Investigation of MHP Wear Pattern for BOF and High Fracture Toughness Type MHP

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Abstract

Development of the multi-hole plug (MHP) type bottom blowing tuyere for the converter is described in this paper. According to the microstructural studies on used tuyere, thermal spalling, which is caused by large thermal gradient near the hot face was determined to be the critical factor of MHP wear. Assuming that improvement of fracture toughness is essential to reducing wear, we developed high fracture toughness tuyere brick by applying matrix reinforcement (MTR) technology that optimizes size, shape and configuration of grain. In addition, Pitch impregnation of the burnt body (PIB) technology allowed carbon bond strengthening. Tuyere bricks to which both MTR and PIB technologies are applied (MTR-PIB brick) possess high fracture energy compared with ordinary material. Thus, spalling was prevented and the wear rate in actual service was significantly reduced with the MTR-PIB MHP tuyere brick.

1. Introduction

Presently, the top and bottom gas blowing (combined blowing) system is adopted in many converters and steel refining by combined blowing is being firmly established in Japan. In comparison, the molten metal in top blowing converters is stirred by only a top blowing jet stream.

Fig. 1   Outline of gas blowing tuyere for BOF.

Thus, there are several disadvantages such as reduction in the decarbonizing reaction in the low carbon region and reduction of Fe and Mn yield due to the relatively poorer metal stirring effect and so on[1]. In order to overcome these disadvantages, a combined blowing system which blows gas from the bottom was adopted and became an effective system. A bottom tuyere for a converter is fixed to a converter bottom as shown in Fig. 1. As mentioned above, it plays an important role in recent converter refining and there are high demands for increased bottom tuyere durability.

Bottom tuyeres contain a stainless steel tube-buried within a refractory, for which various kinds of structures have been suggested and used[2]. The MHP (Multi-Hole Plug) is one of those tuyere structures. It is a structure in which many stainless steel tubes are embedded as shown in Fig. 2. The main feature of the MHP is that a wide range of flow rate control is possible. The MHP makes it easy to adjust the gas flow rate adequately for individually varying metallurgical processes. We manufacture a large mono-piece MHP for the converter using an integrated CIP (Cold Isostatic Press) that presses both the core plug portion, which contains a stainless pipe buried within MgO-C brick for gas blowing, and a block portion that
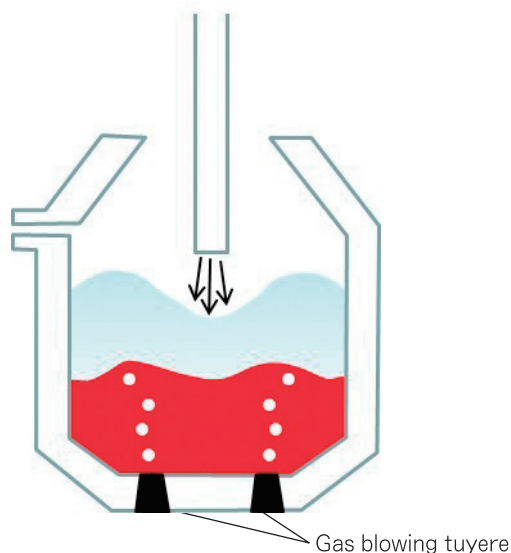
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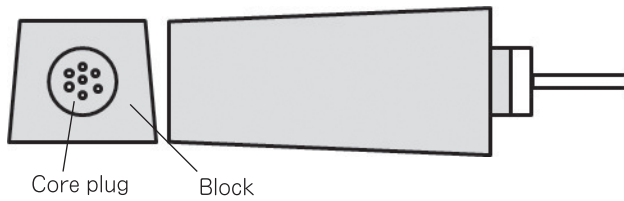*4 Shinagawa Advanced Materials Americas Inc.

Core plug   Block

Fig. 2   Schematic image of MHP.

Fig. 3   Cut section of used large mono-block MHP.

protects the core plug portion together.

In this report, we describe our investigation results of the wear mechanism of the large MHP by analyzing the used brick microstructure. Based on the assumed wear mechanism, we will explain the material development process and comparison to the results obtained from actual converter operation.

2.　General Wear Pattern of MHP

While the hot face of a converter tuyere is exposed to the high temperature of molten steel, the inside of the refractory is cooled by the high flow velocity of gas. Therefore, the temperature difference, or gradient, occurring in the refractory becomes large, and the refractory receives strong thermal stress during steel refining. In addition, a sudden change in temperature occurs when the molten iron is charged, and the tuyere, through which cold gas is blown even during standby, receives extremely large thermal shocks. Thus, it is believed that due to those thermal stresses, cracks develop and propagate inside tuyere refractories, causing intermittent peeling [3]. The cut section of a MHP used in an actual converter and the general wear pattern of the MHP are shown in Figs. 3 and 4, respectively.

With respect to the MHP wear, various factors such as erosion of the hot face, abrasion by molten steel stream caused by blowing gas, mechanical wear due to non-melted scrap impact, and mechanical stress due to expansion of surrounding bottom bricks are assumable. Practically, the MHP often exhibits "step-wise" reduction of residual thickness as shown in Fig. 4. It is thought that the large reduction of residual thickness is attributable to thermal spalling, which is caused by cracks generated at the area comparatively far from the hot face.

The smooth residual thickness reduction period observed in Fig. 3 is considered attributable to thermal spalling in the vicinity of the hot face. It was hypothesized
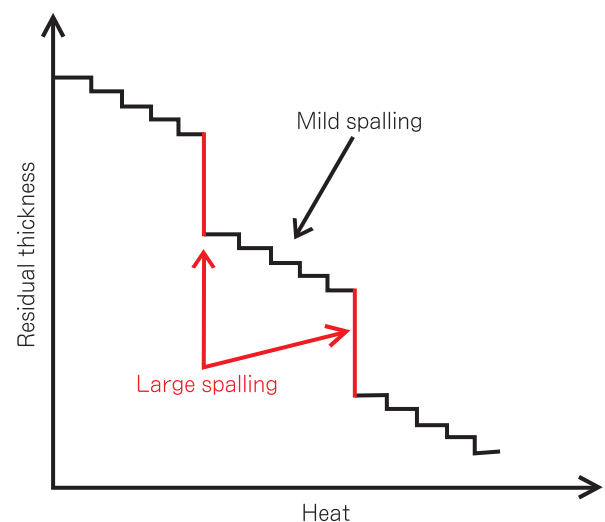

Fig. 4   General wear pattern of MHP.

according to microstructure observation, which will be described in the next section.

3.　Microstructure Observation of Used MHP

3. 1　Microstructure observation by a reflecting microscope

The hot face microstructure of a used MHP was observed by reflecting microscope in order to investigate thermal spalling caused by the thermal gradient generated in the MHP as mentioned in the previous section. The observed MHP was a general unburnt MgO−C brick. Metallic Al and Si were added in both the core plug and
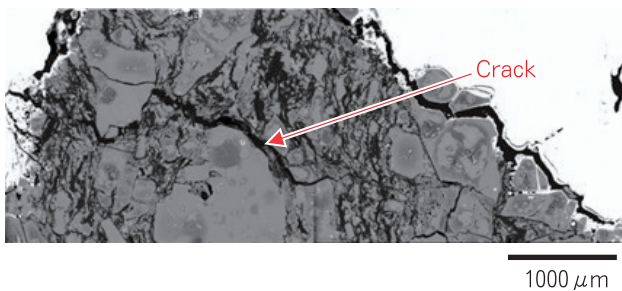
Fig. 5　Cut section of used MHP.

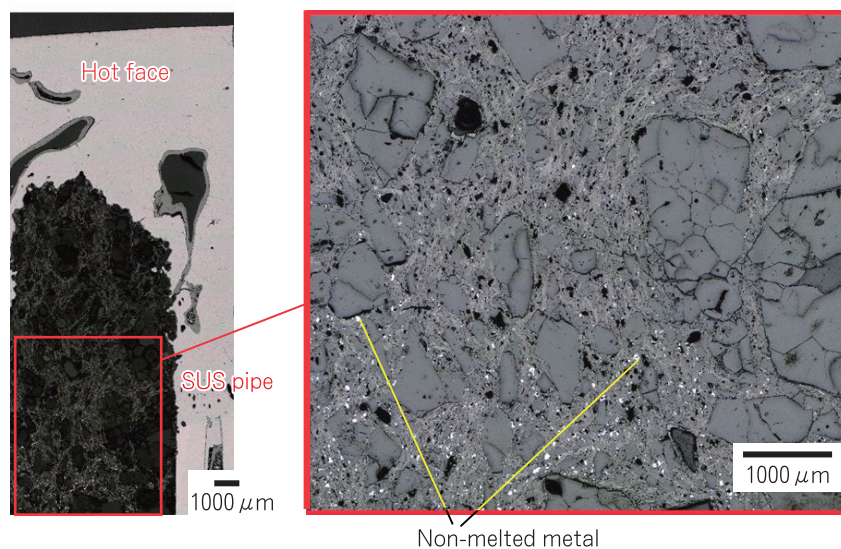Fig. 6　Microstructure between pipes of used MHP.

the block. A MHP was used for approximately 3 months in an actual converter without clogging and a sample was collected for microscopic observation and prepared by cutting. The cut section is shown in Fig. 5. A crack parallel to the hot face can be observed from the core plug to the block in the cut section. The microstructure between pipes in the vicinity of the hot face is shown in Fig. 6. A fine crack parallel to the hot face at 3 mm distance from the hot face can be observed.

Since a melted stainless pipe was observed within 5 mm from the hot face, it is thought that the range within 5 mm from the hot face was heated to 1400 ℃ or higher during service. In the same sample, the melted pipe was not observed at the range more than 5 mm from the hot face. Fine cracks parallel to the hot face were recognized. This is evidence that a large thermal gradient occurred at that region.

3. 2　Temperature distribution estimation of brick by the tracing of metal additives

In order to estimate temperature distribution near the hot face, we focused on the morphology of metallic additives included in the tuyere after use. Usually, metallic Al and metallic Si are added to MgO-C brick to improve the oxidation resistance and hot strength. The melting point of Al and Si are 1414 ℃ and 660 ℃, respectively. Thus, the temperature distribution can be estimated by determining the boundary between non-melted metals and melted metals by visual observation.

Fig. 7　Magnifying observation result between pipes of used MHP.

A microscopic image of the boundary zone is exemplified in Fig. 7. While high brightness grains, which indicates non-melted metallic additives, were seldom observed within 5 mm from the hot face, they were observed frequently at the range of more than 5 mm from the hot face. Hence, the boundary can be determined. The temperature distribution was estimated by tracing the

boundary through several samples. In the microscopic observation, Al and Si was distinguishable according to the difference in brightness.

The observed sample-obtained area and determined boundary of non-melted Al and Si are shown in Fig. 8. With respect to the core plug portion, areas including non-melted Al and Si (lower than 660℃) were observed at 30–50 mm inside the hot face, even at the area without stainless pipes. Regarding the block portion, a non-melted Al–including area (lower than 660℃) was observed at 100 mm inside from the hot face. The area where the melted Si is distributed (higher than 1414℃) was within 10–30 mm from the hot face.

The EDS analysis results at point A and B indicated in Fig. 8, are shown in Figs. 9 and 10, respectively. While a high concentration region of Al was observed at point A, Al was dispersed finely among Mg and O at point B. The high Al concentration region in Fig. 9 is considered to be non-melted Al, taking grain and shape into account. Contrarily, in Fig. 10, the fine Al dispersed texture is considered to be formed by the transfer of molten Al. It ensures the accuracy of the estimation performed by reflecting microscope.

From the result of the metallic additive tracing, it was clarified that non-melted Al and Si were observed at the position nearer to the hot face in the core plug portion compared with the block portion. This supports the assumption that the core plug is cooled intensively by vigorous gas purging even at the position nearer to the hot face.
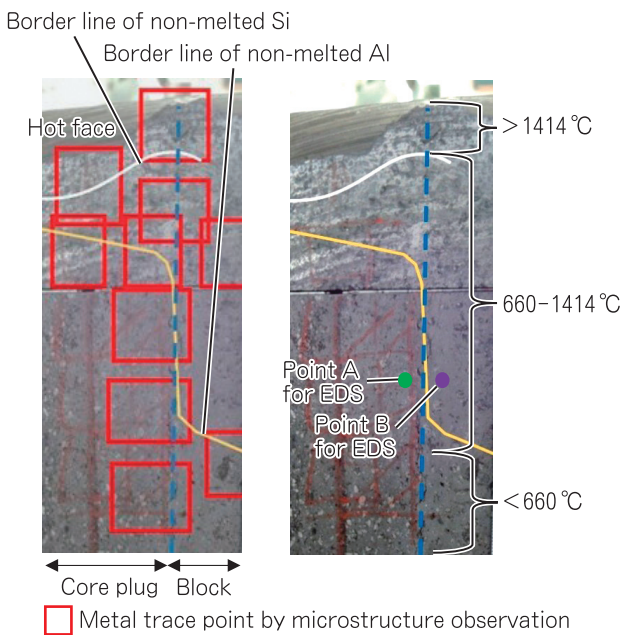

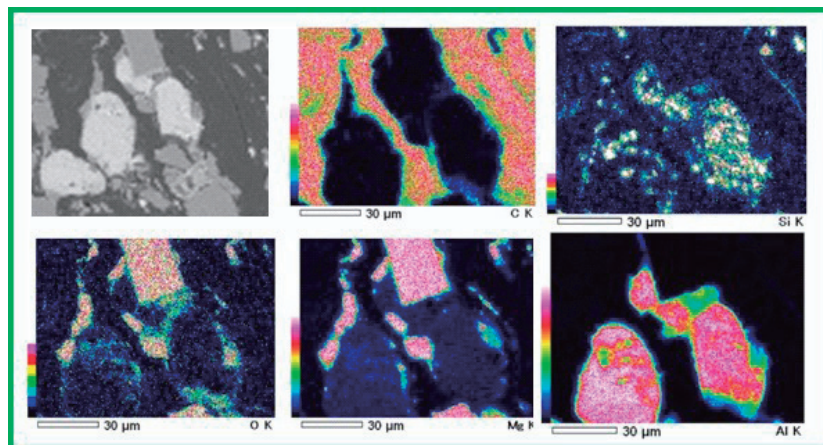Fig. 8 Metal trace points and border lines of non-melted Al and Si on used MHP cut section.

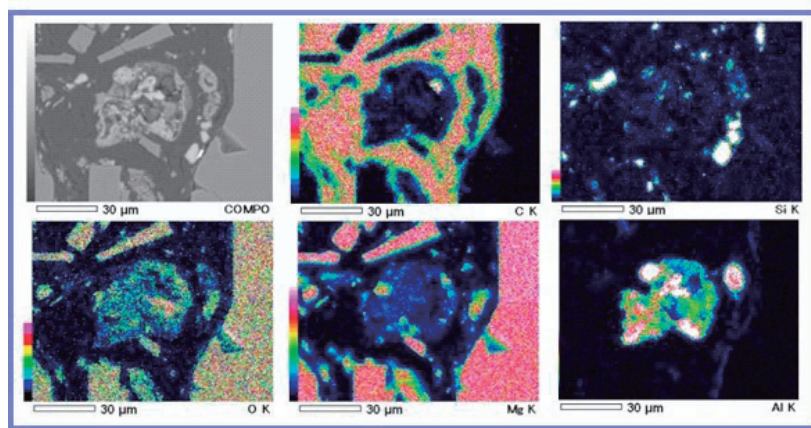Fig. 9 Result of EDS analysis at point A.

Fig. 10 Result of EDS analysis at point B.

4. High Fracture Toughness Type MHP

4. 1 Improvement of fracture toughness by reinforced matrix structure

From the result of the used brick investigation, it was found that the comparatively high thermal stress caused by a large thermal gradient in the MHP for the converter results in wear, i.e., large spalling due to crack initiation and propagation in the inner body resulting in step-wise changes in residual thickness and small spalling in the vicinity of the hot face that causes smooth reduction in residual thickness. In spite of scale difference, crack initiation and propagation is essential for both spalling. Thus, we concluded that improving fracture toughness of the tuyere brick is an effective measure for reducing the wear rate.
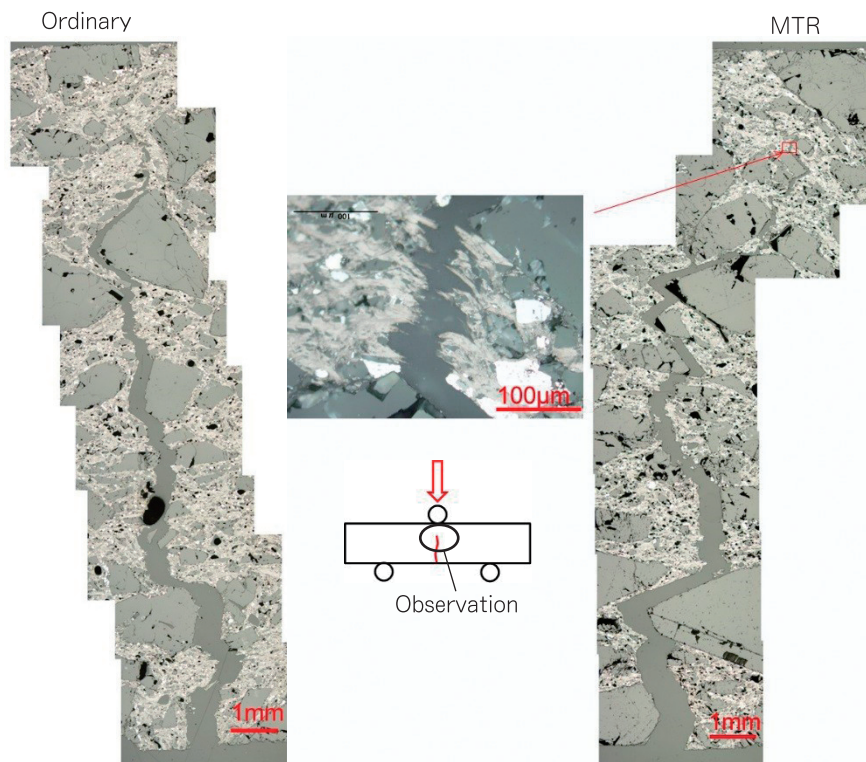

Fig. 11 Crack propagation path observed in MgO-C bricks after bending test.
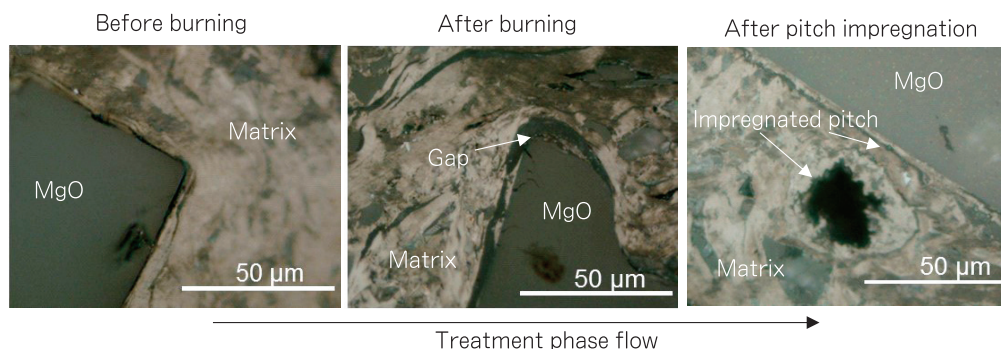
Fig. 12 Microstructure at each phase (before burning, after burning and after pitch impregnation) of pitch impregnation treatment.

Regarding the fracture toughness, we developed high fracture toughness MgO-C brick for the converter charge pad, which is effective for reducing scrap impact wear[4]. Therefore, we attempted to apply this high fracture toughness technology to the MHP in order to inhibit both spalling damage. Despite various causes of cracking, i.e., a mechanical eternal force according to scrap collision and thermal stress, it is thought that cracks are generated at weak spots of the brick structure and propagate followed by connection of cracks. In this case, high fracture toughness is achieved by reinforcing the brick's matrix (Matrix Reinforcement: MTR). Size, shape, and configuration of particles are the adjusting parameters. As a result of manufacturing process optimization, MTR technology was successfully applied to the tuyere brick.

The crack propagation path observed in MgO-C bricks after the bending test is shown in Fig. 11. The zigzag propagation of the crack helps to suppress macroscopic overall crack propagation in the case of the MTR material. Cracks tend to propagate along pores or interparticle planes between graphite and magnesia, which are considered to be structurally weak positions as observed in Fig. 11.

4. 2　Further improvement of fracture toughness by pitch impregnation to burnt body (PIB)

In order to further improve fracture toughness, we tried applying a pitch impregnation to the burnt body (PIB) of MHP. The PIB treatment can make the brick's matrix dense by burning a brick under high temperature and filling the brick's pores by pitch impregnation under high pressure after burning. Although the PIB treatment has been applied to some kind of single hole MgO-C tuyere brick for years, there had been several issues to

overcome if the treatment is applied to large MHPs which contain numbers of stainless pipes in MgO-C brick. The issues were completely overcame by manufacturing process development.

The microstructure of PIB brick at each manufacturing phase as; before burning, after burning and after pitch impregnation, are shown in Fig. 12. Many pores are generated in an unburnt MgO-C brick's matrix due to the volatilization of the volatile matter and the difference of thermal expansion between MgO and C. Those pores are filled with pitch by impregnation under high pressure, so the dense matrix can be achieved.

4. 3　Evaluation of fracture toughness

In order to verify the effect of MTR technology and PIB treatment, the load-displacement curves of materials shown in Table 1 were evaluated at 800℃. It is well known that MgO-C brick shows the lowest strength at 800℃ because it is the temperature above the resin bond-effective range and below the carbon/metal bond development temperature[5]. Thus, evaluation at 800℃ is meaningful to evaluate the effectiveness of structure reinforcement as MTR technology and/or PIB treatment. In Table 1, MTR and MTR-PIB indicate the material with MTR technology and the material with combined application of MTR and PIB technology, respectively. The test was performed by three point bending under an Ar atmosphere. The support points were set in the span of 100 mm and the cross head speed was set to 0.1 mm/min. The load-displacement curves are shown in Fig. 13. The fracture energies were obtained by integrating the curves. The fracture energies were high in the order of MTR-PIB＞MTR＞ordinary material.
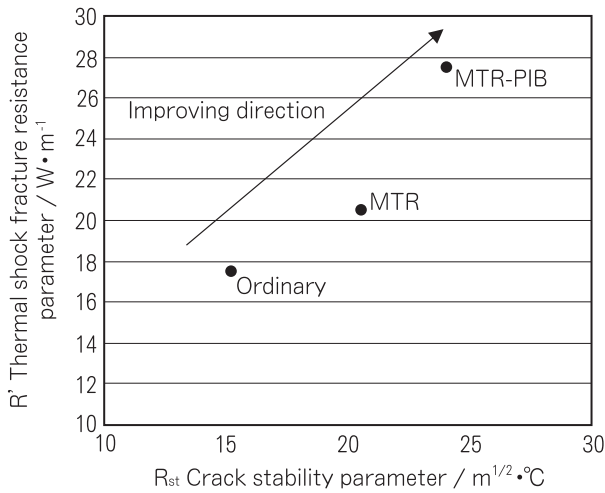
Next, the thermal shock fracture resistance parameter

Table 1 Properties of MgO-C bricks for fracture energy measuring

	Ordinary	MTR	MTR-PIB
Apparent porosity / %	3.5	2.6	1.6
Bulk density	2.97	2.87	2.86
Cold crush strength / MPa	47	35	40
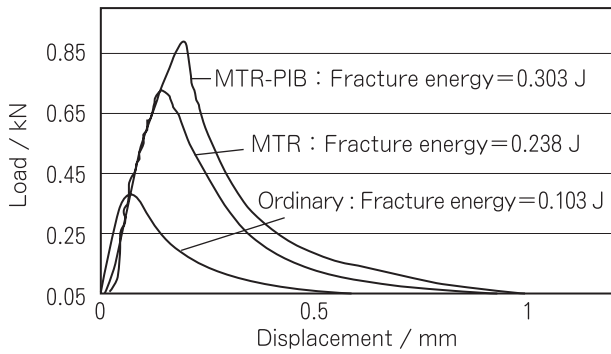
Fig. 13 Load-displacement curves and fracture energy of MgO-C bricks at 800 ℃.

Fig. 14 Comparison of thermal shock fracture resistance parameter and crack stability parameter of MgO-C bricks.

R' and the crack stability parameter R_{st} were compared. These parameters are often used for the evaluation of MgO-C brick as an index of crack generation and propagation. R'and R_{st} are expressed by the following equations.

$$R' = \{S \times (1-\nu) \times k\} / (E \times \alpha) \quad\cdots\cdots\cdots\cdots\cdots\cdots (1)$$
$$R_{st} = \{\gamma \times (1-\nu)^2 / (E \times \alpha^2)\}^{1/2} \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Where, S, ν, k, E, α and γ indicate fracture strength, Poisson ratio, thermal conductivity, modulus of elasticity, thermal expansion coefficient, and fracture energy, respectively. The higher the R', the higher the resistance to crack generation becomes, and the higher the $R_{st,}$ the higher the resistance to crack propagation becomes. The calculated value of 3 materials was plotted in Fig. 14, wherein the horizontal and vertical axis are R_{st} and R', respectively. The top right corner of the figure shows the improved area for crack generation and propagation. MTR-PIB showed a high value compared with ordinary material and MRT.

In Fig. 13, the initial slope until maximum load was almost equivalent for three materials, while, MRT and MRT-PIB showed larger maximum load and displacement when they fractured. It indicates fracture toughness improvement. Also, improvement can be expected in same order from the results of the comparison of R' and R_{st}. According to the above results, it was confirmed that the PIB-treated MTR technology-applied material has the highest fracture toughness among the materials tested this time. The reduction in crack generation and propagation due to the thermal stress caused by the thermal gradient in actual service is expected by improving the fracture energy, R' and R_{st}.

5. Use Results of High Fracture Toughness MHP in The Actual Converter

These materials were applied to a commercial converter at steel mill A. A comparison of the wear rate index of 3 materials is shown in Fig. 15.

By applying the MTR technology, wear rate has been improved approximately 27 % compared with the previous material. Moreover, combined application of MTR and PIB technology reduced wear rate approximately 45 %. The appearance photograph taken from the bottom surface side of the PIB-treated MTR technology-applied MHP before demolition is shown in Fig. 16. Although MHP often shows higher wear compared with the surrounding bottom bricks and is dented locally, the wear rate of the developed MHP was markedly improved and the developed MHP maintained equivalent residual thickness with the surrounding bottom bricks.

The cut sections of the MTR technology-applied MHP and the PIB treated MTR technology-applied MHP used in the same campaign are shown in Fig. 17. A crack parallel
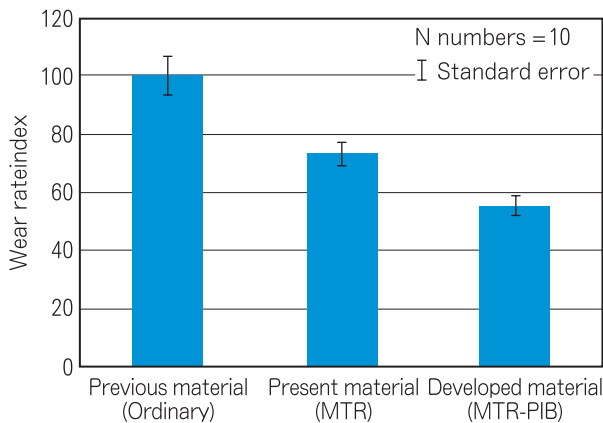
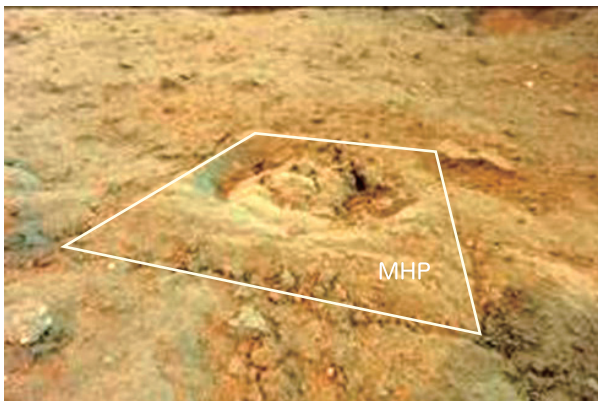Fig. 15 Comparison of wear rate index of MHPs used in steel mill A.

Fig. 16 Appearance of developed material MHP before demolition.

Present material

Developed material

Fig. 17 Cut section of present material MHP and developed material MHP after use.

to the hot face as seen in Figs. 3 and 5 was observed in the MTR technology-applied MHP, but no clear crack was seen and the hot face was worn smoothly starting from the core plug in the PIB treated MTR technology-applied MHP. Hence, it is thought that the main wear factor has been changed from the thermal spalling to the back attack of blowing gas and abrasion by molten steel stream by improving the fracture toughness of MHP.

6. Conclusion

In order to improve the durability of MHP-type bottom blowing tuyere of converter, wear mechanism was investigated followed by high fracture toughness brick development. The obtained results were concluded as follows.

・From the result of the used MHP microstructure observation of which the stainless pipe melts only within

5 mm from the hot face and the crack was observed 3 mm from the hot face, it is understood that there is a large thermal gradient around the hot face of the MHP and a crack is generated.

・By residual metallic additives tracing of a used MHP, the non-melted Al and Si (lower than 660℃) were observed at 30−50 mm inside from the hot face even where there was no stainless pipe arrangement in the core plug. The area including non-melted Al (lower than 660℃) was observed at 100 mm inside the hot face in the block portion. The area 10−30 mm from the hot face was confirmed to be extremely high temperature and show a large thermal gradient according to the melting condition of Si.

・According to the laboratory evaluation, it was clarified that the materials with the matrix reinforcing technology, which was originally developed for a charge pad, and a pitch-impregnated burnt material show high fracture toughness, and are effective for preventing crack generation and propagation.

・From the used results of the high fracture toughness

MHP-type tuyere in actual application, the wear rate has been improved by approximately 27％ with the matrix reinforced material and approximately 45％ with the pitch impregnated burnt matrix reinforced material compared with the previous material.

From these results, it is thought that the thermal spalling caused by the large thermal gradient near the hot face is the main factor of MHP wear, and that the high fracture toughness material is effective against this wear.

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