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Review Article

Future Outlook of Refractories for Iron and Steelmaking

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ABSTRACT

Refractory industry in technologically advanced countries has long been on gradual decline due to leveled-off steel production and decreasing unit consumption of refractories for steel. Notable technological achievements by refractory industry that contributed significantly to steel production are briefly reviewed covering from blast furnace, basic oxygen furnace to continuous casting. Future possibility to revitalize the refractory industry is discussed on the basis of the review, taking into account opportunities available in environment and energy related sector of industries.

Key words* : *Refractory industry, Refractories for steel production, Future outlook of refractories

1. Introduction

Production processes and qualities of refractories for making steel have made substantial progress in the last 20 years to meet ever demanding requirements of steel industry. The progress has, however, been on the horn of a dilemma, countered by declining consumption of the refractories. Such dilemma will continue in the foreseeable future as it has been the case in many materials industry sectors.

There are yet many refractory problems left unsolved in steel industry. Most of the unsolved problems in processing and quality of refractories need to be addressed not only by refractory industry but also by complementary optimization of relevant operations in steel industry. Among them, the quality problems require intelligent solution, i.e., advanced control of mineral phase, microstructure and texture by implementing recent progress in ceramic science and technology. Quantum leaps in the quality to revolutionary solve the problems with affordable cost by closer cooperation with steel industry and academia would assure further development of refractory industry.

This paper will briefly review some of key technological issues in the past progress of steelmaking refractories, and depict important unsolved quality problems with suggestion on continued development of refractory industry.

2. Refractory Industry in Japan

Major refractory materials used in steel industry are bricks and monolithics mostly in the system consisting of the combination of two or more of MgO, Al_2O_3, MgO-Al_2O_3, Al_2O_3-SiO_2, ZrO_2, SiO_2, and carbon/graphite/carbide. Production of refractories for steel industry has kept declining despite the sustained steel production as shown in Fig. 1.[1] In fact, 3.5 mil. ton/yr of refractories was produced in 1973 by 101 companies with 150 plants by 25,000 employees. In contrast, it decreased to 1.3 mil.ton/ yr in 1999, only 37% vs. 27 years ago, by 63 companies, 85 plants and 7,100 employees.[2]

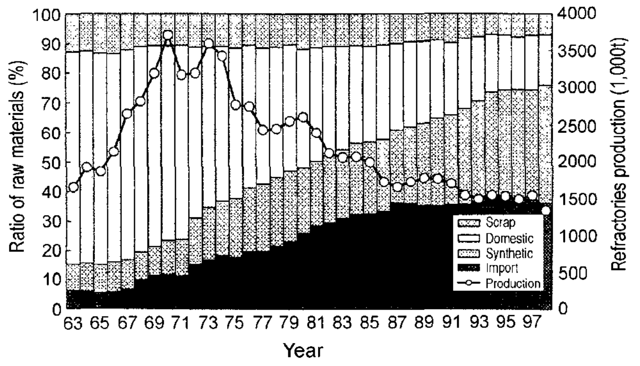

Fig. 1. Chronological change in the production and raw materials of refractories in Japan.[1]

The substantial decline was caused by the reduction in the amount of refractories for construction and consumption, resulting in a marked downturn from 110 kg/t-crude steel in 1949 to 20 kg/t in 1973 to 10 kg/t in 1999.[2] Reduction in construction was due largely to (a) over capacity of blast furnaces (BF's), hot stoves, basic oxygen furnaces (BOF's), and reheating furnaces (RF's), and (b) prolonged life of BF's (cf. 24 years/campaign) and coke ovens (cf. 50 years/campaign). Reduction in consumption was due to (a) development of new operation technology by steel industry (cf. slag coating and splashing in BOF) and (b) improvement of refractory quality and installation technology by refractory industry (cf. MgO-C brick and flame gunning repair monolith-

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ics both for BOF). Sizable imports from overseas where labor cost is inexpensive also contributed to the decline.

Demands to prolong service life of refractories for metallurgical reactors to reduce the refractory consumption have been ever increasing, driven by cost conscious steel industry and environmental concerns of society for energy and waste minimization. Further reduction of the refractory consumption will continue in foreseeable future, aiming at better durability of refractories for increased productivity of steel while steel quality being sustained and possibly improved.

3. Notable Achievements in Japanese Refractory Industry

Prolonged service life of furnaces and reduced consumption of refractories have been materialized due to cooperative development efforts between steel industry and refractory industry. Major achievements in refractory industry are characterized largely by:

1. Composite bricks of synthetic oxides and carbon/graphite/silicon carbide that are denser with less impurities and better controlled grain size distribution.
2. Monolithics upgraded to be economically compatible with bricks.
3. Robotization and mechanization of the setting of the bricks and monolithics, and
4. Increasing production of functional refractories.

Some examples representing the above characteristics are given in the following:

3.1. Large Size Prefabricated Graphite (C)-block with SiC/Alumina for BF Hearth

Chemical and physical wear at elevated temperatures of prefabricated C-block at the hearth wall of BF has limited the service life of BF. As the size of BF increases, the wear has become a bottleneck for the hot metal production. The wear is due to excessive thermal expansion of the block caused by the penetration of hot metal, ZnO and alkali oxides into the block, and chemical dissolution followed by mechanical erosion of the block by insufficient metal coating and erratic, carbon-unsaturated metal flow in front of the block.[3]

Substantial improvements have been achieved to minimize the construction time, and the penetration, dissolution and erosion of the block. Measures taken are, respectively, prefabricating large size C-block by pressurizing, sintering and machining with minimized gap at brick joints, and minimizing pores and increasing thermal diffusivity and block with the addition of Si/SiC. Typical properties of the block are given in Table 1[3] where block code E was used for Tobata No. 1 BF of Nippon Steel. Today, over 24 years of service life or near 16,000t life time hot metal production/m^3 of BF inner volume has been recorded for No. 2 BF of Kurashiki District (formerly Mizushima) Works of JFE Steel. Advanced operational control to keep solidified iron layer coating on the blocks with cooling and decrease hot metal flow rate at the iron coating/hot metal boundary in BF hearth area, are found effective together with the above mentioned improvements in the C-blocks.

3.2. Oxides-carbon/Graphite Composites Bricks for Torpedo, BOF, EAF, and Ladle

Typical example is magnesia-carbon/graphite (MgO-C) bricks for BOF that prevent penetration of iron oxide rich,watery, very oxidizing and corroding BOF slag during high temperature blowing, while standing against thermal spalling and mechanical erosion by aggressive thermal and mechanical impact of scrap and metal flow during charging and tapping.

Combined with slag coating/splashing at the end of blow-

Table 1. Properties of Carbon Block Used for Blast Furnace Hearth Wall[3]

		A	B	C	D	E
Main material	Anthracite coke	○	○	○	○	×
	Graphite	○	○	○	○	○
	Alumina	×	○	○	○	○
	Silicon	×	×	○	○	○
	Silicon carbide	×	×	×	×	○
Total porosity (%)		17.8	17.5	18.2	18.8	20.5
Bulk density (g/cm^3)		1.58	1.57	1.60	1.70	1.57
Cold crushing strength (MPa)		41.3	40.7	45.2	62.6	42.1
Modulus of rupture (MPa)		10.6	11.4	12.3	14.7	12.2
Thermal conductivity [W/(m·K)] at 350°C		14	14	14	20	31
Alkali resistance (ASTM)		LC	U,LC	U,LC	U	U
Mean pore diameter (μm)		12.7	10.0	3.0	0.04	0.2
Chemical composition (%)						
F.C.		96.0	91.0	82.3	76.9	69.0
Al_2O_3		1.4	5.7	5.3	5.4	5.7
SiC						17.5

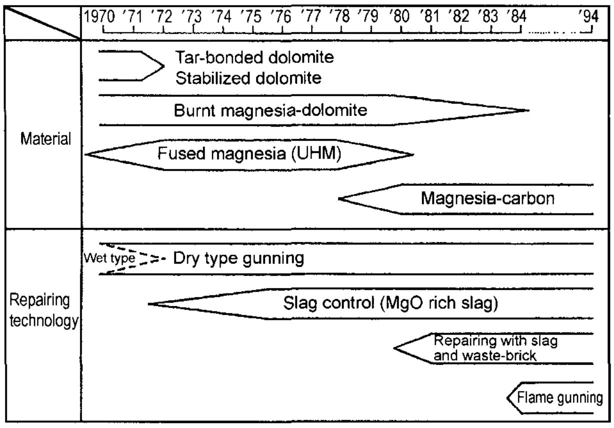


Fig. 2. Development of magnesia-carbon bricks and repair technology for BOF in Japan.[4]

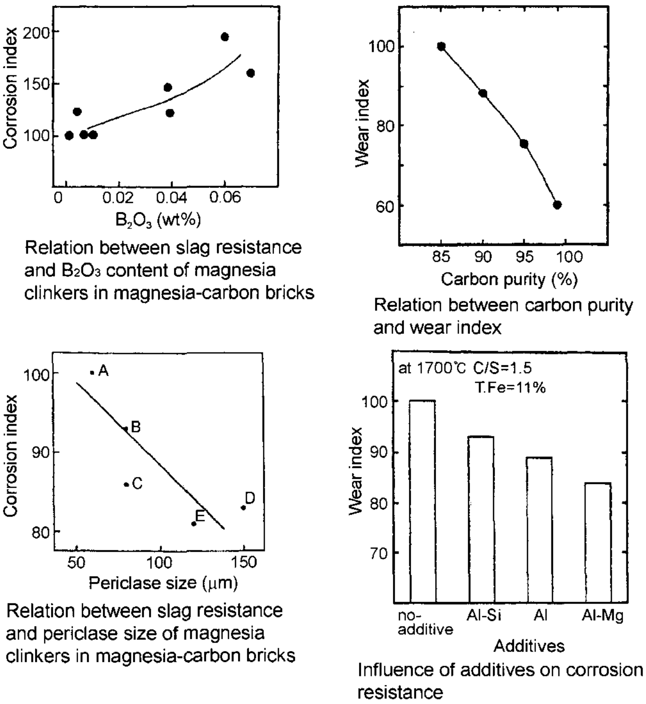
ing to protect the working surface of the bricks, BOF lining is operating, under reasonable conditions, in excess of 10,000 heats/campaign. Gunning repair of monolithics (MgO, MgO-Carbon bond) between the tappings of BOF while they are hot, helps extending the service life considerably. Historical development of MgO-C bricks for BOF is depicted in Fig. 2.[4] MgO-C bricks with slag control, slag coating/splashing and flame gunning dominate the refractory lining of BOF, despite its inherent disadvantage of high thermal diffusivity which can cause vessel shell distortion after a long run.

Wear of MgO-C bricks arises from the oxidation of graphite and dissolution of periclase clinker into BOF slag. Oxidation of graphite by oxygen in both air and iron oxide rich slag enhances penetration of the slag into the bricks. The slag reacts with periclase grains to dissolve them into it to be washed away by the flow of steel- and slag-melt in the vessel. Increased contents of impurities in graphite and periclase accelerate the dissolution. Penetration of air into BOF between tapping and charging oxidizes graphite substantially. Mechanism of the wear has been elucidated to some extent, varying much with working conditions.[5] Thus, zoned lining of different parts of BOF (cf. top cone, slag/metal line, bottom and tap hole) that are exposed to different working conditions is mandatory and executed.

As shown in Fig. 3,[5] adding Al[6] or Al-Mg, decreasing boron oxide, increasing carbon purity and periclase grain size, all help decreasing the wear of MgO-C brick. Increased addition of expanded graphite improves resistance to thermal spalling and mechanical erosion. The metal added MgO bricks with lower content of graphite are favored where mechanical erosion dominates.

Working conditions of BOF are changing by the increased implementation of hot metal pretreating blow and slag minimizing blow, calling for the modification of MgO-C bricks. Further investigation into the detailed mechanism of the wear and possible countermeasures are required to work out best fit properties of the bricks for such blowing modes.

Another typical example is steel ladle, over 80% capacity of which undergoes ladle refining in integrated steel plants.



Relation between slag resistance and B_2O_3 content of magnesia clinkers in magnesia-carbon bricks

Relation between carbon purity and wear index

Relation between slag resistance and periclase size of magnesia clinkers in magnesia-carbon bricks

Influence of additives on corrosion resistance

Fig. 3. Factors influencing the wear of magnesia clinkers and magnesia-carbon bricks.[5]

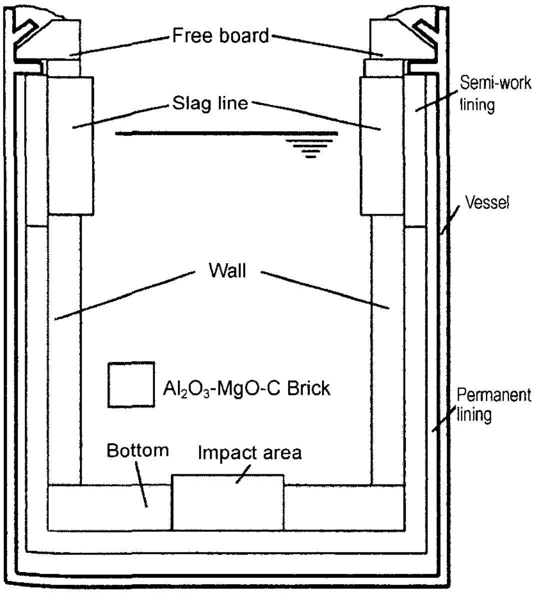
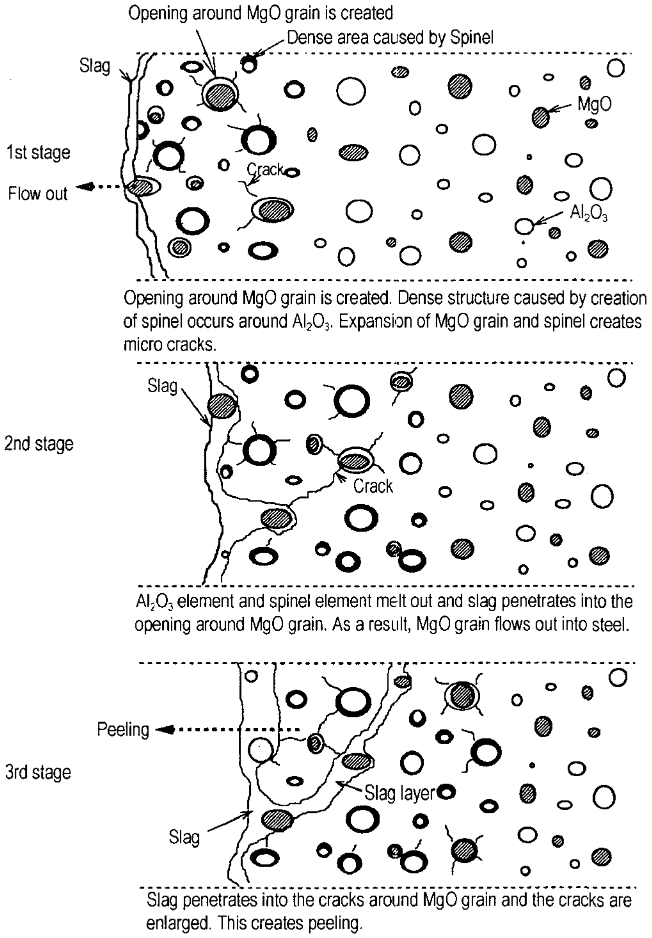


Fig. 4. Schematic of refractory lining of ladle furnace.[7]

Long lasting ladle refining calls for high temperature processing of turbulent melt flow of slag and steel, imposing tough conditions on ladle refractories. Typical lining is shown in Fig. 4[7] where semi-work lining is MgO-C bricks or high alumina bricks, and working lining is MgO-C brick or alumina-magnesia-graphite brick for metal line and MgO-C for slag line. The alumina-magnesia-graphite bricks must stand against thermal spalling, slag corrosion and penetration, erosion by melt flow and oxidation of graphite. To optimize the brick composition and microstructure, high purity

Table 2. Properties of Alumina-magnesia-carbon Brick for Ladle Furnace[7]

	AMC-1	AMC-2
Chemical composition (%)		
Al_2O_3	73	79
MgO	15	10
F.C.	10	5
Apparent porosity (%)	4.0	4.5
Bulk density (g/cm^3)	3.25	3.30
Cold crushing strength (MPa)	50.0	55.0
Modulus of rupture (MPa) at 1400°C	8.0	10.0
Thermal expansion (%) at 1500°C	1.65	1.50
Permanent linear change (%) after 1400°C × 2 h	+0.40	+0.25
Application	For wall	For bottom



Opening around MgO grain is created. Dense structure caused by creation of spinel occurs around Al_2O_3. Expansion of MgO grain and spinel creates micro cracks.

Al_2O_3 element and spinel element melt out and slag penetrates into the opening around MgO grain. As a result, MgO grain flows out into steel.

Slag penetrates into the cracks around MgO grain and the cracks are enlarged. This creates peeling.

Fig. 5. Mechanism of spalling of alumina-magnesia-carbon brick.[7]

electro-fused alumina and magnesia clinkers, graphite, antioxidant and polymer binder are used to give the composition shown in Table 2.[7] Control of both grain size and contact mode of alumina- to magnesia-clinkers is reported to be important to materialize right amount of spinel formation. Spinel formation followed by slag penetration adversely influences the wear of the alumina-magnesia-graphite bricks. Such structural spalling is enhanced when MgO is excessively added or fine MgO is employed. Sequence of the wear is depicted in Fig. 5.[7] Thus, total optimization on the basis of micro structural, chemical, thermal, mineralogical and mechanical consideration is required to further develop better brick for LF ladle.

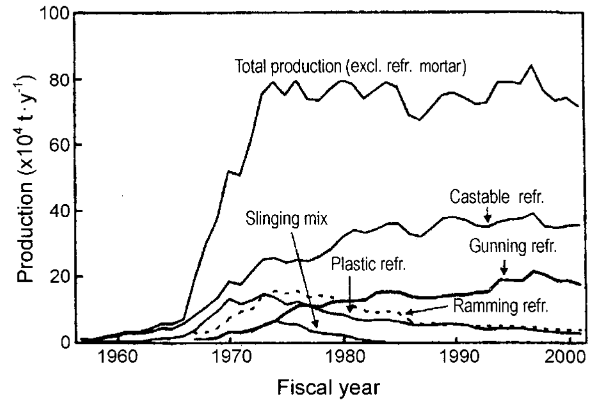


Fig. 6. Production of monolithic refractories in Japan.[8]

3.3. Castable Monolithics for Ladle and Tundish

Ratio of monolithics production to total refractories in Japan has kept increasing since late 1960 to replace bricks. An example is shown in Fig. 6[8] where mortar for joints are excluded from the statistics. Castable and gunning refractories share major portion of the monolithics. The advantages of monolithics over bricks are the elimination of shaping, firing and laying under the condition where compatible economic performance is achieved. In particular, strong demand to cut back labor intensive brick laying by robotization of gunning and casting of monolithics enhanced the replacement. Many efforts have been required to make monolithics competent to bricks in their performance.

For steel ladle, alumina-5% magnesia castable has been utilized to replace alumina spinel castable. As shown in Fig. 7,[9] service life of the ladle lining has increased rather "linearly" from 128 (1990) to 431 (2001) heats. With additional repairs where slag impregnated working surface is not in need of being removed, refractory cost has reduced to about one third (Kashima Works, Sumitomo Metal). This improvement arises from the formation on firing of secondary spinel that expands when formed and is finer than alumina spinel castable, reducing slag penetration and resulting wear. Alumina rich spinel-magnesia is reported to be better than alumina-magnesia in wear resistance and slag penetration resistance,[10] suited for processing increased number of higher temperature heats for secondary refining.

For these monolithics, choice of grain size of constituent alumina or spinel and magnesia is as important as the content of magnesia in forming microstructure that reduces slag penetration. An example is shown in Table 3[10] for the alumina rich spinel-magnesia monolithic castable. How-

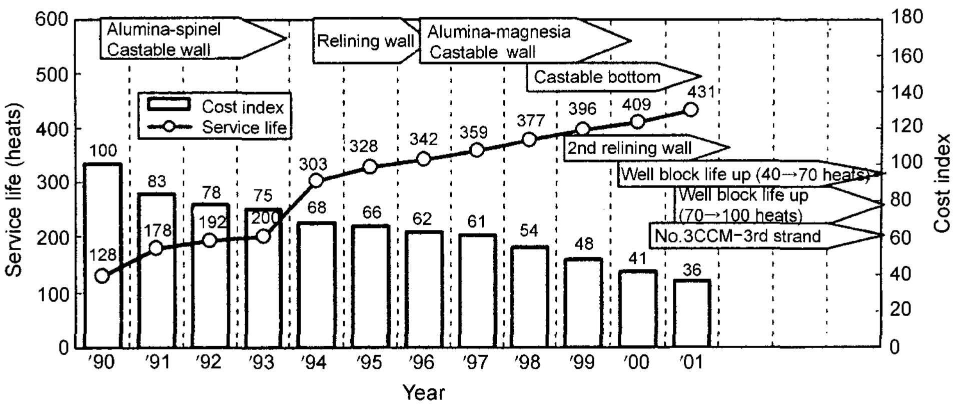


Fig. 7. Improvement of alumina-magnesia castable for steel ladle at Kashima Works, Sumitomo Metal Ind.[9]

Table 3. Improvement of Monolithics for Steel Ladle from Alumina-spinel, Alumina-magnesia to Spinel-magnesia with their Coarse- and Fine-grain Constituents[10]

Grade / Grain size	Alumina-magnesia castable	Alumina-spinel castable	Spinel-magnesia castable
Coarse	Alumina	Alumina (+Spinel)	Spinel
Fine	Alumina+Magnesia	Spinel (+Alumina)	Alumina+Magnesia
After fire	↓	↓	↓
Coarse	Alumina	Alumina (+Spinel)	Spinel
Fine	Alumina+Spinel	Spinel (+Alumina)	Alumina+Spinel

ever, secondary refining in Ladle Furnace (LF) these days demands better wear resistance. Thus, alumina-magnesia-graphite bricks are still utilized. Further investigation to optimize the combination of mineral phases and grain size of constituent materials would lead to better monolithics that hopefully replace the bricks.

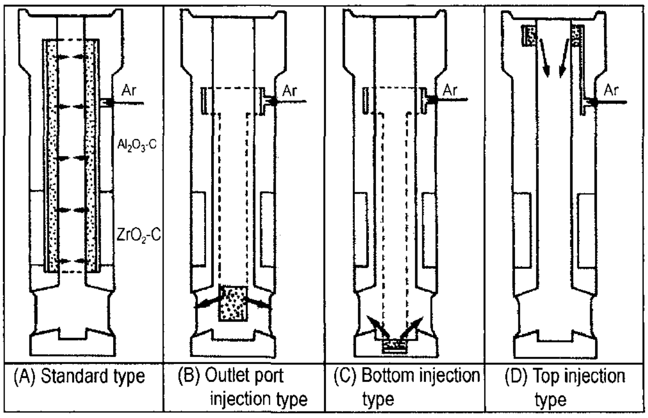
3.4. Alumina-graphite Submerged Entry Nozzle (SEN) for Continuous Casting

SEN and tundish nozzle are taken to be typical examples of functional, fabricated refractories. During continuous casting of Al-deoxidized steel, fine alumina particles (remains of deoxidation product) of up to a few micrometer size, suspending in the steel melt, deposit on melt transfer path where surface/volume ratio is large and flow turbulence occurs, i.e., inner bores of tundish nozzle, slide gate and SEN. The accretion grows as the alumina particles collide, aggregate and carried over to the melt/inner bore refractory interface as casting continues. It clogs and inhibits smooth teeming, causing macro inclusions in cast strand due to dislodging of the accretion itself and erratic melt flow that carries the alumina clusters and engulfed mold slag at the melt meniscus deep into the crater of strand to be captured in the strand.

To avoid the formation of the accretion, intensive cleaning of the melt is done, but not enough. Thus, argon injection through porous refractory wall of the inner bores of tundish nozzle and SEN is often practiced to form fine bubbles and thin film of argon around the inner surface of the bores to prevent the contact of the alumina particles to the surface during the passage of the melt.

On the other hand, SEN needs to be preheated to avoid metal freezing, undergoes thermal shock in the beginning of teeming, must prevent air penetration that reoxidizes the melt, and stand against wear by mold flux. To meet all these requirements and above mentioned need of argon injection simultaneously, a variety of fabricated composite SEN's have been developed. They usually consist of alumina-graphite inner sleeve (with gas-slit and innermost porous surface layer) and zirconia-graphite outer sleeve covering slag/melt level. An example is shown in Fig. 8.[11]

For tundish nozzle, porous refractory layer around the inner bore is also provided to form fine argon bubbles uniformly. Thus, pore size should be fine (ca. 20 μm dia.) and uniform, not to change during exposure to numbers of heats



(A) Standard type | (B) Outlet port injection type | (C) Bottom injection type | (D) Top injection type

Fig. 8. Submerged entry nozzles with porous inner alumina-graphite sleeve for argon injection and zirconia-carbon outer sleeve to reduce corrosion by mold flux.[11]

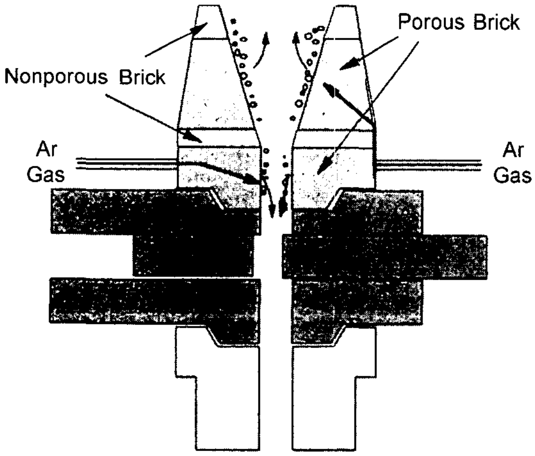


Fig. 9. Advanced tundish nozzle with argon gas injection into upper and lower bore.[12]

of steel melt in sequential casting. In some case, gas passage is split into two circuits to secure uniform bubble formation in the upper part and lower part of the bore as shown in Fig. 9.[12] Durability against wear by melt flow needs to be maintained.

Such functional fabricated assemblies of oxide-graphite composites require high standard of manufacturing precision in many aspects from raw materials preparation, processing, finishing, assembling and testing to on-site validation that leads the assemblies to further development. Integrated technology counts. Porous plug to inject argon into BOF, ladle, LF, sliding gates for ladle and tundish fall in this category.

3.5. Zone Lining Technology of Bricks

Metallurgical vessels are subject to wide variety of working conditions for each of which best suited refractory differs. As partly discussed for BOF lining, even in a single vessel, working conditions differ substantially. To meet such difference, zone lining of refractories at different part of a vessel has long been practiced, as exemplified for steel ladle by MgO-C brick at slag line and alumina-magnesia castable for metal bath. Special care is necessary not to form gap or low melting compounds at the joints of adjacent linings of different refractories.

3.6. Robotized/Mechanized Setting of Bricks in BF and BOF, Flame Gunning/Gunning of Monolithics in Coke Oven, BF, BOF, and RH, and Casting of Mono-Lithics in Ladle and Tundish

Merits of robotization and mechanization for setting bricks are discussed in an early section. Flame gunning of monolithic mixtures has been utilized extensively to extend the service life of coke oven battery wall, BOF lining and RH vessel/snorkel lining. Since the gunning operation is carried out in-situ as hot, mechanization and robotization have been developed substantially. Pneumatic transfer of monolithic powder mix, choice of fuel and bonding materials required detailed consideration and experimental confirmation, to make the monolithics form strong lining immediately after the gunning.

Automation of setting and heating of castable monolithics for ladle (materials mentioned above) and tundish (alumina-silica monolithic with magnesia top coating) has contributed greatly to the propagation of these monolithics. Much attention has been paid rather successfully to improve fluidity, tap density and compaction density for transportation, filling and compacting of the monolithics, respectively.

3.7. Cooling System Design for Refractories in BF, EAF, RF, and Strip Casting

Stave cooling in shaft, trumpet and belly of BF to hold and cool the bricks, and water cooled panel in EAF have long been in industrial operation to extend service life of the bricks and protect slag line with slag coating. Enhanced cooling of BF hearth and bottom even with Cu-stave and refrigerator[13] is developing to further extend the service life, aiming at hot metal production of 16,500 t/m^3. On the contrary, internal heating of side dam refractory on both sides of twin roll containment for steel melt in strip caster is utilized to avoid excessive freezing of steel on the dam.

Fiber castables for skid beam and skid post, and ceramic fiber block for furnace wall have been extensively utilized in modern steel strand reheating furnaces to reduce energy consumption (and refractory weight) effectively.

3.8. Manufacturing Processes and Synthetic Raw Materials to form Denser and Lower-impurity Refractories

Japanese refractory industry has put special emphasis on implementing purer and denser synthetic materials for improving the service life of bricks and monolithics as shown in Fig. 1. Replacing sintered magnesia clinker by electro-fused magnesia clinker with higher MgO content, CaO/SiO_2 ratio, low B_2O_3 content and larger periclase grain size is a typical example. The ratio of domestic vs. import vs. synthetic raw materials was 83 : 6 : 11 in 1965 that changed to 18 : 39 : 43 in 1998,[1] a marked increase in the ratio of synthetic materials. This change has been successful in extending the service life at the expense of cost. However, once performance has been achieved, cost issue has become inevitable focus by users while keeping the quality standard sustained or even better. Cutting high cost of synthetic materials is a prerequisite to stay competitive on international arena of refractory business. Thus, new raw materials to overcome adverse influence of impurities in less expensive synthetic resources should be exploited including ternary systems[14] and non-oxidic carbides and nitrides systems.

4. Changing Climate of Refractory Industry

4.1. Environmental Concerns

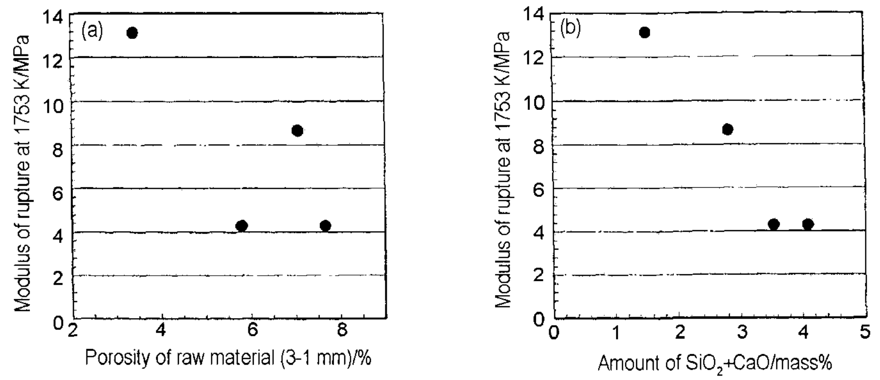
Minimizing the evolution of Green House Gases (GHG's), wastes and energy consumption has become a serious social demand despite the fact that Kyoto Protocol still awaits for its ratification in a more realistic form. In refractory industry, share of monolithics has become 60% of total production, contributing to decrease carbon dioxide emission significantly.

Table 4. Weight Percentage of Refractories for Various Metallurgical Vessels at Kure Works, Nisshin Steel[15]

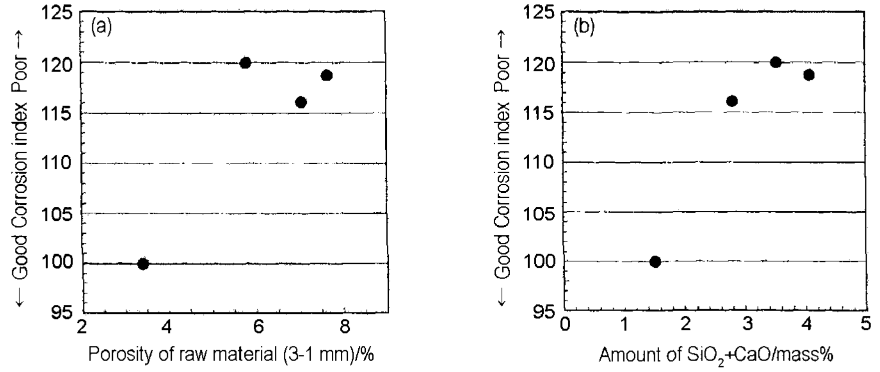
	No	Material	Weight% used	Used area
Monolithic	①	Al_2O_3-MgO castable	15	Steel ladle, RH snorkel
	②	Hi-Al_2O_3 castable	15	Tundish, Lance
	③	MgO castable	10	Tundish coating
	④	Others	1	
Brick	⑤	Al_2O_3-C nozzle	17	L/N, I/N, Sliding nozzle
	⑥	MgO-C brick	13	BOF, Ladle Slagline
	⑦	SiO_2-Al_2O_3 brick	9	Ladle bottom, Hot metal ladle
	⑧	MgO-Cr_2O_3 brick	6	RH
	⑨	MgO brick	5	BOF permanent
	⑩	SiO_2-Al_2O_3-SiC brick	5	Hot metal ladle
	⑪	Al_2O_3-SiC brick	3	Pretreatment of hot metal ladle
	⑫	Hi-Al_2O_3 brick	2	Ladle permanent
		Total	100	

In addition, recycling of waste refractories, although practiced already partially, should be pushed forward in an economical way. The recycling still remains to be less than 10% of raw materials as indicated by "scrap" in Fig. 1. An attempt is shown in Table 4[15] where high quality alumina, contained in SEN and sliding nozzle, is recycled as it shares rather high fraction in the waste, and is more expensive and less contaminated. During pretreatment for recycling of used bricks, crushing and sizing of the bricks are necessary to reproduce bricks with similar porosity and wear resistance to original brick. This is shown in Fig. 10[16] for the recycling of magnesia-chromia brick used in AOD. Here, one has to optimize, by selecting best fit crushing process, the occurrence of fines being disposed and removal of contaminating slag components into the fines to make the recycling cost effective.[16]

Disposing magnesia chromia brick is of another concern since it can be a potential source of poisonous Cr^{6+} at the site of disposal during long run. Magnesia-chromia brick is favored for lining RH- and AOD-vessel due to it's excellent corrosion resistance at high refining temperatures occurring in these vessels. Replacement has been done already by dolomite and the like elsewhere in the world, but in Japan countermeasures have been to develop technology to con-



Relationship between modulus of rupture at 1753 K and (a) porosity of raw material / (b) amount of SiO2+CaO



Relationship between corrosion index and (a) porosity of raw material / (b) amount of SiO2+CaO

Fig. 10. Influence of porosity and slag contamination of recycled AOD magnesia-chromia refractory on the corrosion rate of resulting magnesia-chromia brick.[16]

vert Cr^{6+} to superficially harmless Cr^{3+}. This may not be a satisfactory measure under unexpected circumstances where Cr^{3+} can revert into Cr^{6+}. Further efforts should be paid to replace magnesia-chromia brick by non-toxic one.

4.2. Stepping into Developing Area of Refractory Related Business

Largest consumer, steel industry, of refractory industry foresees that currently leveled off production will not increase substantially again in Japan, whereas decline in refractory consumption will continue. The situation could be similar in Korea. Thus, application of refractories to developing area is a natural consequence of the refractory industry.

Possible candidate is incinerators and gasification melting furnaces for industrial and municipal waste as shown in Fig. 11.[1] The incinerators decompose and combust the wastes at elevated temperatures, and the gasification melting furnaces further melt the resulting ashes into slag to decrease volume, without generating dioxins as shown in Fig. 12.[17] The gasification melting furnaces are classified into a) thermal decomposition gasification-melting type and direct gasification type with many variants for each. For incineration only, fire clay refractory is sufficient since operating temperature is below 1000°C. However, ash melting furnaces operate at 1400−1500°C dealing with molten slags. The slags are characterized by low basicity of 0.5−1.0, high contents of alkalis and phosphorus, low viscosity and corroding nature at elevated temperatures. Thus, alumina-chromia bricks and monolithics are exclusively used due to their excellent wear resistance with increased chromia content as shown in Fig. 13.[17] In view of the toxic nature of chromia, however, replacement to chromia-free refractory is trialed including alumina-magnesia, but requires some break through until the replacement finds full industrial approval.[17, 18]

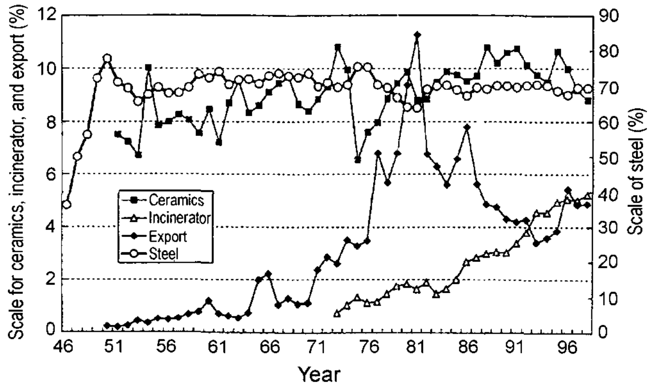


Fig. 11. Increasing sales of incinerator refractories under leveled-off sales of steel and ceramics and declining sales of refractory export.[1]

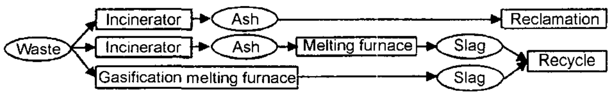


Fig. 12. Three routes of waste processing.[12]

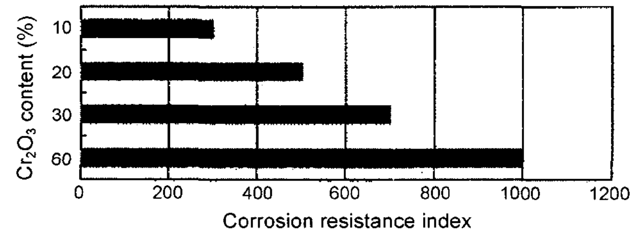


Fig. 13. Relative wear resistance of alumina-chromia castables determined by rotary test (1500°C, CaO/SiO_2=1, wear resistance referring to alumina castable to be 1).[17]

5. Future Outlook

Under declining production of refractories in technologically advanced countries, sustainable growth of refractory industry appears challenging. Viable measures to revitalize the industry in the near future seem to:

1. Enhance cost competitiveness of bulk refractories with a bit better quality than those of competitors in world arena. For this objective, it is necessary to develop clinker materials, that exhibit denser matrix with higher melting temperature, by exploring ternary systems, not limited to oxides but including carbides and/or nitrides. Exploring better combination of binder/ultra fine particles/coarse grain size of the above clinker is also mandatory to develop advanced monolithics for gunning and castables.
2. Further develop functional fabricated refractories to upgrade steel quality, such as a) lance for injecting flux powder and carrier gas into ladle and ladle furnace with superior consistency, b) tundish nozzle and c) SEN that are more effective to prevent clogging, d) less clogging ceramic filter, and e) robust porous refractory for fine argon bubble injection to reduce inclusions in tundish.
3. Overcome technological barrier to develop refractory that can replace magnesia-chromia brick and monolithic currently employed for AOD, RH, incinerator, gasification melting furnace, and rotary kiln in cement industry. This contributes greatly to refractory industry to stay away from toxic pollution and to the progress of environment industry.
4. Look into further possibilities to integrate the existing and above developed refractories with a) robotization/mechanization for handling and setting of brick, monolithic and fabricated/assembled refractories, b) refractory cooling system, c) sensing system for wear, and d) monitoring instrumentation to observe the performance of the setting and assembling of refractories. Recent move to install refrigerator cooled BF bottom assembly with high conductive carbon block and monitoring system, followed by future bottom exchange system, is one of such examples.[13]
5. Secure intellectual properties for the outcome from the above activities, develop international licensing network to propagate the outcome with rational financial reward.
6. Enhance closer cooperation with steel industry and aca-

demia to better implement a) operational knowledge on metallurgical reactors, b) forecast on the future trend of the steel process and reactor development, and c) advanced science and technology already developed and being developed by the academia.

6. Summary

Current status and recent technological achievements in steel sector of refractory industry in Japan are briefly reviewed. The review indicates that there are several key technological issues that may be solved and improved with the development of less expensive new ternary denser materials with higher melting temperatures. Fabricated functional refractories and non-toxic replacement of magnesia-chromia refractory would be additional candidates to put emphasis to develop. Integration could also be a viable avenue with peripheral technologies to provide "service-value" added refractories as a component of advanced metallurgical reactors and waste processing furnaces. The pursuit of the above in corporation with academia and steel industry with efforts paid to protect and propagate intellectual properties, would materialize promising developments to revitalize the refractory industry.

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