# DEVELOPMENT OF HIGH FRACTURE ENERGY MgO-C BRICKS AND APPLICATIONS TO SCRAP IMPACT ZONE AND BOTTOM TUYERE OF CONVERTER*

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## Abstract

In this article, the technologies of highly durable MgO-C bricks for the scrap impact zone and bottom blowing tuyere of converters are demonstrated. On the bases of our recent investigations, wear of scrap impact zone and bottom tuyere are explainable in terms of crack initiation and propagation. Theoretically, crack propagation in brittle material is regarded as generation of new crack surface area. It occurs when the elastic strain energy stored in the material exceeds the energy required to generate a new crack surface area. Since the overall energy consumed for crack propagation until fracture is evaluated by fracture energy, materials exhibiting high fracture energy can be regarded as materials with high fracture resistance. Therefore, two fracture energy-improving technologies for MgO-C bricks were developed. One is matrix reinforcement and the other is carbon bond enhancement. These technologies were applied to bricks for the scrap impact zone and bottom tuyere. As a result of commercial applications, notable decreases in wear rates were recognized for high fracture energy materials for the scrap impact zone and bottom blowing tuyere of converters.

**Keywords:** Converter; Scrap impact zone; Bottom blowing tuyere; Fracture energy.

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# 1 INTRODUCTION

For decades, improvement of the operating efficiency of the energy-intensive integrated steel making process has been an urgent issue in terms of reduction of overall green house gas emission [1-2]. For the purposes of refining time reduction and Fe yield improvement, bottom gas stirring is being intensified [3], which increses the wear rate of tuyere refractories. Additionally, in order to decrease $CO_2$ gas emission, an amount of steel scrap being charged to converters is increasing since it reduces operation of iron making facilities that tend to emit large amounts of $CO_2$ [4]. As a result, mechanical abrasion wear of refractories installed on scrap impact zones of converters is being promoted.

For almost all steel refining converters, MgO-C bricks have been applied since the early 1980's due to their excellent corrosion resistance against high basicity refining agent as well as superior thermal spalling resistance. Until now, many types of MgO-C bricks specialized for specific zones of the converter have been improved according to individually varied critical wear mechanisms.

It is obvious that improving the mechanical properties of MgO-C bricks is essential to reduce the wear rate of the scrap impact zone [5]. While in the case of the bottom tuyere, chemical corrosion, mechanical abrasion and thermal spalling were likely to be assumed as a dominant wear factor. On the bases of our recent investigations, the wear of the scrap impact zone and bottom tuyere are explainable in terms of crack initiation and propagation [6].

In this article, the wear mechanisms of these two zones are explained comprehensively followed by a description of newly developed MgO-C bricks as well as their commercial application results.

# 2 MATERIAL AND METHODS

## 2.1 Identification of dominant wear factor

### 2.1.1 Scrap impact zone

Generally speaking, investigation of used bricks is important for accurate assumption of the wear mechanism. However, it is difficult to obtain bricks from the scrap impact zone of converters after use. Therefore, the influence of scrap charging on the brick wear was evaluated by laboratory experiments where the steel block was dropped onto the brick-assembled structure followed by observation of wear progression [7]. Figures 1 and 2 show a schematic illustration of the steel block dropping experiment and appearance of the apparatus, respectively. 20 pieces of 100 × 80 × 400 mm bricks were assembled in a steel box and fixed tightly. Onto the brick-assembled structure that tilted for 30 º from the horizontal, a steel block of 12 kg was dropped from 2 m height followed by observation of the brick to which the steel block impacted. Typical bricks for scrap impact zones with a graphite content of 16% were subjected to the steel block dropping experiment.

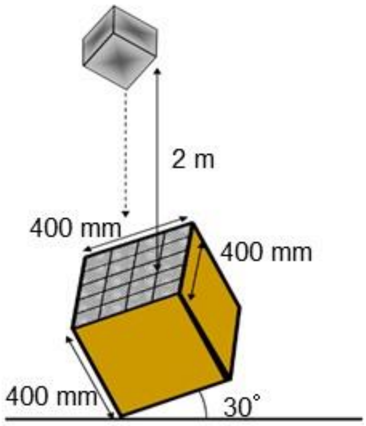

**Figure 1.** Schematic illustration of scrap drop impact test.

**Figure 2.** Appearance of scrap drop impact test.

### 2.1.2 Bottom blowing tuyere

In the case of bottom blowing tuyere, it is much easier to obtain brick samples from the converter after use. From the bottom of the used converter that blows inert gas through a multi hole plug, bottom tureye, i.e., multi hole plug, were obtained and the cut surfaces were observed. In addition, the microstructure of the area in the vicinity of the working surface was observed by optical microscope.

## 2.2 Improvement of high fracture energy MgO-C brick

On the bases of the investigated results that will be described later, it was concluded that inhibition of crack propagation is essential to reduce the wear rate of the scrap impact zone as well as bottom tuyere. According to Griffith's theory, crack propagation in brittle material is regarded as generation of new crack surface area which occurs when the elastic strain energy stored in the material is at least equal to the energy required to generate new crack surface area. Theoretically, materials that requires larger energy to generate new crack surface area show superior crack propagation resistance. In practice, the overall energy consumed for crack propagation until fracture is evaluated by fracture energy. Therefore, increase in fracture energy of material improves crack propagation resistance. Thus, the effects of technologies for improving the fracture energy of MgO-C bricks were evaluated experimentally.

### 2.2.1 Materials

Two ways for fracture energy improvement of bricks were evaluated. One was matrix reinforcement and the other was carbon bond enhancement. The Brick matrix structure can be reinforced with suitably arranged particles. Carbon bond enhancement is achievable by optimization of pitch addition. In this study, these technologies were applied to the bricks for scrap impact zone and bottom tuyere. Table 1 provides chemical compositions of materials. Six materials were prepared for evaluation. Three were materials for the scrap impact zone and another three were for the bottom tuyere. In Table 1, the first letter “S” and “T” show “scrap impact zone” and “tuyere”, respectively. The Following “conv”, “mtx” and “cb” indicate “conventional”, “matrix reinforcement” and “carbon bond enhancement”, respectively.

**Table 1.** Properties of MgO-C bricks for evaluation

| **Sample I.D.** | **S-conv** | **S-mtx** | **S-cb** | **T-conv** | **T-mtx** | **T-cb** |
|---|---|---|---|---|---|---|
| Applied site | Scrap impact zone | | | Bottom blowing tuyere | | |
| MgO / mass% | 77 | 79 | 78 | 78 | 78 | 78 |
| F.C. /mass% | 15 | 13 | 14 | 17 | 17 | 17 |

*S: Bricks for scrap impact zone, T: Bricks for bottom tuyere,*
*conv: conventional, mtx: matrix reinforced, cb: carbon bond enhancement*

### 2.2.2 Laboratory evaluation

These materials were heated at 1500 °C for 3 h in coke breeze-filled sagger utilizing an electric furnace followed by fracture energy and hot modulus of rupture (hereinafter referred to as HMOR) evaluations. The fracture energies and HMORs of each material were evaluated for the 40 × 15 × 150 mm specimens without notches by three point bending method, performed at 800 °C in an argon gas flow.

The thinnest plane of the specimen was put on two supporting pins set in the span of 100 mm. On the center of the specimen, vertical bending force was loaded at a rate of 0.1 mm/minute gauging a bending displacement. According to the measurements, load-displacement curves of the materials were obtained by plotting bending load as a function of bending displacement. Fracture energy and HMOR are defined by the integral of load-displacement curve and maximum load of load-displacement curve, respectively.

Additionally, the statuses of T-conv and T-mtx crack propagation after fracture energy evaluation were observed by optical microscope in order to confirm how the matrix reinforcement technology functions. The status of carbon bond enhancement was verified by microstructure observation of S-cb after heating at 1500 °C for 3 h.

The bulk specific gravities and cold crushing strengths of as-received materials were measured by Archimedes method and compressive method, respectively.

### 2.2.3 Commercial application

These materials were applied to commercially operated converters and the wear rates were evaluated under similar operating conditions.

## 3 RESULTS AND DISCUSSION

### 3.1 Identification of dominant wear factor

### 3.1.1 Scrap impact zone

Figure 3 shows the appearance of a specimen on which a steel block was dropped in a steel block dropping experiment. The part impacted by the steel block scraped off and the defect was observed. The state of the side surface of the steel block-impacted part is shown in Figure 4. Crack propagation from the scraped area was observed. Hence, it is concluded that inhibition of crack propagation is considered to be essential to decrease the wear rate of the scrap impact zone.

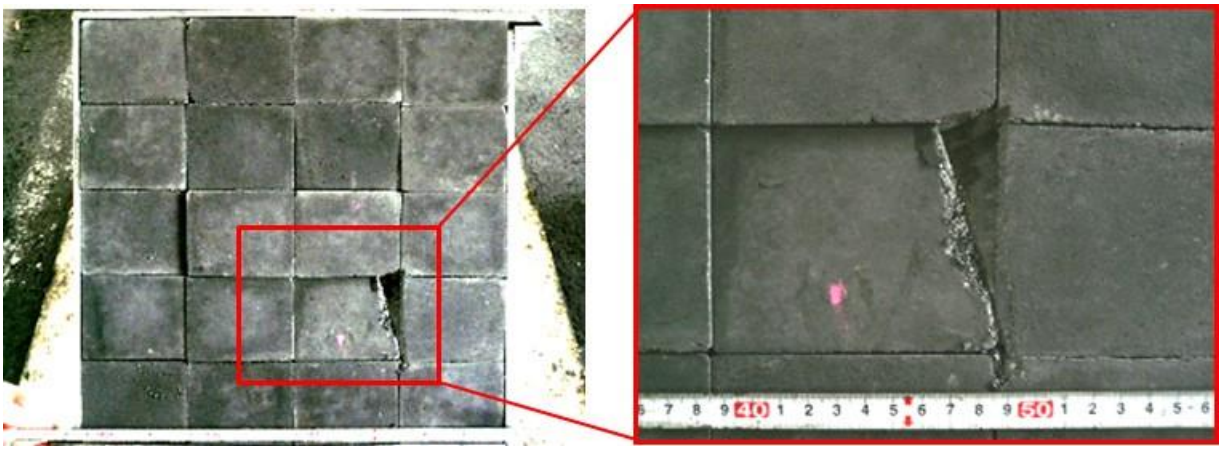

**Figure 3.** Photos of surface after steel block dropping experiment.

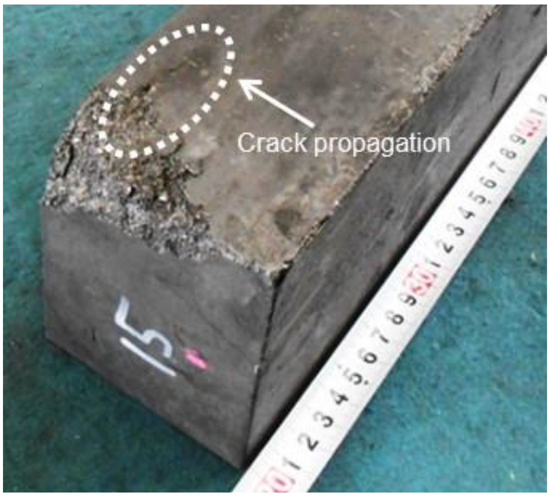

**Figure 4.** Appearance of brick after steel block dropping experiment.

### 3.1.2 Bottom blowing tuyere

Figures 5 and 6 show the cut surface and microstructure of a bottom blowing tuyere after use, respectively. While no obvious traces of slag corrosion on the working surface were observed, cracks parallel to the working surface were recognized at the inner part and in the vicinity of the working surface of the bricks. As a result of the observation, the wear progression process of the tuyere was presumed as Figure 7. During refining, tuyere bricks show a steep temperature gradient in the body due to the combined effects of heating from the molten metal and cooling by blowing gas through the pipes. Furthermore, the hot face of the tuyere is cooled rapidly after tapping since gas blowing through the pipes continues after tapping. Such thermal gradient and thermal fluctuation probably cause the fine cracks observed in the vicinity of the hot face of the used tuyere brick. Continuous wear of the tuyere is considered attributable to fine scale peeling-off due to initiation and propagation of fine cracks.

Furthermore, as a result of observation of the brick after use, it is considered that the crack observed at the inner part of the tuyere was caused by external stress since the crack seems to have began at the outside and extended to the inside of the tuyere. In addition, discontinuous wear of the tuyere, which occurs frequently during continuous reduction in residual thickness, is evidence of large scale spalling. According to Figure 5, it is natural to assume that large scale spalling is a result of sufficient propagation of inner cracks. Hence, both continuous and discontinuous tuyere wears are considered attributable to crack propagation.

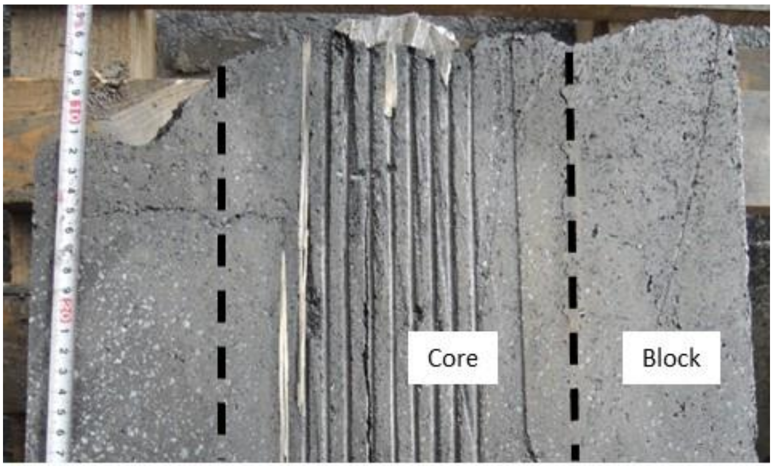

**Figure 5.** Cut surface of used bottom blowing tuyere.

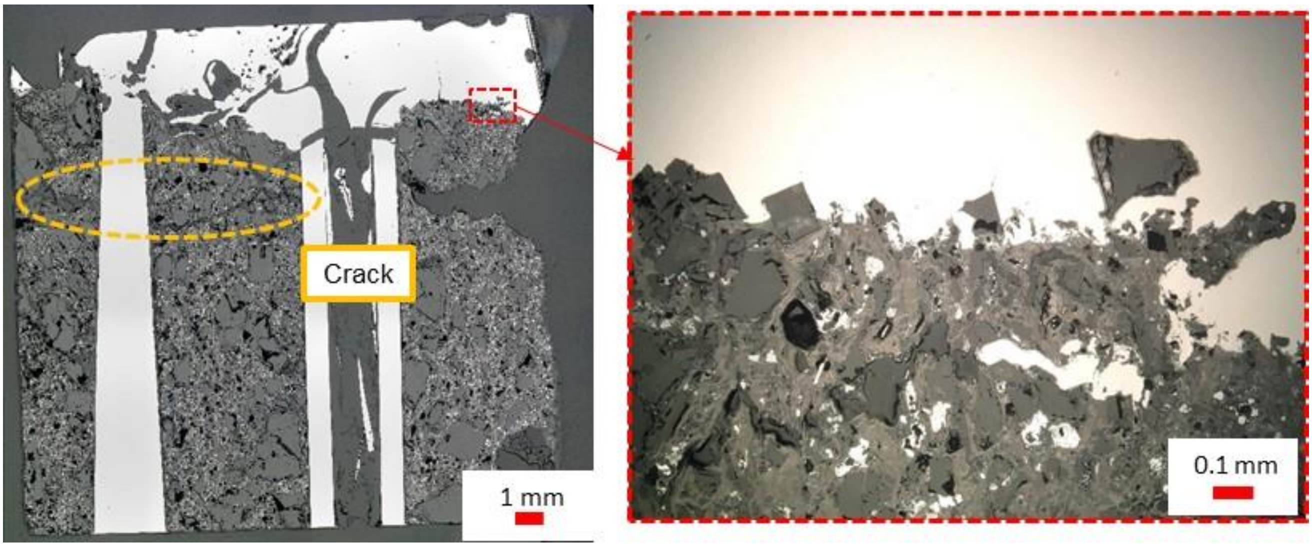

**Figure 6.** Microphotographs of working surface.

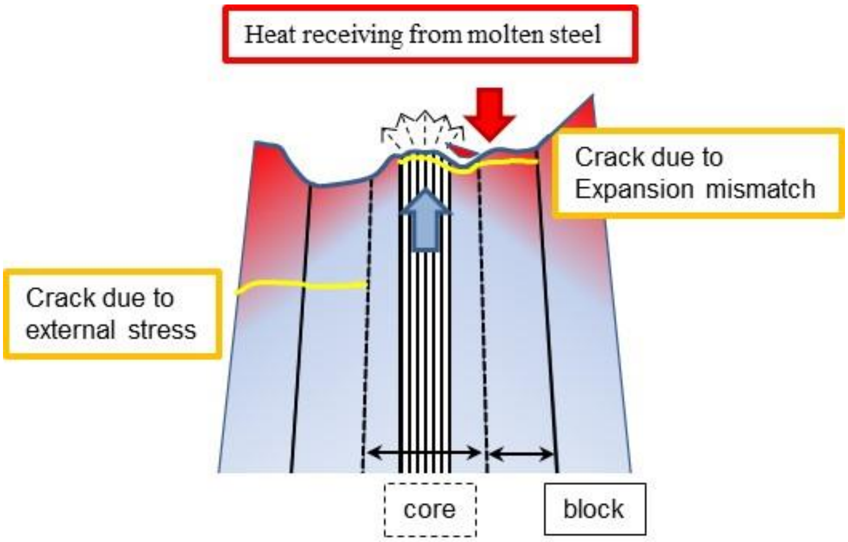

**Figure 7.** Progression process of wear of tuyere.

## 3.2 Improvement of high fracture energy MgO-C brick

Figure 8 shows load-displacement curves of the materials. The blue thick lines and the red thin lines in Figure 8 show curves of bricks for the scrap impact zone and bricks for the bottom blowing tuyere, respectively. Conventional materials showed strongest maximum load. While matrix reinforcement materials and carbon bond enhancement materials showed smaller bending strength than conventional materials, they showed gradual decrease of the load after the maximum load.

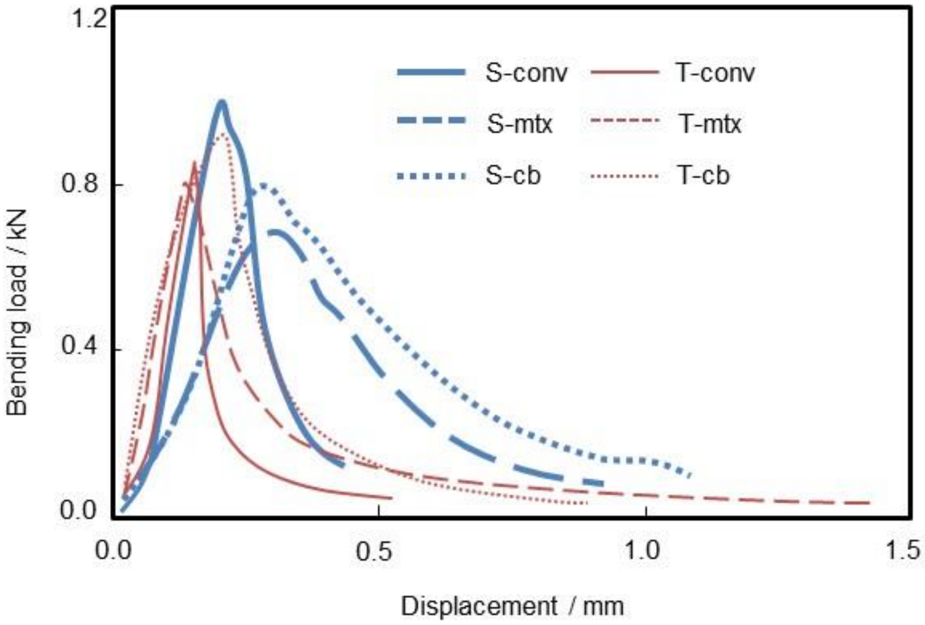

**Figure 8.** Load-displacement curve obtained from three-point bending test.

Figure 9 shows the crack propagation path observed in T-conv and T-mtx after the bending test. Matrix reinforced T-mtx showed large zigzag deviation of the crack propagation path, which increases crack propagation resistance. Crack branching and graphite pulling-out effectively functions in reinforced matrix obtained from suitable particle arrangement technology.

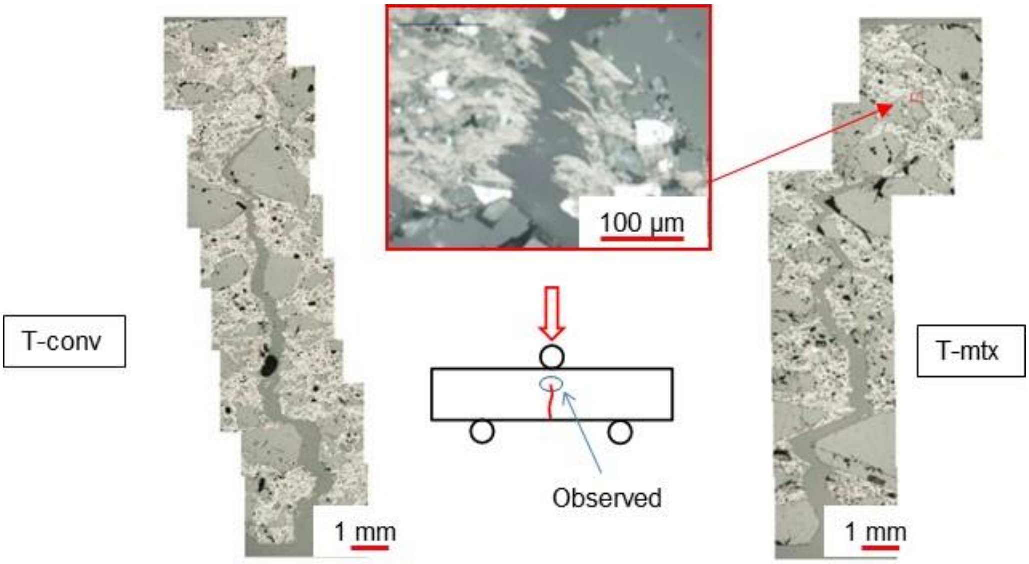

**Figure 9.** Crack propagation path observed in MgO-C bricks after bending test.

Figure 10 shows the enhancement of microstructure by the evaporation and condensation effect of pitch observed in S-cb. The pitch-derived carbon condenses and fills pore and fine interstices between the MgO gains and graphite flakes. It can be seen from Figure 9 that the crack propagates connecting weak parts of the matrix structure such as gaps between the MgO grains and graphite matrix. Therefore, resistance to crack propagation can be increased by improving the structural defects of the matrix texture. Based on the above, carbon bond enhancement by pitch addition is effective for suppressing crack propagation. Namely, carbon bond enhancement materials were designed to improve fracture toughness.

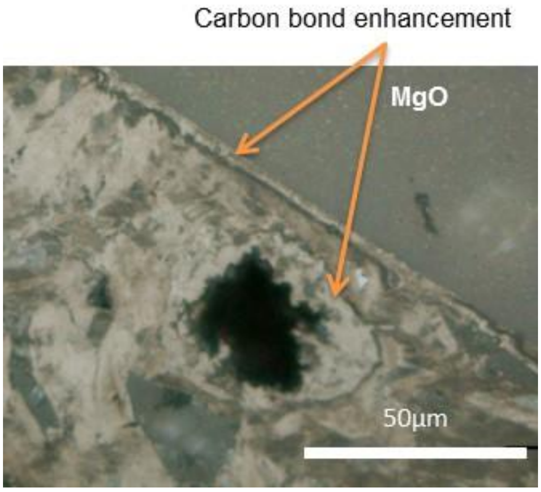

**Figure 10.** Carbon bond enhancement.

Table 2 summarizes the evaluated properties. The HMORs and fracture energies shown in Table 2 were obtained from Figure 8. While the HMORs of the developed materials were smaller than the conventional one, noticeable improvements in fracture energies were evaluated.

**Table 2.** Evaluated properties of MgO-C bricks after heating at 1200 °C in coke breeze for 3 h

| **Sample I.D.** | **S-conv** | **S-mtx** | **S-cb** | **T-conv** | **T-mtx** | **T-cb** |
|---|---|---|---|---|---|---|
| Applied site | Scrap impact zone | | | Bottom blowing tuyere | | |
| Bulk specific gravity / - | 2.99 | 2.97 | 2.92 | 2.89 | 2.88 | 2.86 |
| Cold crushing strength / MPa | 50 | 54 | 52 | 47 | 45 | 49 |
| HMOR at 800 °C / MPa | 16 | 11 | 13 | 13.5 | 12.8 | 14.5 |
| Fracture energy at 800 °C / J | 0.26 | 0.40 | 0.49 | 0.12 | 0.21 | 0.23 |

*S: Bricks for scrap impact zone, T: Bricks for bottom tuyere,*
*conv: conventional, mtx: matrix reinforced, cb: carbon bond enhancement*

## 3.2 Commercial applications

### 3.2.1 Scrap impact zone

The influences of HMOR and fracture energy on the wear rates of the scrap impact zone of a converter are demonstrated in Figures 11 and 12, respectively. While no obvious correlation was found between wear rate and HMOR, the wear rate decreases proportionally as the fracture energy increases. This fact suggests that inhibition of crack propagation by improving fracture energy is effective compared to improving the HMOR. Thus, it was validated that high fracture toughness material is suitable for charging pads of converters which are impacted by large amounts of steel scrap.

● : Conventional, ▲ : Matrix reinforcement, ◆ : Carbon bond enhancement

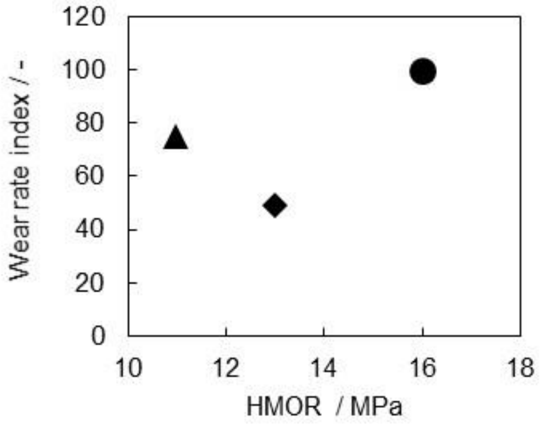

**Figure 11.** Variation of wear rate of scrap impact zone of a converter as a function of HMOR of bricks.

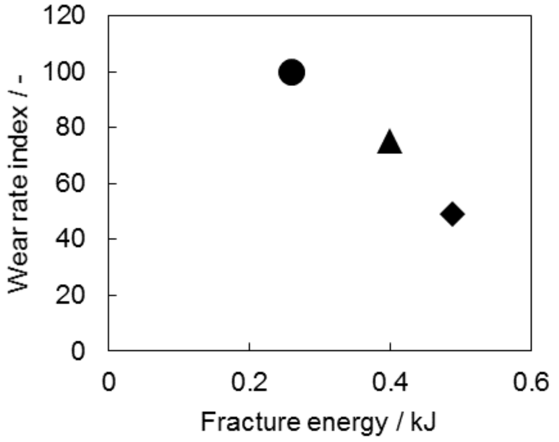

**Figure 12.** Variation of wear rate of scrap impact zone of a converter as a function of fracture energy of bricks.

### 3.2.2 Bottom blowing tuyere

Influences of HMOR and fracture energy on wear rates of bottom blowing tuyere of a converter are demonstrated in Figures 13 and 14, respectively. Similar to the case of scrap impact zone, good correlation was found between the wear rate index and fracture energy. Thus, it was validated that high fracture energy material is also suitable for bottom blowing tuyeres, which are worn by peeling-off due to expansion mismatch and spalling due to external stress. This result shows that these technologies are also applicable to bricks for the bottom blowing tuyere.

● : Conventional, ▲ : Matrix reinforcement, ◆ : Carbon bond enhancement

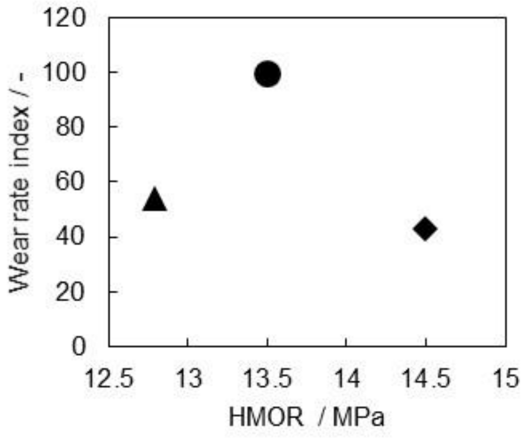

**Figure 13.** Variation of wear rate of bottom tuyere of a converter as a funciton of HMOR of bricks.

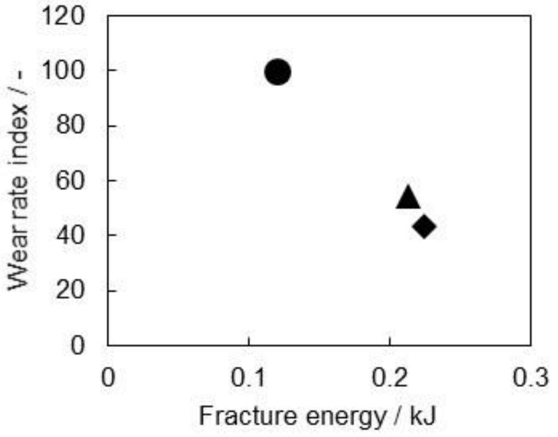

**Figure 14.** Variation of wear rate of bottom tuyere of a converter as a funciton of HMOR of bricks.

## 4 CONCLUSION

The wear mechanisms of the scrap impact zone and bottom blowing tuyere were investigated. According to the investigation results, the wear mechanisms of these two zones were hypothesized to be attributable to crack propagation. On the bases of that hypothesis, the fracture energy-improved MgO-C bricks were developed and applied for commercial applications. As a result, considerable reduction in wear rates were recognized. Hence, the hypothesis was validated by commercial application.

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