Improvement of the Bottom Impact Pad Life for Steel Ladles at Kimitsu Steel Works

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1. Introduction

Kimitsu Works has several types of secondary refining processes to manufacture various kinds of steel products. To make high-grade steel products, the refining operations must be at high temperature for a long time. The steel ladles used for the severe secondary refining operations are required to have a low-cost, stable refractory lining. Figure 1 shows a cross section of a ladle lining, the life of each of the part refractory lining, and the repair pattern of the steel ladles.

The ladle refractories can be divided into four zones, including sidewall, slag line, SN tuyere and the bottom impact pad, as shown in Figure 1. The bottom impact pad has the shortest life, and it was easily estimated that the ladle operation could become more stable, and the cost of the refractories reduced, if the life of the impact pad was increased to about 120 charges (chs), which is almost the same as the life of the slag line refractory and SN tuyere.

This paper reports the results of several trials to prolong the life of the impact pad, to get more stable operation, and reduce the cost of the steel ladle used for the secondary steel refining process. Specifically, the goal was to increase the service life of the impact pad from 65 chs to 120 chs.

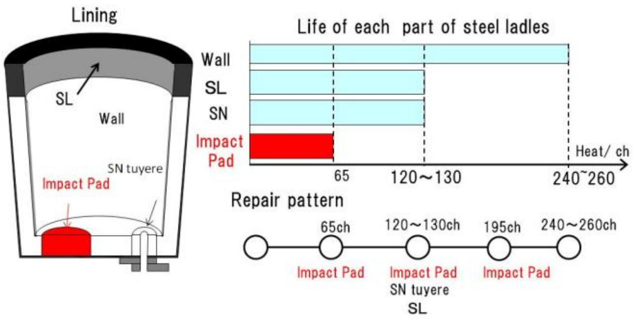

Figure 1. Cross section of a ladle lining, the life of each part of the refractory lining, and the ladle repair pattern.

2. Characteristics of the impact pad and bottom refractory.

The impact pad, surrounded by bottom castable , is located at the position where the molten steel tapped from the converter makes a direct hit. The impact pad and the bottom castable were both alumina-magnesia castable refractories, as shown in Table 1.

Table.1 Characteristics of the impact pad and bottom refractories.

		Impact Pad	Bottom
chemical composition (mass%)	Al_2O_3	88	90
	MgO	10	8
	CaO	1	1
Bulk density(-) 110℃x24h		3.12	3.02
Apparent porosity(%) 110℃x24h		16.0	19.0

3. Improvement of the impact pad

3.1 Field Observation of the impact pad

According to the observation of the impact pad during operation, it became clear that cracks appeared on the surface of the impact pad in the early stage of ladle operation. Figure 2 shows the cracks on the surface of the impact pad after 3chs. A prior study showed that the cracks were caused by the very high impact force of the molten steel stream from the converter[1)]

So it became necessary to find a test method to evaluate the resistance of the refractory materials against cracking due to the molten steel impact. The cracks were observed very early in the ladle life, and actually the cracks were initiated with the very first molten steel impact. Therefore, it was supposed that the surface of the impact pad was about 1000°C for the first charge, which is the temperature right after preheating with a gas burner, and just before receiving molten steel. So a bending strength test was conducted at 1000°C, to evaluate the crack initiation resistance of the refractory blocks.

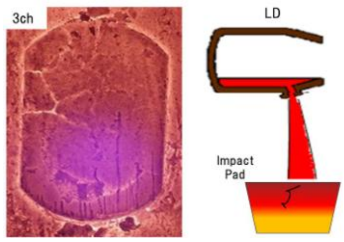

Figure 2. Photograph of the impact pad surface after 3ch.

3.2 Improvement of the impact pad castable against crack initiation

It was known that an increase of the strength of the castable could be useful against crack initiation, caused by external impact forces. Densification of the material, to improve the strength, was tried by reducing the aluminum metal and organic fiber content of the castable refractory, to avoid a vapor explosion during preheating. It was possible to avoid problems due to vapor explosion by reducing the Al and organic fibers, and by heating the refractory blocks carefully and cautiously.

Table 2 shows the characteristics of the castable refractories tested, with no Al in Samples 1 and 3, and reduced organic fiber content in Samples 2 and 3.

It was confirmed that the porosity of the refractory was reduced by reducing the amount of added Al and organic fibers. Figure 3 shows the results of the hot bending strength test at 1000°C. By reducing the amount of Al and organic fibers, the hot bending strength at 1000°C was improved.

Table.2 Characteristics of the impact pad refractories tested

		Base	Sample 1	Sample 2	Sample 3
chemical composition (mass%)	Al_2O_3	88	88	88	88
	MgO	10	10	10	10
	CaO	1	1	1	1
Metal Al		a	0	a	0
Organic fibers		b	b	0.4b	0.4b
Bulk density(-) 110℃x24h		3.12	3.15	3.19	3.21
Apparent porosity(%)110℃x24h		16	14.2	13.1	12.1

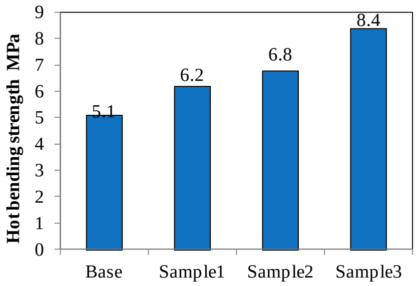

Figure 3. Results of hot bending strength test at 1000 ° C

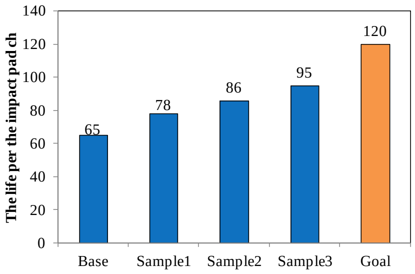

Figure 4. Average service life of trial impact pads

3.3 Actual use of the impact pads with improved strength

Impact pads, made of samples 1, 2 and 3, were tested in ladles, in actual operations; Figure 4 shows their service lives. It was confirmed that the improvement of the hot bending strength was effective in prolonging the service life of the impact pad, but the improvement was not sufficient enough to meet or exceed the established goal of 120 chs, so further investigation was continued. Figure 5 shows a cross section of the impact pad block, made of Sample 3 material, after use in a ladle for 100 chs. An open space, or void, was observed between the top of the hot face layer and the bulk material below, and this hot face layer would peel off from the bottom area some charges later. It was a fact that this type of space or void was not seen in the conventional impact pads. So a mechanism for the formation of this space/void was proposed, as shown in Figure 6. The improved material had higher thermal expansion, because of its higher density, and the difference of temperature between the hot surface and the lower material caused a larger difference of expansion. So the hot surface layer had more expansion than the cooler material below, which promoted formation of the space/void, but the high strength of the material resisted cracking[2]. It was observed that this thin, high strength surface layer bowed, causing the space/void to increase, and that the surface layer became thinner after more charges.

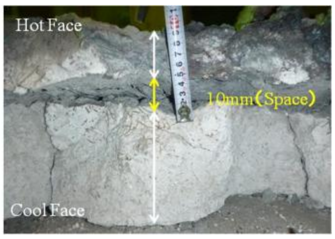

Figure 5. Appearance of the impact pad after 100ch

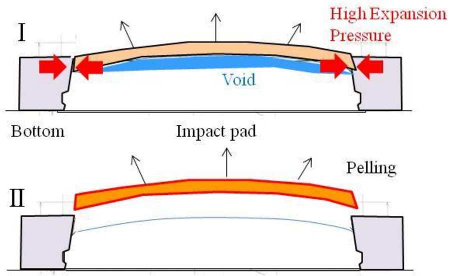

Figure 6. Proposed mechanism of space formation

3.4 Simulation test of crack/void formation in the impact pad

It was necessary to confirm the damage mechanism(s) of the impact pad, to permit consideration of countermeasures, so a damage simulation test method was developed, as shown in Figure 7. The test sample was roughly 1/20 the size of the actual impact pad, surrounded by the bottom castable, was tested in the panel spalling test furnace. The sample was heated at 1300° C for 60 min and then cooled down in air for 60 min. The heating/cooling cycles were repeated five times. In the actual operation, it took 60 minutes each for heating and cooling, which was simulated in the test. However, the 1600°C temperature of the actual molten steel was not simulated in the test because of the temperature limit of the test equipment.

Table 3 shows the properties of the castable materials that were tested for the impact pad and the surrounding bottom refractory. The tests involved three different material combinations, as the Table shows.

The materials of Case 1 were the same as the material combination of the actual ladle in which cracks were observed in the both the impact pad and surrounding bottom refractory.

In Case 2, the magnesia content of the bottom refractory was reduced 1%, aiming to suppress the thermal expansion[3]. In Case 3, the magnesia content of the bottom refractory was 1% lower than that of Case 2. The composition of the impact pad material was not changed in any of the three cases.

Figure 8 shows the results of the simulation tests for the above test conditions. A crack was observed in the impact pad in Case 1, but no cracks were observed in Cases 2 and 3. The result of Case 1 was very similar to the result observed in actual use, thus it was considered that the test provided a sufficient simulation of the actual condition. From the results of Case 2 and 3, it was suggested that decreasing the thermal expansion of the bottom refractory surrounding the impact pad was effective for suppressing the crack generation in the impact pad.

On the basis of the above test results, the material combination of Case 2 was tested in an actual ladle, and Figure 9 shows the resulting service life of the impact pad. Figure 10 shows a cross section of the impact pad of the Case 2 combination after actual use and it was noticed that there was no void on the surface layer, as was seen before.

Due to the adoption of the lower thermal expansion material as the bottom refractory, the life of the impact pad increased by 10% and no cracks were observed.

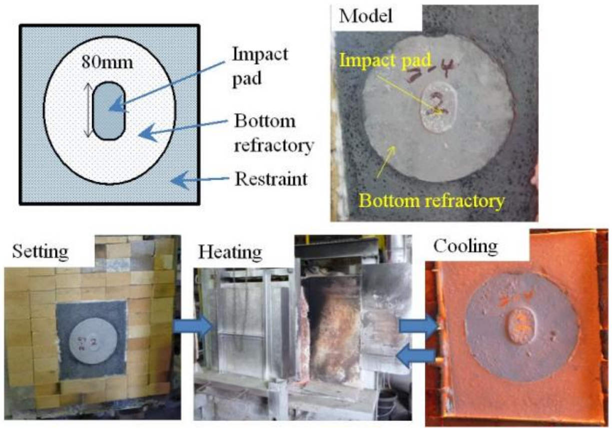

Figure 7. Simulation test of impact pad crack/void formation

Table 3. Characteristics of the refractories tested for crack generation

		Case 1		Case 2		Case 3	
		Impact Pad	Bottom	Impact Pad	Bottom	Impact Pad	Bottom
chemical composition (mass%)	Al_2O_3	88	90	88	91	88	92
	MgO	10	8	10	7	10	6
	CaO	1	1	1	1	1	1
Bulk density(-) 110℃x24h		3.21	3.02	3.21	3.03	3.21	3.03
Apparent porosity(%)110℃x24h		12.1	19.0	12.1	18.7	12.1	18.2
Coefficient of thermal expansion (%) @1500℃		2.12	1.87	2.12	1.62	2.12	1.53

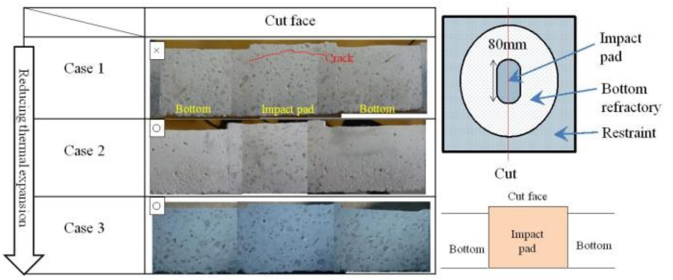

Figure 8. Results of the simulation test for crack generation

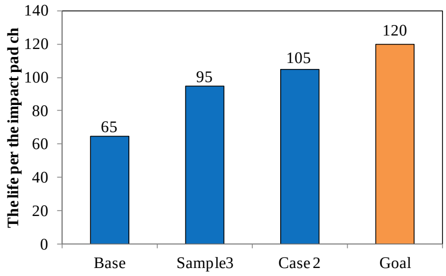

Figure 9. Average service life of impact pad trials

Figure 10. Cross section of the Case 2 impact pad after actual

3.5 Effect of changing the impact pad thickness

The thickness of the impact pad was increased from 230 mm to 330mm, aiming to increase its life. Figure 11 shows a cross section schematic view refractory structure of the ladle bottom. The impact pad stood 100 mm higher than the bottom refractory, in the case of 330 mm thick impact pad. Figure 12 shows a comparison of the wear rate for the impact pads of 230 mm and 330 mm thickness, for actual operation. It was recognized that a 100 mm increase of the impact pad thickness didn't make a significant difference in the life. In other words, the increase of the thickness didn't work well.

But it was observed that the 330 mm thick impact pad thickness reduced very rapidly during the first 40 charges and then maintained a relatively similar thickness as the initial 230 mm thick impact pad. It was suggested that the difference in height between the surfaces of the impact pad and the bottom refractory caused the rapid wear of the impact pad, and that the wear mechanism was peeling rather than slag corrosion or molten steel erosion.

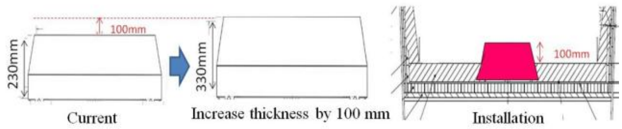

Figure 11. Schematic structure of the ladle bottom using a 100 mm thicker impact pad

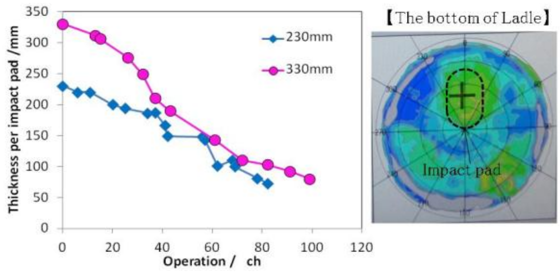

Figure 12. Comparison of the wear rate of impact pads of 230 mm and 330 mm thickness in actual ladle service.

3.6 Stress analysis of the ladle bottom structure

To clarify the detail of the peeling, stress analysis was done for the ladle bottom, focusing on the stress generated at the boundary between the impact pad and the surrounding bottom refractory. Specifically, the thermal stress generated around the boundary at high temperature was calculated.

Calculations were made for three bottom designs. In the first design, the thickness of the impact pad and the bottom refractory were the same, and the surfaces were flat. The second design was for an impact pad that was 100 mm thicker than the bottom refractory, so there was a 100 mm step between the two. The third design was similar to the second pattern, but the 100 mm step was filled by sloping the bottom refractory material. The following conditions were adopted for the calculations:

Hot surface at 1600°C: Heat transfer rate 1.16 W / m^2 K

Cold bottom face at 30°C: Heat transfer rate 35W / m^2 K

Side faces and bottom face were under restraint but not the upper face.

Data of elastic modulus, thermal conductivity, and thermal expansion of the materials were measured at 30~1600° C. and applied for the calculations.

Figure 13 shows the results for the stress analysis (including the three model designs), temperature gradient, and maximum principal stress (tensile strength). In the first design, the tensile strength generated at the boundary between the impact pad and the surrounding bottom refractory was 4.0 MPa. But in the second design, with a stepped boundary, the tensile strength generated at the boundary was 14.4 MPa, which is more than three times greater than that of the first design. The tensile strength at the boundary for the third design, in which the surrounding refractory was sloped, was 5.0 MPa, which was similar to that of the first design.

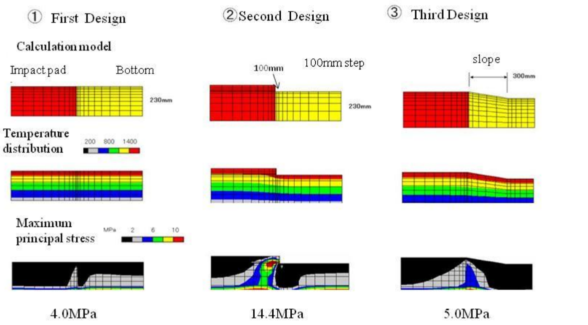

Figure 13. Results of stress analysis for 3 ladle bottom designs

These results suggested that the step-like structure at the boundary of the impact pad and the bottom refractory caused larger tensile stress than the flat structure, and the wear of the impact pad, which stood higher than the bottom refractory, was significantly greater, early in the ladle campaign. Furthermore, it was apparent that the sloped structure, where the stepped offset was eliminated by filling with the bottom refractory, was effective in reducing the tensile stress.

It was considered that the wear mechanism of the impact pad, mentioned above, clearly explained the reason why the 330 mm thick impact pad wore rapidly by peeling during the first 40 chs of operation, as shown in Figure 12. It was estimated that the wear rates of the impact pad and bottom refractory became almost the same after 40 chs, because the stepped offset disappeared, which created a flat surface, similar to the first design in the stress analysis. Finally, it was decided to adopt the third design structure using a thicker impact pad in an actual ladle to increase the life of the impact pad. Figure 14 shows photographs of the actual ladle bottom where an impact pad of 330 mm thick was surrounded by the bottom refractory of 230 mm thick and the stepped offset was filled with bottom refractory, making a sloped structure. The wear results of this trial are shown in Figure 15. It was clear that the wear by rapid peeling in the early stage of operation was suppressed by the adoption of the sloped bottom structure. Figure 16 shows the progressive increase of the actual impact pad life for each of the three successful material/design improvements that were evaluated and applied, based on this study. The ladle bottom life was improved about 85% from the starting point (65 chs.), and the target life of 120 chs. was achieved, which permitted balancing of the ladle repair schedule.

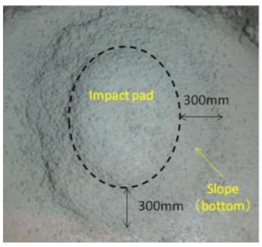

Figure 14. View of the third design combination for the impact pad and bottom refractory

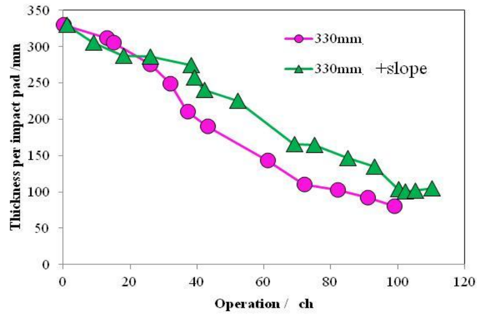

Figure 15. The transition of the residual thickness per impact pad

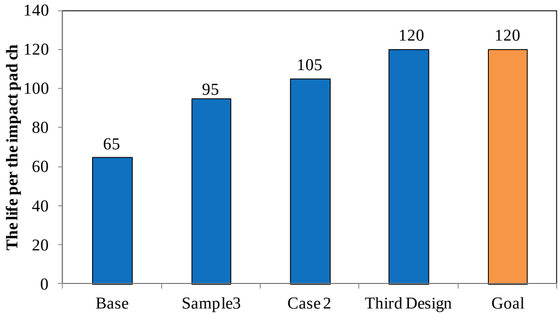

Figure 16. Transition of the impact pad life for the trials

4. Conclusions

Because the service life of the impact pad installed in the bottom of ladles at Kimitsu Steel Works was too short, it was determined that the repair interval of the ladles should be extended, to improve the bottom impact pad life, so three improvements were tried to achieve this goal.

First, the strength of the alumina-magnesia impact pad castable was increased, because of the damage caused by the impact of molten steel during charging. The improved impact pad castable, had roughly two times higher strength than the previous impact pads. The improvement of the impact pad castable also included densification.

The second change was to lower the thermal expansion of the bottom refractory installed around the impact pad. The thermal expansion was decreased to prevent the damage caused by high expansion pressure between the impact pad and the surrounding bottom refractory.

The third change was optimization of the structure of the ladle bottom refractories. The impact pad and the bottom refractories were installed without a stepped offset, to provide a flat bottom surface; it was determined that the height difference of these refractories generated a high stress concentration at the contact interface between the lower bottom refractory and the higher impact block.

Good success was achieved on this project, because the life of the impact pads was almost doubled (65-120 chs), based on the three improvements discussed above.

5. Reference

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