The Development of Improved Lining Material for DRI Shaft Furnaces*

J. Sperber

The production of direct reduced iron has become a continuous increasing iron making process through the last four decades. Nowadays app. 7 % of the iron used for the steel production comes out of the direct reduction plant routes around the world. Especially in developing countries where natural gas is relatively inexpensive the natural gas based reduction process with its lower investment costs in comparison to the blast furnaces route has become more and more important. The increasing emphasis on environmental issues leads to a production route with far less emissions than coal based processes. The actual lining concept based on standard material for the gas inlet area of DRI shaft furnaces is discussed. According to the special requirements in this application an improved brick was designed. The better performance is described by the analysis of the structure composition.

1 View on the Process

In this paper the focus will be on a reduction process which will be generated by the use of natural gas. This natural gas is given to a reformer unit which will produce a reducing gas with a high content of carbon monoxide and hydrogen.

The feedstock for the process can be any blend of pellets and lump ores with an iron content of more than 65 %. The feedstock will react in the furnace with the heated reducing gas to get a product with a metallisation level of more than 90 % which can be used as charge material for electric arc furnaces or supplements scrap in the steelmaking process. It can be also used in the burden to optimize the performance of a blast furnace. A schematic diagram of the process is shown in Fig. 1.

1.1 Relevant working conditions and the requirements

If we take a look on a DRI shaft furnace we have three major problems to solve. The first one is the working temperature itself of about 850 – 1200 °C. Combined with that is the gaseous attack on the lining caused by carbon monoxide and hydrogen. And the third problem is the abrasion caused by the feedstock in the upper parts of the furnace and by the DRI in the lower parts. Abrasion will also occur in the gas inlet area through the reduction gas which will be blown in with a high velocity. The relevant chemical reactions in that kind of process are the following ones:

Reforming of the reduction gas:

$CH_4 + CO_2 \rightarrow 2\ CO + 2\ H_2$

$CH_4 + H_2O \rightarrow CO + 3\ H_2$

Reduction of ore:

$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$

$Fe_2O_3 + 3\ CO \rightarrow 2\ Fe + 3\ CO_2$

Carburisation of metallic iron:

$3\ Fe + CO + H_2 \rightarrow Fe_3C + H_2O$

$3\ Fe + CH_4 \rightarrow Fe_3C + 2\ H_2$

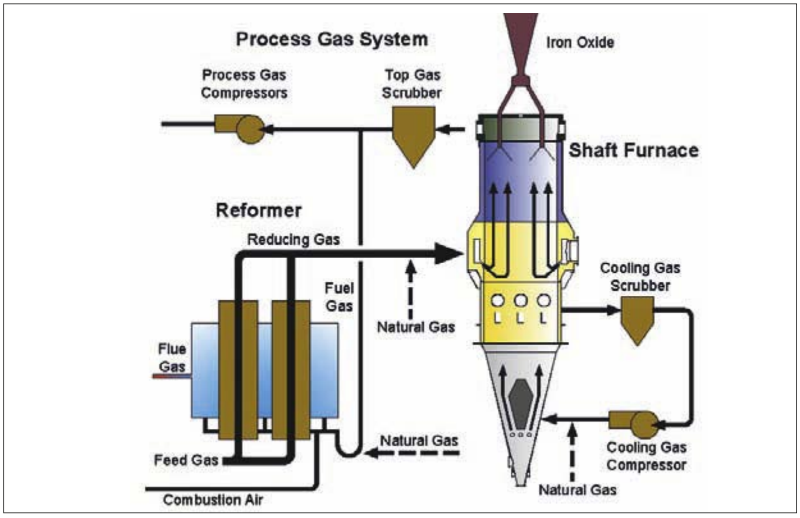

Fig. 1 Schematic diagram of the DRI process

Jens Sperber
STEULER Industrieller Korrosionsschutz GmbH
Head of R&D and Application Technology
Höhr-Grenzhausen, Germany

E-mail: jens.sperber@steuler.de

Keywords: refractory lining, DRI shaft furnace

---

*) Paper to be presented at the UNITECR 2009 on 13–16 October in Salvador / Brazil

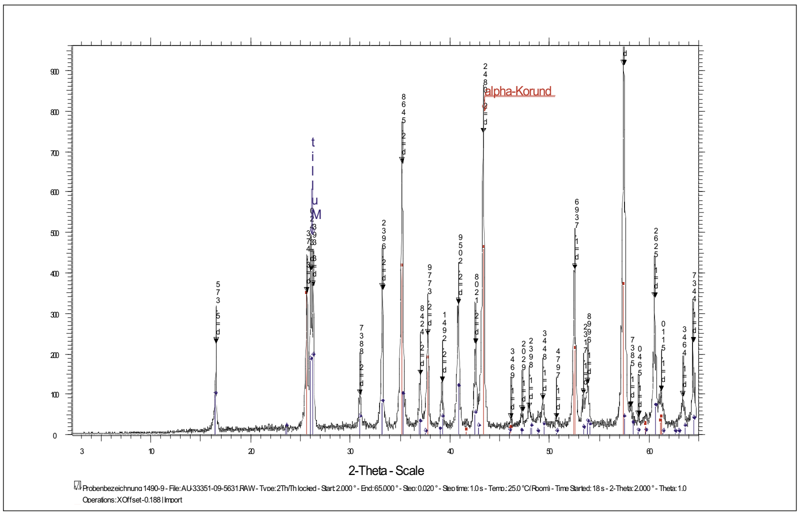

Fig. 2 XRD diagram of the standard material

Concerning the requirements the lining material has to be resistant against CO and H_2 atmosphere combined with excellent wear resistance. The working temperature itself should not be a problem for any kind of refractory material. Although all CO-resistant refractory material may be used in the upper and lower shaft as a hot face material we have to focus on the gas inlet area where we have the highest temperatures. Therefore, some problems can occur if the material is not able to withstand the given hydrogen attack. Standard lining material for the upper and lower shaft is based on aluminium silicates whereas the alumina content will be in a range of 42 to 75 %. The critical gas inlet area with the highest temperatures is in contradiction to that lined with high alumina bricks with more than 85 % alumina.

2 Standard material

The common used standard material for the gas inlet area contains two main phases in the structure with different thermal expansion like mullite and corundum. Based on these two phases we obtain a very low Young's modulus of abt. 15 – 20 GPa, with the result of a very elastic behaviour of the material. Fig. 2 shows the XRD diagram of the standard material.

Regarding the basic phase composition we get a relatively low thermal expansion in the range of 6,0 • 10^{-6}/K (35 –1000 °C). As a result one can see a very good thermal shock behaviour in total. It is a well known practice that the second phase in the structure leads to micro cracks in this area. So they are working like crack brakes. In Tab. 1 the relevant properties are shown.Based on the above given physical properties we can calculate an indicative value for the thermal shock resistance. In this case we will use the thermal shock parameter according to Hasselman which will be calculated

$$R = \sigma \cdot (1-\mu)/E \cdot \alpha$$

This so-called first thermo-stress factor indicates the maximum temperature difference for crack initiation. For the standard material we get a value of 100,4 K. Taking a look on the formula it is obviously that a higher Young's modulus or higher thermal expansion yields to a lower value of R. Meanwhile a higher strength will increase the value.

The strength is related to the abrasion resistance and in general one will get an enhanced abrasion resistance with an increasing strength. Therefore, it is necessary to work on the strength of the material, but without loosing all the other excellent properties, especially the thermal shock behaviour. This is the most critical point of the development of material for the gas inlet area. But for the improvement of the performance it is indispensable to enhance the abrasion resistance and if possible also the thermal shock resistance.

If one now wants to increase the strength a material in the direction of a single-phase material has to be developed. The associated mechanism would be the increase of the Young's modulus and therefore as one result a worse thermal shock resistance. In this case the Young's modulus can reach values about 3 to 5 times higher than the values of

Tab. 1 Properties of standard material for the gas inlet area of DRI shaft furnace

Chemical analysis [mass-%]			
Al_2O_3	SiO_2	Fe_2O_3	$Na_2O + K_2O$
90	10	0,2	0,2
Physical properties			
Bulk density		3,03 g/cm³	
Apparent porosity		15 vol.-%	
Cold crushing strength		120 MPa	
Modulus of rupture		14 MPa	
Abrasion		15 cm³	
Young's modulus		18 000 MPa	
Thermal expansion coefficient		6,04 •10^{-6}/K	
Poisson's modulus (estimated)		0,22	

Tab. 2 Properties of a mullite material for the gas inlet area of DRI shaft furnace

Chemical analysis [mass-%]			
Al_2O_3	SiO_2	Fe_2O_3	$Na_2O + K_2O$
78	21	0,2	0,2
Physical properties			
Bulk density		2,70 g/cm³	
Apparent porosity		14 vol.-%	
Cold crushing strength		120 MPa	
Modulus of rupture		18 MPa	
Abrasion		16 cm³	
Young's modulus		32 000 MPa	
Thermal expansion coefficient		5,06 •10^{-6}/K	
Poisson's modulus (estimated)		0,22	

Tab. 3 Properties of a corundum material for the gas inlet area of DRI shaft furnace

Chemical analysis [mass-%]			
Al_2O_3	SiO_2	Fe_2O_3	$Na_2O + K_2O$
94	5	0,2	0,2
Physical properties			
Bulk density		3,25 g/cm³	
Apparent porosity		13 vol.- %	
Cold crushing strength		220 MPa	
Modulus of rupture		24 MPa	
Abrasion		6 cm³	
Young's modulus		50 000 MPa	
Thermal expansion coefficient		7,88 •10^{-6}/K	
Poisson's modulus (estimated)		0,22	

the original material. Regarding this enormous decrease of elasticity the thermal shock parameter according to *Hasselman* will be decreased to R = 20 – 40 K. Con-

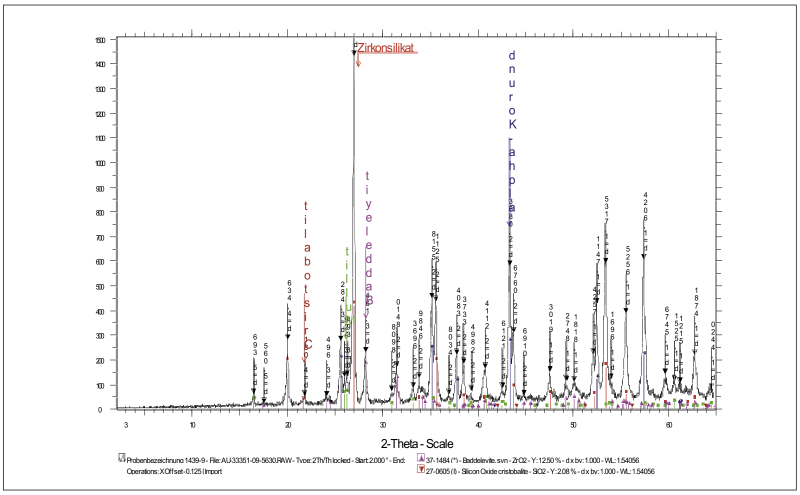

Fig. 3 XRD diagram of the improved material

Tab. 4 Properties of a claybonded brick based on corundum, mullite and zircon

Chemical analysis [mass-%]			
Al_2O_3	SiO_2	Fe_2O_3	$Na_2O + K_2O$
64	12	0,2	0,2
ZrO_2		P_2O_5	
23		-	
Physical properties			
Bulk density		3,35 g/cm³	
Apparent porosity		16 vol.-%	
Cold crushing strength		100 MPa	
Modulus of rupture		13 MPa	
Abrasion		18 cm³	
Young's modulus		15 000 MPa	
Thermal expansion coefficient		6,55 •10^{-6}/K	
Poisson's modulus (estimated)		0,22	

Tab. 5 Properties of the improved material for the gas inlet area of DRI shaft furnace

Chemical analysis [mass-%]			
Al_2O_3	SiO_2	Fe_2O_3	$Na_2O + K_2O$
63	12	0,2	0,2
ZrO_2		P_2O_5	
23		1,3	
Physical properties			
Bulk density		3,31 g/cm³	
Apparent porosity		16 vol.- %	
Cold crushing strength		170 MPa	
Modulus of rupture		21 MPa	
Abrasion		10 cm³	
Young's modulus		22 000 MPa	
Thermal expansion coefficient		6,63 •10^{-6}/K	
Poisson's modulus (estimated)		0,22	

cluding it is obvious that this will not lead to any kind of improved material for this special application.

In Tab. 2 and 3 two different types of monophase material are described. The first one is based on fused mullite, the second one on fused corundum. The resulting thermal shock parameter according to *Hasselman* is about 86,7 K for the mullite brick and about 47,5 K for the corundum brick. Both brick types are clay-bonded.

So in the case of the mullite brick the basic raw material and bonding has nearly the same mineralogical composition, whereas the corundum brick has a bonding structure based on mullite. Therefore the resulting properties and values according to the thermal shock resistance are relatively good.

Taking a direct-bonded corundum brick the parameter according to *Hasselman* will be decreased down to 20 – 25 K because of the very high Young's modulus of abt. 80 000 MPa and an increased thermal expansion to 8,2 • 10^{-6}/K (35 – 1000 °C).

Closing this chapter, one can see that the commonly used standard material is obviously the best solution for the lining of the described special areas in this application. To go ahead some changes have to be done to get an optimised brick material for the gas inlet area.

3 Improved material

To affect this process in the brick structure in the opposite direction a third mineral phase should be introduced into the material structure. Based on some experiences the addition of ziconia will be beneficial, caused by the known martensitic transformation and leading to the qualified properties.

This effect can be reached by the addition of a small percentage of zirconia, decreasing the Young's modulus down to about 30 000 MPa. This kind of material with a relatively low content of silica or even silica free will have a good thermal shock resistance but not a very good one, because the thermal expansion coefficient is in the range of about 8,3 • 10^{-6}/K (35 – 1000 °C). Products based on e.g. corundum and zirconia will have these properties.

If there is no need to minimize the silica content of the material as for the lining of the described gas inlet area the use of zircon instead of zirconia is possible. With a higher addition of zircon in comparison to the addition of zirconia also much more mullite is obtained in the bonding structure of this kind of material. This will lead to a lower thermal expansion coefficient of about 6,5 • 10^{-6}/K (35 – 1000 °C). Caused by the higher content of mullite the Young's modulus is reduced to 15 – 20 GPa aligned with a cold crushing strength of about 100 MPa.

The data shown in Tab. 4 gives an impression on the properties of that kind of brick. The resulting thermal shock parameter according to *Hasselman* will be R = 103,2 K. So one gets a slight improvement of resistance against thermal spalling but no improvement of the abrasion resistance.

3.1 Chemically bonded lining material

To increase the mechanical strength, a chemical bonding system based on aluminium phosphate is used which yields to a higher Young's modulus of more than 20 GPa and to a higher cold crushing strength of more than 150 MPa. The resulting properties are reflected in Tab. 5.

Based on these data one can calculate the thermal stress factor according to Hasselman to R = 112,2 K. Summarised, a material behaviour has been obtained with similar properties regarding the thermal shock resistance, which is a bit better, but with a considerable increase in abrasion resistance which enhances the performance of a gas inlet bloc in the critical area.

4 Brick structure

To clarify the working of the created brick structure the mineral composition of the improved material has been analysed. Fig. 3 shows the XRD diagramme of the The proved material.

In Tab. 6 the mineral composition of the standard and the improved lining material is listed.

The standard brick based on corundum and mullite shows a mullite content of 36 %. About 70 % of this mullite is added as primary raw material. So the bonding of the brick contains about 11 % mullite and 3 % amorphous matter.

In contradiction to that, the improved brick contains 18 % mullite, which will be created through the firing process and 2 % cristobalite and also 5 % baddeleyite, which is resulting from the decomposition of zircon. The low content of cristobalite is inoffensive in case of thermal shock resistance, but the content of baddeleyite will be additionally responsible for the initiation of the above described micro-cracks.

5 Conclusion

As a result of this investigation there are some items to focus on for a further development of lining material for the gas inlet area of a DRI shaft furnace. One important thing is to get an elastic behaviour of the lining material with the addition or creation of more than two mineral phases with different thermal expansion in the brick structure. On the other side it seems to be helpful to get a material with a high strength by adding a chemical bonding system, which enhances the strength and will work like a shock absorber in the brick structure.

Tab. 6 Mineral composition of the two different lining materials

Mineral	Standard brick	Improved brick
Corundum [%]	61	52
Mullite [%]	36	18
Cristobalite [%]	-	2
Baddeleyite [%]	-	5
Zircon [%]	-	21
Amorphous [%]	3	2