INVESTIGATION OF EFFECTIVE PARAMETERS ON INCREASING THE DURABILITY OF PITCH-BONDED MgO-C BRICKS USED IN THE TRUNNION AREA OF THE STEEL CONVERTER

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ABSTRACT

In this paper, the effective parameters on increasing the durability of pitch-bonded MgO-C bricks used in the trunnion area of the steel converter has been studied. In this relation, the durability of the pitch-bonded MgO-C bricks containing B_4C, and carbon fiber and different types of magnesia and graphite has been compared together. For this reason, the thickness measurement of remainder bricks by use of laser has been considered as durability of bricks and has been used to compare their wear rates. Besides, the physical, mechanical, and thermo-mechanical properties, microstructure, thermal expansion during the thermal cycle and the oxidation resistance of these bricks has been investigated. The results showed that the purity and crystal size of magnesia grains, the purity of graphite and B_4C addition have a great effect on the durability of pitch-bonded MgO-C bricks used in the trunnion area of the steel converter.

INTRODUCTION

The Basic Oxygen Furnace (BOF) is the name given to a vessel in which pig iron is converted into steel. By blowing pure oxygen onto or into the molten iron via oxygen lances or nozzles, carbon is removed from the hot metal. Thus, the hot metal is transformed into liquid steel with a low carbon content. It is possible with the BOF process to make any grade of steel required from cans and automotive exteriors to garbage cans and rail. MgO-C brick is now the widely accepted refractory brick used in every part of the BOF sidewall. Because each BOF refractory lining region does not require the same physical properties or performance, suitable, and appropriately designed, MgO-C bricks are installed in each region, and this lining concept is called a zoned lining (Fig.1). Despite using a zoned lining in a BOF, each lining region shows uneven wear of the bricks.

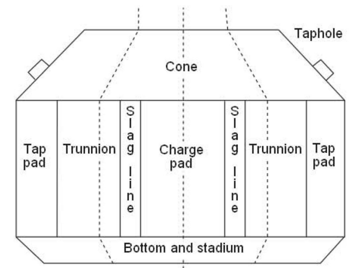

Fig.1: Areas of a basic oxygen furnace

Generally, the trunnion areas are subjected to higher temperatures and are therefore exposed to increased oxidation, mechanical stress at high temperatures and severe thermal cycling during operation. Hence, the wear conditions in trunnion area contains of oxidizing atmosphere, slag corrosion and slag and metal erosion. Therefore, trunnion brick lining should possess exceptional resistance to BOF slags. Suitable high temperature strength and oxidation resistance are also desirable. Accelerated wear is also experienced in the trunnion areas of any BOF, mainly because this area is the most difficult to protectively coat with slags or gunning. Such application requires refractories with both, improved strength, and toughness, although these properties are mutually exclusive in most materials. Hence, MgO–C bricks designed for BOF trunnions zone can be classified as engineering structural products due to the mechanical and thermal stresses that they are subjected to. It has been proved that characteristics of MgO grains and flake graphite can influence the wear of MgO-C bricks used in the trunnion areas. In this case, the magnesia-carbon bricks containing large-crystal size fused magnesia and high-purity graphite serve favorably under more severe conditions in trunnion. Besides, with a view to restraining oxidation of graphite, which is an essential drawback of magnesia-carbon bricks and is considered to have a great effect on wear rate, the magnesia-carbon bricks containing antioxidants such as Al, Al-Mg alloys, and borides such as B_4C and CaB_6 have been supplied to converters with good performance.

In present study, the effective parameters on the durability of pitch-bonded MgO-C bricks used in the trunnion area of a steel converter have been investigated. For this purpose, referring to the conventional works, the effects of magnesia and graphite types, and B_4C addition on the durability of these bricks were investigated in actual BOF campaign. Besides, the effect of carbon fiber addition has been investigated to recognize its effect on the properties of these MgO-C bricks. Utilization of carbon fibers has been attempted to improve fracture toughness of these bricks in the same way as fiber reinforced ceramics and concrete. Due to the greater wear of MgO-C bricks containing metal antioxidants in the early heat stages in the converters, metal antioxidants were not used at the request of the steel plant where the brick was to be tested. Additionally, the physical, mechanical, thermo-mechanical properties, cycle thermal expansion, microstructure, the oxidation resistance, and the slag corrosion resistance of these bricks has been investigated. To this end, an attempt has been made to find a relationship between the parameters of the brick and its wear rate in the trunnion to predict the durability of the brick.

EXPERIMENTAL PROCEDURE

Two different types of the fused magnesia (0-8 mm) are used to produce the MgO-C bricks, which their specifications are shown in Table I. Magnesia FM2 has the higher purity and larger crystal size than magnesia FM1.

Table I: The specifications of the fused magnesia used in this study

Specifications		Type of the fused magnesia	
		FM1	FM2
Mean crystal size (μm)		900	1060
Oxide (wt.%)	MgO	97.57	97.86
	CaO	1.11	1.05
	SiO_2	0.56	0.46
	Fe_2O_3	0.49	0.43
	Al_2O_3	0.17	0.09
	C/S	1.98	2.28

Besides, two different types of the flake graphite are used, which their specifications are shown in Table II. The graphite G2 has the higher purity and larger particle size than graphite G1.

Table II: The specifications of the used graphite

specifications	Type of graphite	
	G1	G2
C (wt.%)	95	98
particle size (D_{50})	150 μm	180 μm

In this study, a carbon fiber (SGL Carbon Co.) has been used to investigate its effect on the properties of MgO-C brick that its specifications are shown in Table III.

Table III: The specifications of the carbon fiber used

Specification	amount
Density (g/cm^3)	1.8
Mean fiber length milled (μm)	80
Filament diameter (μm)	7
Tensile strength (GPa)	4.0
Tensile modulus (GPa)	240
Elongation at breack (%)	1.7
Rest carbon (%)	97.20

Four MgO-C compositions were selected to study the effect of magnesia and graphite type, as well as B_4C (3M Technical Ceramics) and carbon fiber addition as presented in Table IV. In this relation, the optimum amounts of B_4C and carbon fiber has been used. They were designed to have the same grain size distribution of the fused MgO. The pitch binder used was Carbores F90 M, a product of RÜTGERS company, which is an eco-friendly binder due to its low benzo[a]pyrene content. According to information stated by this company, the coke structure of Carbores is completely anisotropic compared to the isotropic glassy carbon like coke structure of phenol resin. The anisotropic coke structure of Carbores is highly flexible and stress-absorbing and results in outstanding thermo-shock resistance. The anisotropic coke structure also results in high oxidation resistance which makes the use of antioxidants unnecessary.

Table IV: The compositions used to produce MgO-C bricks

The raw materials used	Brick name			
	D	S	S-A1	S-A2
Magnesia	FM1	FM2	FM2	FM2
Graphite	G1	G2	G2	G2
Carbon Fiber	-	-	+	-
Boron Carbide	-	-	-	+
Binder	Pitch	Pitch	Pitch	Pitch
Total C (%)	13	13	13	13

After hot mixing the raw materials in a hot mixer, the mixtures were pressed by a hydraulic press (LAEIS) under 210 (bar) at Intocast AG company. Then, the pressed bricks were cured at 280 °C/6 h in a tempering kiln. After curing, the bricks were impregnated with pitch to reduce their open porosities. The physical and mechanical properties were evaluated for all compositions. Bulk density and apparent porosity were measured according to DIN EN 993-1. Cold crushing strength was carried out in universal mechanical testing equipment (Form+Test MEGA 10-1000-50 DM1) according to DIN EN 993-5. For the evaluation of hot modulus of rupture (HMOR) and hot modulus of elasticity (HMOE) evaluations, no previous thermal treatment was carried out and tests were performed at 1500 °C with 0.5 h hold time, 0.15 MPa/s loading speed, 300 K/h heating rate and under Argon gas atmosphere, according to DIN EN 993-7. Index of thermal resistance (S/E) was calculated as HMOR divided by hot elastic modulus. The oxidation resistance test was applied on the cylindrical specimens with 50 mm in diameter and 50 mm in height. All four types of samples were heated simultaneously (at the same time) in an electric laboratory kiln in air atmosphere at a rate of 5 °C/min to a temperature of 1550 °C with holding time of 5 hours at the maximum temperature. After firing, cooling, and transversal cutting of samples, the extent of the oxidized area was monitored macroscopically, comparing to the original un-oxidized area, and then the percentage of oxidized area was calculated. Oxidation index is determined by the following formula:

$$\text{Oxidation index} = (\text{Area of oxidized zone}/\text{total area}) \times 100$$

Slag resistance experiments were carried out adopting static crucible method. The MgO-C bricks were firstly cut into cubic shape with the dimension of 70 ×70 ×70 (all in mm), then a cylindrical cavity 35 mm in diameter and 40 mm in depth was made on each cubic sample. The crucibles were dried and filled with converter slag. The chemical analysis of the used converter slag is shown in Table V. The amount of slag used in each crucible was 30 g, covering up to approximately half depth of the cavity. All bricks were placed in an alumina refractory box and heat treated at 1650 °C/2 h in an electric furnace with heating rate of 5 °C/min.

Table V: The chemical analysis of the used converter slag

Oxide	Al_2O_3	SiO_2	Fe_2O_3+Fe	TiO_2	CaO	MgO	MnO_2	C/S
wt.%	1.25	20.02	33.82	0.48	45.59	1.83	1.61	2.27

After the corrosion test, the crucibles were cut, to evaluate their corroded areas and the infiltrated depths of slag. Using the R.U.L device (Netzsch RUL/CIC 421), a thermal cycle like the converter operation was created in the 1200 and 1650 °C range. During this thermal cycle, the thermal expansion of the bricks was measured. This test was carried out under 0.2 MPa load and under argon atmosphere. The first heating rate is carried out with 5 K/min, after reaching 1650 °C, cooling and heating is carried out with 10 K/min. The last cooling down is recorded with values up to 1500 °C and the furnace is switched off. The microstructures of the refractory samples were studied using a scanning electron microscope (Hitachi TM3000) equipped with an electron dispersive X-ray (EDX) detector (Bruker Q70). These produced MgO-C bricks were installed in the trunnion areas of converters (210 t) in a steel plant in Germany. The thickness measurement of remainder bricks in these converters during operation has been evaluated by use of a laser-measuring device. These measurements have been used to evaluate of the MgO-C brick wear rate in the converter. The maintenance strategy was mainly slag splashing, with no gunning in the trunnion area. However, the linings were repaired and maintained with magnesia gunning mixes in the areas of less than 127 mm thickness.

RESULTS AND DISCUSSION

The physical, mechanical, and thermo-mechanical properties of the investigated bricks are shown in Table VI.

Table VI: The physical, mechanical, and thermo-mechanical properties of the investigated bricks

Physical, mechanical, and thermo-mechanical properties		Brick name			
		D	S	S-A1	S-A2
After tempering and pitch impregnation	Bulk Density (g/cm^3)	3.07	3.09	3.08	3.09
	Open Porosity (%)	2.64	2.09	2.39	2.67
	C.C.S (MPa)	26	27	27	27
After firing at 1000 °C under reducing atmosphere	Bulk Density (g/cm^3)	3.01	3.01	3.01	3.03
	Open Porosity (%)	6.65	6.18	6.80	5.42
	C.C.S (MPa)	26	27	25	32
Thermo-mechanical properties	HMOR at 1500 °C (MPa)	5.05	5.15	5.12	5.15
	HMOE at 1500 °C (GPa)	16.27	16.17	18.19	15.28
	Spalling resistance index ($\times 10^{-3}$)	3.103	3.184	2.814	3.370

According to these results, the bulk density, open porosity, and the cold crushing strength of the investigated bricks after tempering are the same. On the other hand, the results show that the cold crushing strength of brick containing B_4C after firing at 1000 °C has been increased due to decrease of open porosity of this brick. Besides, the carbon fiber addition has been led to decrease of cold crushing strength of brick after firing at 1000 °C due to increase of its open porosity. The results show that there is no significant difference between HMOR of these bricks; meanwhile, the addition of B_4C has been led to decrease of HMOE and therefore, increase of spalling resistance index of the brick. On the other hand, addition of carbon fiber has been led to increase of HMOE resulting in decrease of spalling resistance index of the brick. The microstructures of these bricks are shown in Fig. 2.

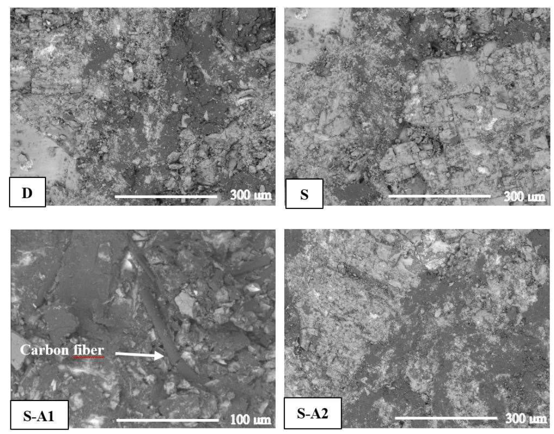

Fig.2: The microstructure of the investigated bricks after pitch impregnation.

With respect to these micrographs, very good compaction of the aggregates and the matrix can be seen. Besides, the low porosity can be seen in the microstructure of all bricks. In addition, the carbon fibers can be seen in the structure of S-A1 brick. In Fig. 3, the cross sections of the oxidized samples after test are shown. As can be seen from Fig. 3, the carbonaceous materials of these bricks got oxidized at high temperature particularly from the outer surface.

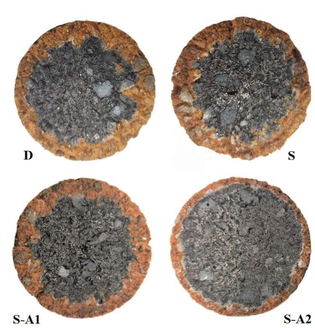

Fig. 3: The cross sections of the oxidized samples

The color of the oxidized part became lighter than the black color of the non-oxidized brick, and so the boundary between the non-oxidized and the oxidized regions was quite clear. The results of oxidation resistance are shown in table VII.

Table VII: The results of the oxidation resistance test

The oxidation resistance results	Brick type			
	D	S	S-A1	S-A2
Weight loss (%)	10.00	10.00	9.26	6.18
Oxidizing index (%)	38.87	40.27	39.87	19.98

In general, lower oxidation index indicates higher oxidation resistance of brick. As expected, the brick containing B_4C has higher oxidation resistance than other bricks. From very low temperatures (approx. 800 ° C) according to the following reaction:

$$B_4C + 6CO \rightarrow 2\ B_2O_3 + 7C$$

B_4C reacts with CO in brick to form molten B_2O_3. The formed melt fills up the pores and compacts the brick according to Table VI, thus forming a protective layer that can inhibit the diffusion of oxygen and increase its resistance to oxidation. The cross section of the investigated bricks after slag corrosion test are shown in Fig. 4.

According to Fig. 4, there is no significant difference between the slag corrosion resistance of these bricks. This means that the using the static crucible method is not effective to distinguish the slag corrosion resistance difference between these bricks. The cyclic thermal expansion curves of the investigated MgO-C bricks are shown in Fig. 5.

One can see that there are similar changes in cyclic thermal expansion curves of these bricks in response to multiple heating and cooling cycles. Since the pitch impregnated bricks have been used for this test, there is a shrinkage process in these bricks in temperatures higher than 200 °C due to release of volatile materials from bricks. Besides, the formation of a glassy carbon bond tends to densify the structure and shrinkage results. According to results of Fig. 5, one can extract the change results in length, which are inserted in Table VIII.

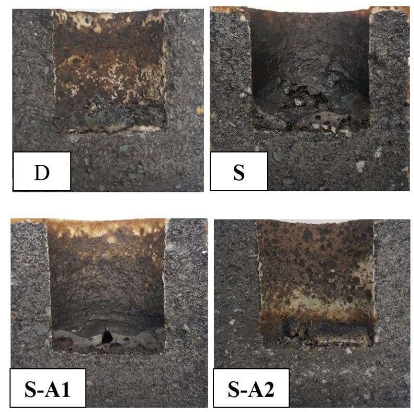

Fig.4 : The cross section of the investigated bricks after slag corrosion test

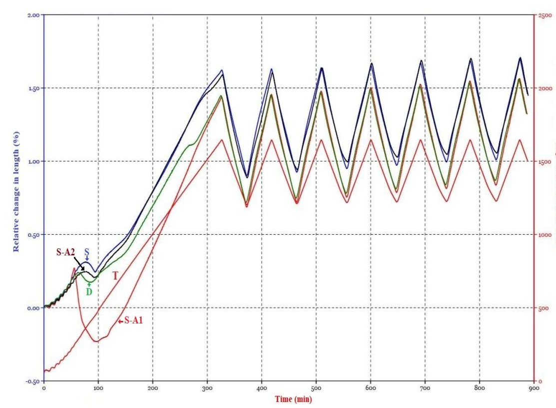

Fig. 5: Cyclic thermal expansion of the investigated bricks

Table VIII: The change in length for the investigated bricks

Change in length (%)	Brick name			
	D	S	S-A1	S-A2
at beginning of thermal cyclic	1.45	1.62	1.43	1.62
after 4.5h at 1650 °C	1.49	1.65	1.50	1.67
after 9.0h at 1650 °C	1.56	1.70	1.56	1.71
Rate of change in length between 4.5 h and 9.0 h (%/h)	+0.0155	+0.0111	+0.0133	+0.0088

The results show that S brick has higher thermal expansion than D brick. Therefore, one can conclude that the use of the fused magnesia with larger crystal size and higher purity graphite can lead to increase the thermal expansion of MgO-C brick. On the other hand, S-A1 brick has lower thermal expansion than S brick, but the thermal expansion of S-A2 is like S brick. Hence, the results show that the carbon fiber addition has been led to decrease of thermal expansion of brick and B_4C addition has not significant effect on the thermal expansion of MgO-C brick. Generally, the thermal expansion of MgO-C brick at high temperatures must be in optimum range. The high thermal expansion can lead to high stress at the surface of bricks and then, lead to cobblestone formation and higher wear rate. On the other hand, the low thermal expansion can lead to open joints between bricks and then, lead to infiltration of slag and molten steel. However, the optimum thermal expansion can lead to close the open joints and then, the lower wear of brick in the converter. Besides, the results show that rates of change in length for all bricks are positive and all bricks have the similar behavior in increasing their length over time and show a slow permanent thermal expansion.

Generally, the positive rate can lead to close the open joints during cycles heating/cooling in the converter. S-A2 brick containing B_4C has lower rate in comparison with other bricks. This indicates that boron-containing liquid phases can soften at high temperatures and absorb stresses from heating/cooling cycles, so that it may be able to suppress a decrease in spalling resistance. Fig. 6 shows a color map of the lining thickness in the BOF after 1188 heats. The red color shows the thinnest bricks, so the map indicates that the MgO-C bricks in the trunnion area were more damaged than the other zones.

In Fig. 7, the residual thickness of the installed bricks in the trunnion area are compared together as a function of heat number. According to this results, rapid trunnion wear was experienced in the first 900 heats. As stated before, the maintenance strategy was mainly slag splashing, with no gunning in the trunnion area. However, the linings are repaired and maintained with magnesia gunning mixes in the areas of less than 127 mm thickness.

According to these results, S brick has lower wear rate than D brick. As stated in the literature, the magnesia-carbon bricks containing large-crystal size fused magnesia and high-purity graphite can decrease the wear of MgO-C bricks used in the trunnion areas. This is mainly because MgO grains have high corrosion resistance against basic slag, and graphite has high thermal shock resistance to the severe thermal cycling during operation.

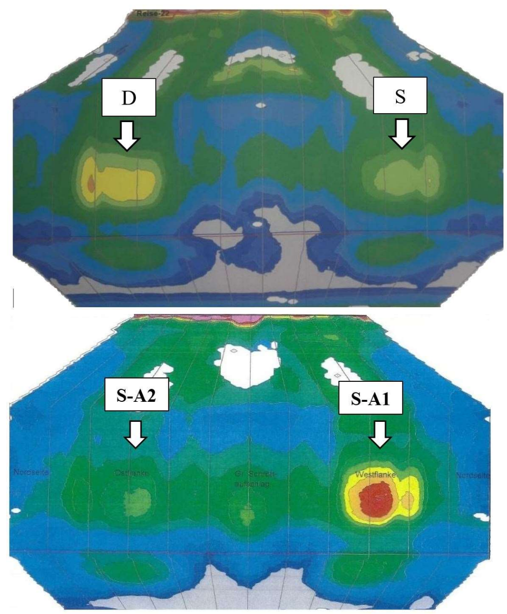

Fig. 6: Comparison of the wear-rate of the installed bricks in the converters after 1188 heats

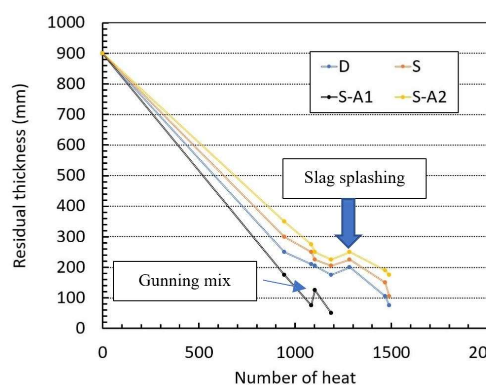

Fig. 7: The residual thickness of the investigated bricks in the converter as a function of consecutive heats (The initial shape thickness is 900 mm)

The results show that the S-A2 brick has the lowest wear rate and the S-A1 brick has the highest wear rate in comparison with other bricks. Therefore, one can conclude that the B_4C addition in these bricks can lead to decrease of wear rate and carbon fiber addition can lead to increase of wear rate. With comparison between the properties of these bricks and their wear rate, one can conclude that there is a reasonable relation between the wear rate and thermal shock index of these bricks. The higher thermal shock index shows the lower wear rate. Besides, there are a relation between rate of expansion in length of these bricks (Table VIII) and their wear rate. The lower rate of expansion in length can lead to lower wear rate. On the other hand, the oxidation resistance index is another parameter, which can show the durability of these bricks. Therefore, the wear rate and durability of a MgO-C brick can be estimated by use of its thermal shock index, rate of expansion in length, and oxidation resistance index.

CONCLUSIONS

In this study, the parameters such as the crystal size and purity of the fused magnesia and purity of graphite, as well as the B_4C and carbon fiber addition on the durability of pitch-bonded MgO-C bricks used in the trunnion area of the steel converter were investigated. The thickness measurement of remainder bricks by use of laser was considered as a wear rate of these bricks. Besides, the physical, mechanical, thermo-mechanical properties, the microstructure, thermal expansion during the thermal cycle and the oxidation resistance of these bricks were investigated. The results showed that the purity and the crystal size of magnesia grains, the purity of graphite and B_4C addition have a great effect on increasing the durability of these bricks. The formation of magnesium borate phases with low melting points in S-A2 brick containing B_4C can decrease the open porosity of this brick after firing at high temperature and then, increase of its oxidation resistance. Besides, the formation of magnesium borate phases can lead to a reduction in the HMOE compared to other bricks and improvement of its thermal shock index. The results of this research show that the wear rate and durability of a MgO-C brick can be estimated by use of its thermal shock index, rate of expansion in length, and oxidation resistance index. The higher thermal shock index shows the lower wear rate. On the other hand, the lower rate of expansion in length and lower oxidation resistance index can lead to lower wear rate. In the end, the wear rate and durability of a MgO-C brick can be estimated by use of its thermal shock index, rate of expansion in length, and oxidation resistance index.

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