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Transition of Refractory Technologies for Furnaces and Recent Insulating Technologies

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Abstract

Heating furnaces, such as those used for hot rolling of steelmaking processes, consist of refractories in the furnace structure to enable high-temperature operation. They heat semi-finished products such as blooms with a pre-heat pattern and convey them to the rolling process. Heating furnace operation produces high temperature but cools to room temperature when the furnace is repaired in campaign. Such a harsh environment causes damage to their refractories. In addition, due to the intense conditions of the heating furnace, the refractories must have a more insulated structure (meaning energy-saving) and a longer service life to reduce the energy cost.

1. Introduction

In steel production processes, mainly water, rolls and refractories come into direct contact with molten pig iron and molten steel, and have a major influence on the surface quality of steel products. In the reheating furnaces of hot rolling mills, semi-finished products such as slabs and blooms are heated based on a predetermined heating pattern and supplied to the subsequent process of hot rolling. In the operation of the reheating furnace, temperatures vary from a relatively low range of about 900°C up to a very high range exceeding 1300°C. Reheating furnaces are cooled down to an ordinary temperature for maintenance and thus encounter very large temperature fluctuations, which creates harsh conditions for refractories. Refractories require properties such as high heat resistance, high resistance to thermal shock and furthermore, high heat insulation (energy-saving performance) from the viewpoints of global warming prevention and energy cost reduction. Hereunder, the transitions of the refractory technologies for reheating furnaces and the latest heat-insulating technology of Nippon Steel Corporation are described.

2. Transition of Reheating Furnace Refractory Technology

In Japan, after the 1960s, numerous steelworks and rolling mills were built. **Table 1** shows the transition of the refractory technologies of Nippon Steel for about the past 60 years. An overview reveals that until the 1970s, refractory bricks (regularly shaped bricks) were mainly used and in the 1970s, plastic refractories and refractory castable (monolithic refractories), and the casting method began to be employed. The material of the alumina-silica system is mainly used for the refractory castable (hereinafter referred to as castable). Since around the year 1980, for energy-saving, strengthening of the insulation of skid support and beam was pursued and R&D regarding the cracks of skid refractory and the properties of castable[1] was promoted. The application of ceramic fiber (hereafter referred to as CF) to the skid support and side walls of reheating furnaces also increased.[2] In 1986, an all CF reheating furnace was built in the heavy plate mill of East Nippon Works (Kimitsu Area) and it played an important role in the Thermo Mechanical Control Process (TMCP)[3]. It was operated as an efficient, low-heat inertia and energy-saving type reheating furnace.

In the decade of 1990 to 2000, in compliance with the global trend of reducing greenhouse gas (CO_2) emissions, there were many reports regarding newly constructed reheating furnaces equipped with regenerative type burners and then-existing reheating furnaces being converted to the regenerative burner type. In line with these new constructions, reheating furnace refractories having higher insulation and durability performance were required. Monolithic refractories of the castable of the alumina-silica (Al_2O_3-SiO_2) system and the CA6 ($CaO \cdot 6Al_2O_3$) castable that uses fine porous aggregate were also developed. Furthermore, as for refractories of the fiber system, CF and high density CF molded body were employed (**Fig. 1**). In recent years, accompanied by the trend of weight reduction of car bodies, demand for high tensile strength steel material has increased and the high production level thereof has continued. Therefore, high-function refractories with reasonable maintainability and

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Table 1 Trends of refractory structure on heating furnace in Nippon Steel Corporation

	1st generation		2nd generation	3rd generation	4th generation
Part \ Age	-1970	1970-1980	1980-2000	2000-2005	2005-
Roof	Refractory brick	Plastic refractories Castable refractories	Ceramic fiber block		CA6 castable+insulation panel+Lightweight insulating castable
Side wall	Refractory brick	Plastic refractories Castable refractories	Ceramic fiber block		CA6 castable+insulation panel+Lightweight insulating castable
Partition wall	Refractory brick	Fire castable	Ceramic fiber	Ceramic fiber block	CA6castable
Hearth	Refractory brick	Plastic refractories Castable refractories			Refractory aggregate
Skid post	Refractory brick	Plastic refractories Castable refractories	insulating castable Ceramic fiber	Vacuum formed ceramic fiber ring CA6 castable+ insulation panel	CA6 castable+insulation panel+Lightweight insulating castable CA6 precast block
Skid beam	Refractory brick	Plastic refractories Castable refractories	insulating castable Ceramic fiber	CA6 castable+ insulation panel	CA6 castable+insulation sheet+Lightweight insulating castable CA6 precast block

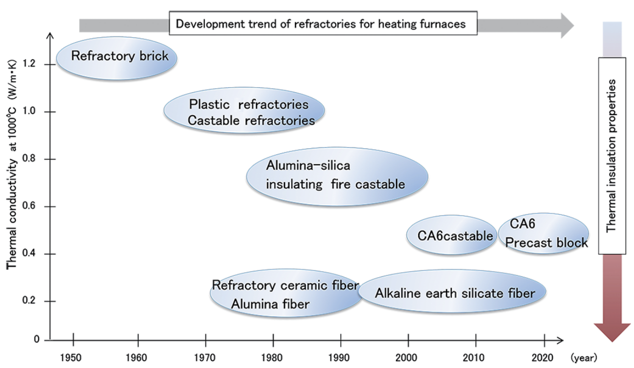

Fig. 1 Development trend and thermal insulation performance of refractories for heating furnaces

low cost are becoming increasingly required. Hereunder, the transition of the reheating furnace refractory technologies is explained based on the reports issued in each generation and the future development of the reheating furnace refractories and insulating technologies is described.

2.1 The first generation refractory technology

In the years from 1960 to the 1970s, many continuous reheating furnaces were built and for the refractories of the period referred to as the founding period of the reheating furnace refractory technologies, refractory bricks were mainly used in the early period.[4] Later, as heavier steel materials began to be rolled and as reheating furnaces became larger, the number of burners increased and the furnace pressure became higher. Consequently, gas leaks through masonry joints became problematic; therefore, refractories with fewer masonry joints were pursued and replacing bricks, plastic refractories were employed.[5, 6] For plastic refractories, clay excellent in plasticity was blended as refractory aggregate. Water was then added and refractory in clay paste was prepared. The refractory is constructed using the ramming driving construction method. Since unlike bricks, the construction quality of the plastic refractories has a major influence on the life of reheating furnaces, the construction technique was enhanced and resulted in a higher rate of use.

2.2 Second generation refractory technology

In the 1980s, development of the construction technology for plastic refractory was promoted and the high performance, gunning construction method was developed.[1] This method has several advantages such as construction without a molding box and application to furnace walls with a complicated configuration. Consequently, labor saving and shortening of the construction time were realized. Furthermore, as for the CF technology, since the manufacturing method and the supply system of CF of Japanese manufacturers were established, and due to its high heat insulating and low thermal inertia properties and ease of construction, CF was employed in large numbers.[7] There are two types of CF: amorphous and crystalline. The amorphous type is refractory ceramic fiber (hereafter referred to as RCF) that is classified as capable of withstanding temperatures up to about 1 500°C; the crystalline type is alumina fiber (hereafter referred to as AF) that is classified as capable of withstanding temperatures of up to about 1 600°C.

In July, 1986, an all CF reheating furnace started operation in the plate mill of East Nippon Works (Kimitsu Area) (**Fig. 2**).[3] Before the construction of the all CF reheating furnace, the wear mechanism, properties and the structure of CF were studied and the CF block structure as shown in **Fig. 3** was finally determined. The reheating furnace was constructed after the block underwent an extensive assessment test in an actual reheating furnace.[8] As a result, due to the effect of low thermal inertia of CF, the time required to change the furnace temperature could be shortened (**Fig. 4**), thus greatly reducing the heat radiation loss from the furnace during operation and the heat accumulation loss in intermittent operation. Furthermore, in September 1988, an all CF reheating furnace was built and started operation in a hot rolling mill in Kansai Works (Wakayama Area).[9] In the said reheating furnace, the fiber-on-fiber construction method was employed. In this method, to reduce the repair of deteriorated CF, the surface of the CF block was covered with a 50 mm thick veneer of fiber module to provide a double-layered structure. Due to the structure, a longer life of the back fiber block was obtained.

2.3 Third generation refractory technology

To comply with the global move towards the reduction of greenhouse gas (CO_2) emissions, the development of skid heat insulating technology and its structure that share a considerable percentage of the heat losses in reheating furnaces was promoted. The application of CF as a water cooling heat releasing measure conducted to date is reported.[7] In the construction method conducted to date, a studless structure with high construction efficiency using a ring-type ceramic fiber blanket laminated in the thickness-wise direction was employed (**Fig. 5**). However, along with the growth of harshness in furnace operation, falling of the ring-shaped CF and/or joint opening occurred. In either case of damage, the steel face of the skid pipe was exposed directly to the external furnace atmosphere and the heat loss increased. As countermeasures to this, a coating material that can withstand a heat of 1 600°C was applied, which proved to be insufficient for suppression of the joint opening.

Then, a high density CF molded body with a density of over 200 kg/m^3 was developed using the vacuum form method (hereafter referred to as VF) (**Fig. 6**).[10] In the VF method, cut CF fibers are suspended in the solution of an organic binder and an inorganic binder. The suspension is conveyed to a vacuum mold, demolded and dried, and a high density CF molded body (**Fig. 7**) is produced. A semicircular-ring-shaped studless structure body with a high density CF molded body having an identical jointing structure to form a ring with each other (**Fig. 8**) was developed and applied to a hot rolling mill reheating furnace at Nagoya Works (**Photo 1**). The new type VF ring has high workability and durability equivalent to those of

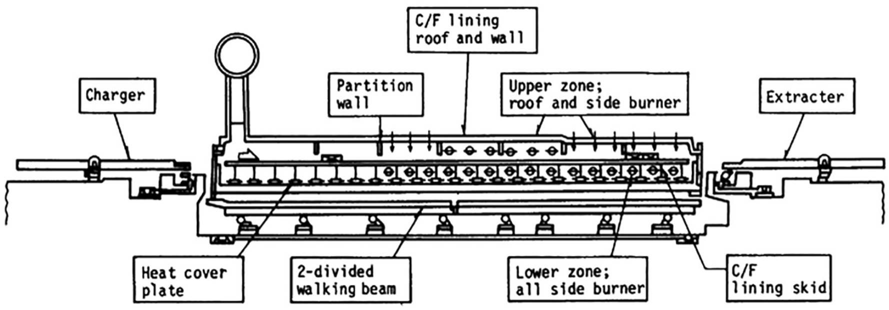

Fig. 2 Schematic diagram of East Nippon Works Kimitsu plate No. 4 heating furnace

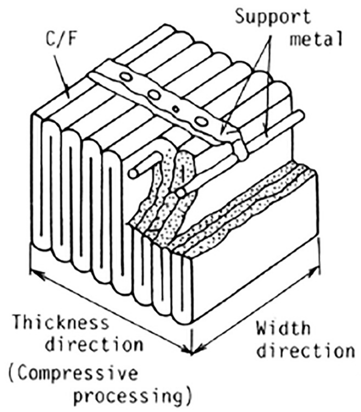

Fig. 3 Ceramic fiber block (Z-BLOK)

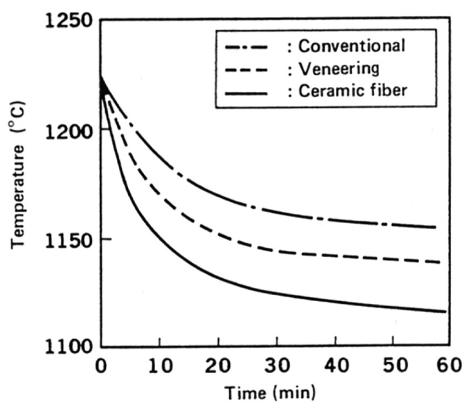

Fig. 4 Comparison of thermal inertia refractories

the conventional ring type CF and is currently used as a CF block structure.

Since CF and RCF were classified in the carcinogenic category of "Man-Made Vitreous Fibers (MMVFs)" by the European Union (EU) in 1997, Morgan Advanced Materials and ex. Shinnikka Thermal Ceramics Corporation (present "Shin-Nippon Thermal Ceramics Corporation") developed a biosoluble fiber (Alkaline Earth Silicate Wool (AES)) Superwool (hereafter referred to as SW).[11] The vitreous CF is of the Al_2O_3-SiO_2 system while SW is of the SiO_2-CaO-MgO system. The high-temperature grade SW607HT of the biosoluble CF has a permanent linear change of about −2% at heating up to 1300°C, and therefore is categorized as tolerable to a maximum of 1260°C.

However, SW readily reacts with other materials, forms a low-melting point material and exhibits abnormal contraction. Furthermore, the crystallization temperature in reheating is low and fibers are embrittled. Heat resistance is reported as being not equivalent to that of RCF and the employment thereof requires consideration of its working condition. In the EU, the sales of SW are more than double that of the amorphous CF and it is widely employed in the fields of shipbuilding and architecture. In Nippon Steel, SW was employed in a batch type annealing furnace in East Nippon Works (Kimitsu Area) in 2005 and continues to be used to date.

Entering the 2000s, global efforts to mitigate the global environmental problem (reduction of greenhouse gases such as CO_2) intensified. In the iron and steel industry, further energy-saving efforts were demanded. In reheating furnaces, burners were changed from the conventional low NO_X type to the regenerative type having high thermal efficiency, and refractories with high heat insulating performance and high temperature resistance properties (high resistance to corrosion due to scale) were developed and applied. Until then, for skid castable, light weight argillaceous aggregate, heat insulation aggregates such as hollow alumina, vermiculite, pearlite and CF had been used. Then, Alcoa developed fine porous aggregate $CaO \cdot 6Al_2O_3$ (hereafter referred to as CA6). The CA6 is a crystal of the hexagonal system, forming fine pores. Furthermore, it is characterized by heat resistance to about 1830°C, bulk density of 0.7 g/cm^3 and high heat insulating performance with a porosity of 75%. Furthermore, CA6 consists of two compositions of $Al_2O_3 \cdot CaO$ almost without SiO_2 and the chemical reaction with scale (FeO) is slight. Therefore, CA6 is an excellent refractory aggregate for reheating furnace refractories. The properties of CA6 aggregate are shown in **Table 2**.

Furthermore, the development of heat insulation castable using CA6 aggregate was also promoted (**Photo 2**). By adjusting its volumetric ratio with respect to the entire castable, casting and force feeding by pumping are compatibly enabled and application to skid

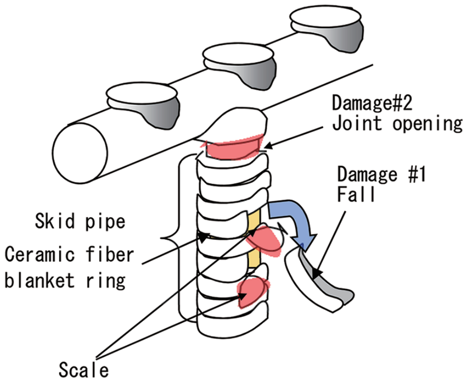

Fig. 5 Damage of the ceramic fiber blanket ring caused by scale

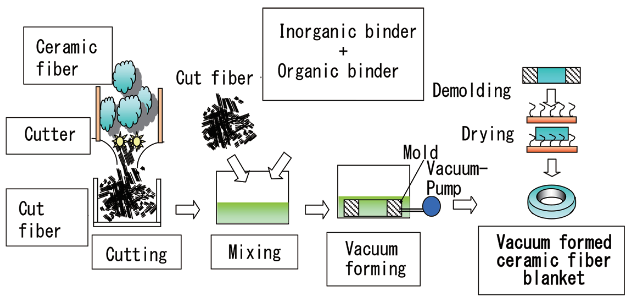

Fig. 6 Making method of Vacuum form

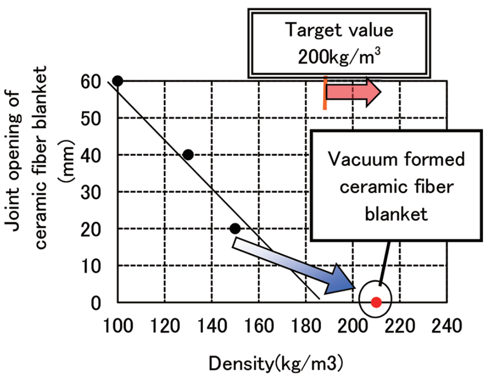

Fig. 7 Relationship between joint opening of ceramic fiber blanket and their density

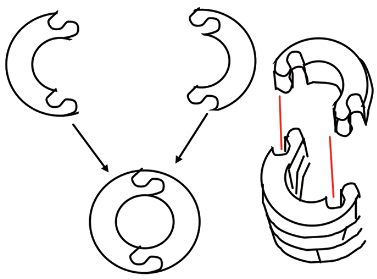

Fig. 8 Schematic figure of new joint combination structure

Photo 1 Vacuum form ring under construction

castable was attempted. Compared to the conventional CF heat insulating castable (**Table 3**), CA6 is advantageous in that (1) permanent linear change is small and cracks are few, and (2) it is excellent in corrosion resistance to scale (**Photo 3**). However, in a long distance force feed by pumping, the aggregate was separated and poor transportability occurred due to clogging under the pressurized condition in the feed pipe. Then, prevention of separation of CA6 aggregate was studied and in order to obtain compatible heat insulating performance and transportability by pumping, by setting the volumetric blending ratio of the light weight refractory aggregate at 0.65 to 0.85, a CA6 castable was developed that enables construction after force feeding by pumping and the gunning construction method (**Fig. 9**) that is advantageous in shortening the construction period.[12] In the three-year field operation test in an actual reheating furnace of a hot rolling mill in Nagoya Works, neither cracks nor falling was recognized and high durability was confirmed. In subsequent years, CA6 castable was employed as skid refractory in other steel works, contributing to energy-saving.

Table 2 Properties of CA6 aggregate

Chemical compositions / mass%	Al_2O_3	92.5–93.5
	CaO	6–7
	SiO_2	0.05–0.07
Bulk density	0.65–0.7	

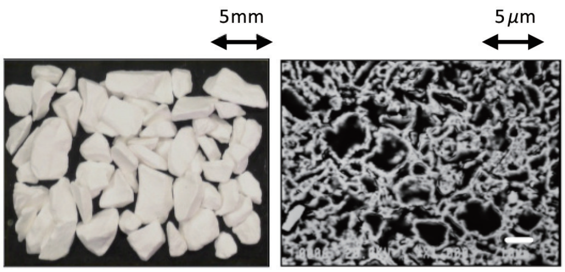

Photo 2 Picture shows CA6 grains
Left SEM micrograph is cross-section of the grain.

Table 3 Properties of refractories

		CA6 castable	Ceramic fiber castable
Chemical compositions / mass%	Al_2O_3	81	79
	CaO	11	–
	SiO_2	–	15
Permanent linear change / %	After 1400°C	−0.06	−1.95
Modulus of rupture / MPa	After 1400°C	2.1	0.6
Thermal conductivity / $W \cdot m^{-1} \cdot K^{-1}$	After 1400°C	0.47	0.27

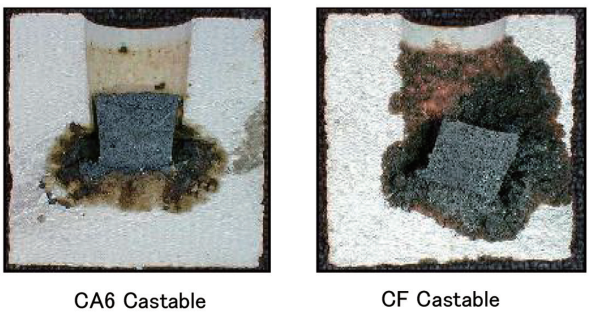

Photo 3 Scale corrosion test of CA6 insulating castable and ceramic fiber castable

2.4 Latest reheating furnace heat insulating technology

As countermeasures for energy losses in reheating furnaces, energy-saving measures have been implemented by employing refractories excellent in heat insulating performance. However, the energy loss in skid supports and beams still occupies a significant percentage. **Figure 10** shows the thermal energy loss ratios of the reheating furnace of a hot rolling mill in Kyushu Works (Oita Area). The heat loss through cooling water of the skid support and beam occupies 25% which is about four times higher than the heat radiation loss through the furnace shell and crucial to energy loss countermeasures of reheating furnaces. As described earlier, since the skid refractories are subject to chemical corrosion due to scale (FeO), physical wear damage due to direct heating by burner flames and the mechanical damage due to thermal hysteresis, in recent years, CA6 castable excellent in heat insulation performance and resistance to scale has been employed by a number of reheating furnaces.

On the other hand, the high density CF molded body VF ring is employed depending on its working environment as it is inferior in resistance to scale.

To intensify heat insulation, a triple heat insulation structure is employed, which consists of CA6 castable as the first (top) layer, low-cost AES having high heat insulation performance as the second layer and a high-insulation panel with a thermal conductivity of 0.035 W/m·k at 500°C as the third layer.[13] In **Fig. 11** and **Table 4**, the thermal conductivity and the properties of the respective refractory are presented.

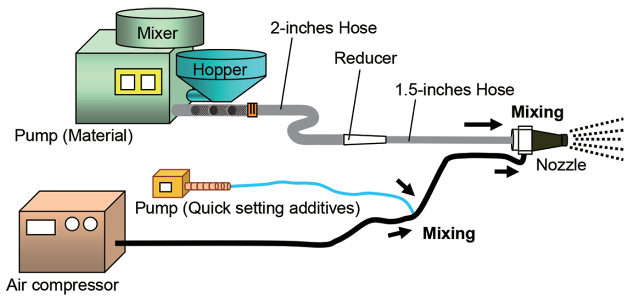

Fig. 9 Schematic diagram of CA6 insulating castable gunning system

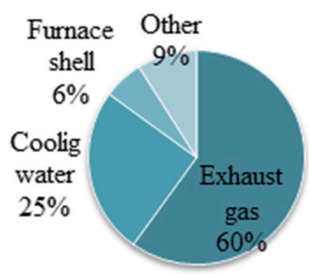

Fig. 10 Thermal energy loss ratio of Kyushu Works Oita hot strip continuous furnace

Although thicker skid refractories are desirable from the viewpoints of durability and heat insulation, the thickness must be determined by considering the skid stroke range, securing effective heating from the bottom side of the steel material and the heat resistant temperature of employed refractories. Then, Satoh et al. pursued the overall heat resistance ΣR_{th} based on steady heat transfer calculation on a cylindrical model, studied the inner temperatures of refractory linings and determined an optimum lining structure.[13] The first layer is CA6 castable with a thickness of 85 mm wherein durability was considered and the second layer is AES with a standard specification thickness of 25 mm. The thickness of the third layer of a high-insulation panel is 15 mm that was determined in the following manner and the inner temperature distribution of the lining was calculated (**Fig. 12**). To calculate the temperature distribution, the surface temperature of the lining was set at 1 300°C as the in-furnace temperature and the opposite side temperature of cooling water was set at 30°C. The application maximum temperature of the high-insulation panel was set at 800°C and from the result of the calculation of the relationship between the thickness of the high-insulation panel and the surface temperature in a thickness range of 5 to 30 mm (**Fig. 13**), the optimum thickness was set at 15 mm so as not to exceed the maximum temperature. Then the lining was designed.

Based on the lining so designed, the refractories of skid support and beam were constructed. As compared with the conventional alumina-silica (Al_2O_3-SiO_2) castable, energy-saving improvement of the skid support and beam by about 60% (**Fig. 14**) and good durability have been obtained (**Photo 4**). In addition to the triple heat insulation lining (CA6+AES+high-insulation panel), a double heat insulation lining using light-weight heat insulation castable is also employed. The light-weight heat insulation castable uses the hollow light-weight aggregate of coal ash (fly ash balloon) having the high heat insulation property of a bulk density of 0.5 g/cm^3 and thermal conductivity of 0.16 W/m·k (at 500°C). Any construction work execution form of casting, trowel-coating and gunning is possible, e.g. for skid, trowel-coating is applied.

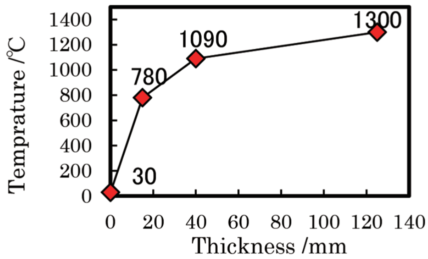

Fig. 12 Inner temperature of the improved lining for a skid-support

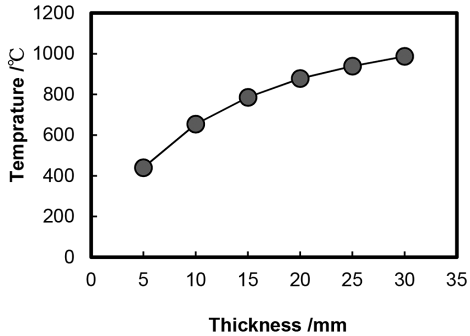

Fig. 13 Calculation of the relationship between the thickness of the high-insulation panel and the surface temperature

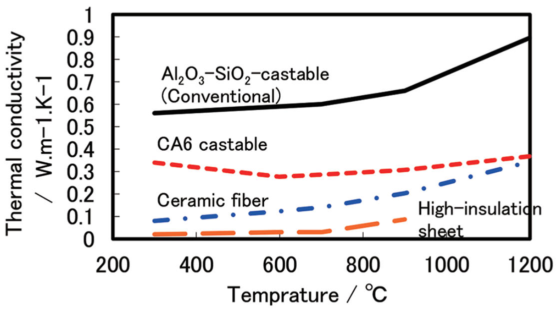

Fig. 11 Thermal conductivity of refractories

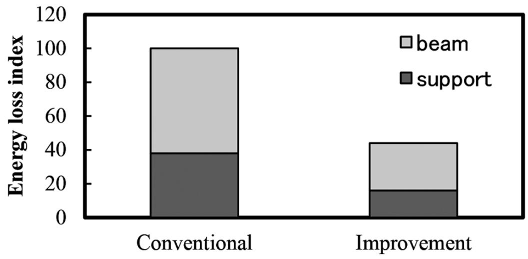

Fig. 14 Calculation of energy loss index through skid-beam/support lining

Table 4 Properties of refractories

		CA6 castable	Alkaline earth silicate fiber	Insulation panel
Chemical compositions / mass%	CaO	11	–	–
	SiO_2	–	70–80	80
	CaO+MgO	–	18–25	–
	Other	–	–	20
Permanent linear change / %	After 1400°C	−0.06	–	–
Modulus of rupture / MPa	After 1400°C	2.1	–	–
Thermal conductivity / W·m^{-1}·K^{-1}	After 1400°C	0.47	0.27 (at 800°C)	0.035 (at 600°C)

Photo 4 Skid-supports after 5 years in the furnace of the hot-strip mill

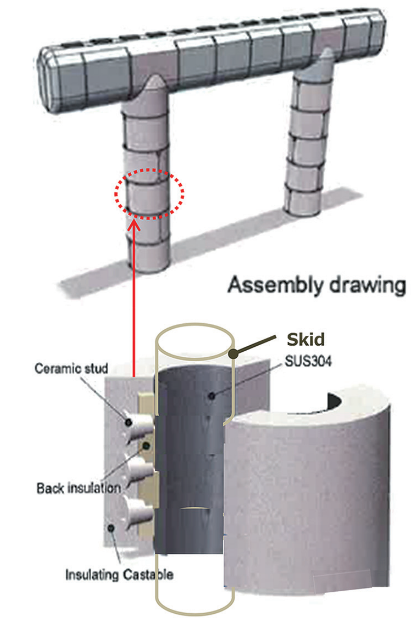

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Fig. 15 KSB construction method

Furthermore, in recent years, along with the increase of high-function rolling materials such as that of high-strength steel products, requirements for reheating furnace operation are becoming increasingly strict and enhancement of the heat insulation performance and the longer durability of refractory structure is being pursued. As a part thereof, the precast block method by using CA6 castable[14] is being trialed. In the precast block construction method, a block is preformed to a predetermined configuration and constructed in the furnace. Unlike the casting method, setting of molds, curing and dismantling of the molds has become redundant and shortening of the construction period is possible. Furthermore, as the refractory is split, the provision of expansion clearance of refractory is easy. Therefore, stable high durability as a structural body is obtained. **Figure 15** shows the precast block construction method.

3. Future Development

Along with the increase of high-function materials of high-strength steel products like those for light-weight cars and eco-cars (hybrid cars, electric vehicles), requirements for reheating furnace operation are becoming increasingly strict. By heating steel materials like slabs uniformly, or by reducing skid marks to the extent possible, quality and yield are improved. Furthermore, ceaseless efforts to combat global warming will be required in the future as well, and the energy-saving measures of reheating furnaces through the refractory heat insulation technologies are considered to play further important roles. Higher heat insulation performance and durability of refractories and refractory structure are being pursued. Enhancement of the function and the development for practical application of the studless structure (precast block) of the aforementioned CA6 castable is also being sought. Figure 1 chronologically plots the development of the major reheating furnace refractory thermal conductivity described to date. An overview of the trends is as follows: since before 1960 up to the 1980s, refractory bricks and plastic refractories with relatively high thermal conductivity were mainly used, either of whose thermal conductivity is about 1.0 W/m·K.

Later on, the castable of the alumina-silica system with high heat insulation performance (low thermal conductivity) and CF was developed and put into actual use. In the early 2000s, among monolithic refractories, CA6 castable of low specific weight (≈ low thermal conductivity) was introduced and as its corrosion resistance to scale is high, it has been used widely to date. The overview of the transition of refractories in reheating furnaces shows that refractories of low thermal conductivity (≈ low specific weight) have been pursued intensively from the desired function of energy-saving (reduction of CO_2 and fuel cost), while maintaining the function of working as a structural member of reheating furnaces. This trend will continue unchanged, thus requiring higher energy-saving performance and higher durability (resistance to corrosion due to scale) etc.

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