately 7MPa when it was moved back to the heating position. During the second 1500°C keeping, the stress decreased gradually.

From this calculation result, we thought that cracking occurred during the first temperature

は今回のスポーリング試験と同じような熱応力分布を生じ、稼働面と平行な亀裂を生じることで損耗速度を助長していると考えられる。

次に材質A(試料 No.1) について、1500℃保持中の試料内応力をFig. 19に示す。材質Bの場合(Fig. 17) に比べて発生応力は大きく低下しており、実験で亀裂が発生しなかった結果とよく対応している。したがって、材料の熱膨張率、熱伝導率、弾性率を変化させることで、その都度実験をしなくてもMHP羽口としての耐スポーリング性を評価することが可能となった。

4. 結言

実機製品と同じようにSUS細管を含むMHP一体構造体を拘束し、中心部分を水冷しながらバーナー加熱する新規スポーリング試験を開発した。この試験方法を用いることで、実機と同じような亀裂を発生させるスポーリング試験が可能となった。今後、この試験方法を活用してMHPレンガ材料の改良を進める。また、有限要素法による構造解析において、スポーリング試験の温度と応力状

rise due to the temperature difference between the hot face and the cooling tube, and propagation of the crack was accelerated by the thermal shock caused by the rapid heating after cooling.

In actual operations, MHP tuyeres are faced with both rapid cooling by gas blowing after the tapping and rapid heating by hot metal charging. We think such thermal fluctuation will cause a stress distribution similar to this new spalling test and cause cracking parallel to the hot face.

Fig. 19 shows the stress distribution in sample No. 1 (material A) during the 1500℃ keeping. Compared to sample No. 2 (material B), the stress was significantly low, which was consistent with the result of the new spalling test of the sample No. 1 (no cracking). Thus, we think the computer aided FEM analysis with the abovementioned model gives reasonable simulation results by inputting different properties of MgO-C materials such as thermal expansion, thermal conductivity and modulus of elasticity, even without conducting laboratory spalling tests one by one.

4. Conclusion

We developed a new spalling test method using panel spalling test equipment in which restraint against a monoblock and partial cooling of the core brick of an MHP were introduced. Cracking parallel to the hot face, which is similar to the cracking behavior seen in actual usage, was successfully reproduced by this new spalling test. We will apply this new test method to evaluate the thermal spalling resistance of MHP brick materials for further improvement. Furthermore, we conducted computer aided FEM analysis and established a reasonable analytical model for simulating the temperature and stress distribution of MHP

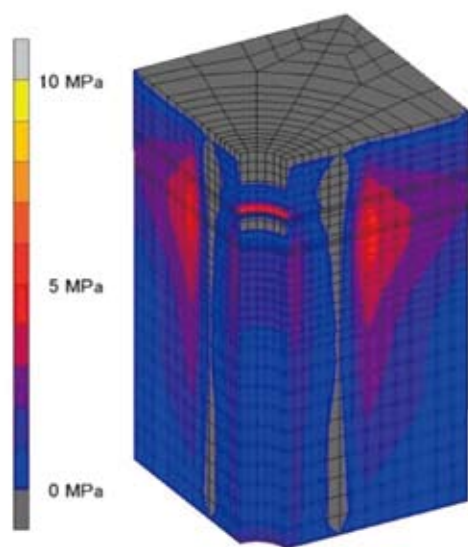


Fig. 19 Calculated stress distribution of the MHP monoblock (material A) at 1500℃.

態を再現する計算モデルを確立した。この計算モデルを発展させて、れんが材料だけでなく構造的な要因（例：SUS細管の配列，ライニング構造）についても検討する予定である。

monoblock samples in this new test. By the application and improvement of this analysis technique, we will investigate structural factors such as alignment of stainless pipes, shape and configuration of a monoblocks, and others, as well as brick material properties.

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