In order to prolong the service life of coke ovens, the tolerable limit of localized force on damaged oven walls is investigated by discrete element method simulation. A simulation model comprising three flues and five or fifteen layers of bricks was constructed and the effect of various wall damages on the tolerable limit of localized force was examined. It was found that the following liner brick damages cause an extreme decrease in the tolerable limit: 1) loss of tongue and groove constraint, 2) wear which reaches tongue and groove (ca. over 35 mm), 3) cracks over 2.5 mm wide, and 4) loss of horizontal constraint. These findings provide useful guidelines for effectively repairing old coke ovens to prolong oven life.

KEY WORDS: coke oven; localized wall force; tolerable limit; DEM simulation; liner brick damage.
two straight cracks from the oven chamber side to the flue side at the position of 25 mm from binder brick surfaces in the two-cracks model (Fig. 1(c)). Localized force was applied on a circle (20 mm diameter), the center of which was placed 20 mm apart from the crack in the direction toward the center of the flue and at the center in the vertical direction in the one-crack model, and at the center of the two cracks in the two-cracks model.

Vertical boundary conditions on the top surface of the model were determined so that the applied stress was identical to the condition where the center of the model structure was placed 1.5 m above the oven sole and the structure received the weight of the bricks placed above. Bracing force from buckstays was applied on both the pusher side and coke side surfaces and the surfaces were fixed in the direction of localized force (x-direction in Fig. 1). The top and bottom side surfaces were also fixed in the direction of localized force. Mortar joints were neglected because the brickwork of old ovens was expected to have no sticking ability. In this software, each single brick corresponds to one element in DEM, and stress within a brick is calculated by the FEM method. For the contact surfaces, the Coulomb slip model is applied and the parameters used in the analyses are summarized in Table 1. We employed fairly large normal and shear stiffness values for the surfaces because we wanted to restrict the deformation of a single element to clearly demonstrate the movement of the element as well as the stability of the calculation. Applied localized force on the damaged brick was gradually increased quasi-statically and the displacement of the bricks was calculated. The simulation was conducted by repeating the process of contact judgment, force calculation and displacement calculation until the load reached the upper limit or a loaded brick became completely separated from the model structure. The displacement increased as the force increased, and the force of wall breakage was defined as that when the displacement reached the depth of half the brick width. The effect of various model conditions such as tongue and groove state, wear of bricks, width of the crack, etc. on the force of wall breakage was estimated.

3. Results and Discussion

3.1. Effect of Tongue and Groove Condition

The model in which the center brick had two cracks each of 0 mm width was employed and the effect of the tongue and groove condition was examined. A damaged tongue and groove was represented by placing a horizontal crack of 0 mm width at the bottom of the tongue to separate the brick into two parts so that the tongue part could move separately from the brick. The calculated deformation of the model structure upon applying localized force is shown in Fig. 2 (damaged tongue and groove) and Fig. 3 (sound tongue and groove).

The magnitude of the force of wall breakage was 600 N where the tongue and groove was damaged, and 1 200 N
where no damage existed, which means that damage in the tongue and groove part greatly affects the tolerable limit of the wall. When the tongue and groove linkage is damaged, the possibility of wall breakage is thought to be fairly high because the measured localized force often reaches 600 N in coke cake compression experiments. On the contrary, when tongue and groove linkage works effectively, the possibility of wall breakage is much lower. In the case where the damaged brick has one crack of 5 mm width, the same effect of tongue and groove is observed as shown in Figs. 4 and 5 (detailed deformation of one crack model was described in the previous report).

With these models, the effect of bracing force was also examined in order to know whether a strong bracing force decreases the possibility of wall breakage or not. However, no significant difference was observed between the usual case and under strong bracing force (twice as large as the usual force).

### 3.2. Effect of Wear in Liner Brick

Based on the above results, the loss of tongue and groove linkage by excessive wear of liner bricks is expected to lower the tolerable limit. To clarify this effect quantitatively, the force of wall breakage when the wall consists of worn bricks with sound tongue and groove linkage was investigated. The thickness of the liner wall was decreased from its original thickness of 100 mm while the distance of the tongue and groove position from the brick’s flue side surface remained unchanged. The width of the crack was 5 mm as in the case mentioned above. Figure 6 shows the deformation of the bricks (vertical sectional view) for various wear amounts. The forces of wall breakage for wear of 0 mm, 35 mm and 40 mm were 1 000 N, 900 N and 400 N respectively. From these results, wear of over 35 mm causes a steep decrease in the force of wall breakage. This amount of wear is almost identical to the distance from the brick surface to the edge of protrusions of the brick, and such wear up to this point is considered to be critical for liner wall strength.

However, the difference of observed force of wall breakage between 0 mm and 35 mm wear is unexpectedly small. We reviewed the results and found that swelling of the model in the vertical direction is observed in the case of 0 mm wear with sound tongue and groove. Figure 7 shows the swelling of the whole model, revealing that the swelling is larger in the 0 mm wear model than in the 40 mm wear model (we also confirmed that swelling of the 35 mm wear model is similar to that of the 0 mm model). We consider that loosening of all the bricks enables the damaged brick to move in the 0 mm wear model, whereas no such loosening is necessary in the 40 mm wear model. This implies that in the more strongly constrained condition such as in an actual oven where swelling is restricted, the tolerable limit will be much higher than that observed in a small model.

To confirm this effect, we conducted simulations with a 15-layer-3-flue model that has the same configuration of bricks except for the number of layers. Figure 8 shows that the swelling of the whole model is more restricted in the 15-layer model than the 5-layer model (cf. Fig. 7 wear=0 mm,
load = 1 000 N). The deformation of the region around the damaged brick is shown in Fig. 9 and the estimated force of wall breakage in the 15-layer model is over 2 000 N, which is the upper limit of the applied load in this calculation. With a compression test of 250-kg coke cake,\textsuperscript{31} it was confirmed that a localized wall force of over 1 000 N was not observed in usual pushing operation even in the case of stickers, so no wall breakage is predicted if the wall has sound tongue and groove and small amount of wear. The relationship between wear amount and the force of wall breakage including the results with the 15-layer model is shown in Fig. 10. Although the critical wear amount was not determined in the 15-layer model, we consider that the critical wear amount would be the same in 5-layer or 15-layer model because the effect of excessive wear up to the tongue and groove region of the brick is essential to wall breakage.

### 3.3. Effect of Crack Width

In Sec. 3.1, it was estimated that the possibility of liner wall breakage is high if the brick has a crack of 5 mm width and tongue and groove linkage is lost. However, the force of wall breakage is expected to decrease when the crack width is narrower even if the tongue and groove linkage is damaged. To clarify the effect of crack width on the force of wall breakage, various cases with different crack widths were investigated.

During this study, it was found that the boundary condition of the pusher and coke side surfaces greatly affects the results. In the boundary condition where only bracing stress from buckstays was applied to both surfaces, the force of wall breakage was 600 N even when the crack width was 1 mm, and no big difference in deformation was observed between the cases of crack width of 1 mm and 5 mm (Fig. 11). However, under the boundary condition where both the pusher side and coke side surface were fixed in the coke pushing direction (y-direction), the force of wall breakage markedly increased with the model with a crack width of 1 mm (Fig. 12), whereas the force remained unchanged with the model with a crack width of 5 mm. Under the fixed boundary condition, the deformation behavior changed between crack width of 2 mm and 3 mm (Fig. 13). The rela-
The relationship between crack width and the force of wall breakage is shown in Fig. 14. The results show that a larger force is necessary to cause wall breakage in the condition where the crack width is less than 2.5 mm even if tongue and groove linkage is lost. We cannot fully rationalize the reason why the critical width is 2.5 mm, however, we consider that the large frictional force in the narrow crack restricts the deformation.

The effect of boundary condition implies that a slight movement in the pushing direction lowers the tolerable limit of the localized force and the possibility of wall breakage markedly increases in the case where the brickwork is loosened such as partial expansion and contraction of the wall, existence of several cracks in the wall, tie rod damage, and so forth. In general, taking into consideration this effect, as well as the result that tongue and groove linkage greatly affect the deformation and that the bracing force has no effect on deformation (cf. Sec. 3.1), bricks in the oven wall are considered to be fixed mainly by the surrounding bricks and not by bracing stress.

3.4. Prevention of Wall Breakage

Based on these simulation results, the following suggestions for preventing wall damage are proposed. To prevent wall breakage in an old oven, there are two measures: decrease the localized force by decreasing the pushing force, and increase the wall strength by wall repair. Decreasing the pushing force is effective but cannot solve all the problems because it is very difficult to avoid hard push completely, especially when the working rate is high. Based on the above-mentioned quantitative analyses on the tolerable limit of localized force in an old oven, such a hard push can cause wall breakage because a localized force of around 600 N often occurs under the hard push condition and reaches the tolerable limit in damaged ovens. On the other hand, if wall damage is not as serious as the criteria described above, the wall can withstand localized force generated even in the case of a hard push or stickers.

In other words, the occurrence of wall breakage largely depends on the wall conditions, and to prevent wall breakage it is important to repair the weak part of the oven. To do this, we should know the damages and their effect on the wall strength, and should determine the priority of repairing various damages in old batteries. As recent progress in oven inspection technologies enables us to understand oven conditions more precisely, we expect the analysis results described in this report will contribute to more effective oven repairs in combination with detailed oven diagnosis.

Of course, the simulation results can be affected by the method, model and conditions employed and so forth. However, the results obtained here provide qualitatively important guidelines for oven repair.

4. Conclusions

The relationship between coke oven wall damage and the possibility of occurrence of wall breakage was quantitatively analyzed by discrete element method simulation, and the following results were obtained:

(1) Loss of tongue and groove linkage markedly increases the possibility of wall breakage.
(2) Excessive wear up to the tongue and groove region of the brick increases the possibility of wall breakage even if no damage exists in the tongue and groove part.
(3) In case where the crack width is less than 2.5 mm, the possibility of wall breakage is small even if tongue and groove damage exists.
(4) In the case where oven wall brickwork is loosened, the possibility of wall breakage increases even if the crack is narrow.

Based on this study, the following recommendations are proposed for extending the service life of coke ovens:

(1) It is difficult to precisely determine the tongue and groove damage, however, special care is required for the replaced bricks in past repair works because the tongue and groove linkage is often lost.
(2) If wear reaches the tongue and groove part (in the case of liner bricks that were originally 100 mm thick, wear of over 35 mm), the part should be repaired to restore the thickness of the brickwork, such as by ceramic welding.
(3) Cracks of over 2.5 mm in width should be repaired by ceramic welding, for example.
(4) Loosening of the brickwork must be repaired. In an extreme case, wall replacement should be considered.

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