Prolonging CSN BF2 Refractory Lining Campaign Through Robotic Shotcreting

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The paper describes the methodology used to assess, evaluate and implement robotic shotcrete technology aiming at preserving the integrity of CSN BF2 refractory lining while prolonging its campaign in the time frame 2004 to 2009. Furthermore, the technical, operational, and economic advantages of shotcrete technology over gunning are shown which was used in the early stages of BF campaigns.

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Keywords: BF campaign, robotic shotcrete, prolonging campaign

Received: 10.05.2010
Accepted: 12.10.2010

1 Introduction

Generally speaking, Blast Furnaces (BF) require considerable investments and managing them requires an appropriated maintenance plan, which in turn involves short-, medium- and long-term actions, in order to prolong as long as possible their campaigns, without jeopardizing operators' safety or prompting operational losses. Tabs. 1 and 2 show the main characteristics of CSN BF2 design as well as a summary of its 5th campaign.

The operational results achieved in this campaign (Figs. 1 and 2) by far exceed design parameters, with operational rates comparable with the best blast furnaces in the world (productivity expressed in cubic metres of in-

Tab. 1 Main characteristics of BF2 design

Blast furnace BF2	Design characteristics
Inner volume	1653 m³
Burden distribution	rotary chute (Paul Wurth)
Charge	screening of sinter, iron ore and coke conveyor belt 2 charging hoppers 3 probes for burden level equalization with partially clean gas and nitrogen
Hot blast stoves	3 Units with inner Combustion Chamber Blast Temperature: 1 100 °C.
Cooling system	cooling staves: stack, belly and bosh spray: hearth
Gas cleaning	top pressure control: Bischoff-type system (1100 kp/cm²) gas scrubber: Venturi
Cast house	2 tap holes slag granulation 24 tuyeres hearth diameter: 9 m natural gas injection system PCI (in place since June 1997): 200 kg/t
Control systems	top gas analysis: CO, CO_2, H_2 uptake gas temperature gas temperature at the top: stationary probe throat temperature: skin flow stack gas analysis and temperature: below burden probe refractory lining temperature: stack, belly, bosh and hearth pressure measuring points: 11

Tab. 2 Summary of CSN BF2 5th campaign

Assessment parameters	Campaign					
	1st phase: Feb. 1991 – Nov. 2000		2nd phase Dec. 2000 – Mar. 2009		Total	
	Est.	Actual	Est.	Actual	Est.	Actual
Campaign [years]	10	10	4	8	14	18
Output [Mt hot metal]	12	12,5	6	13,5	18	25

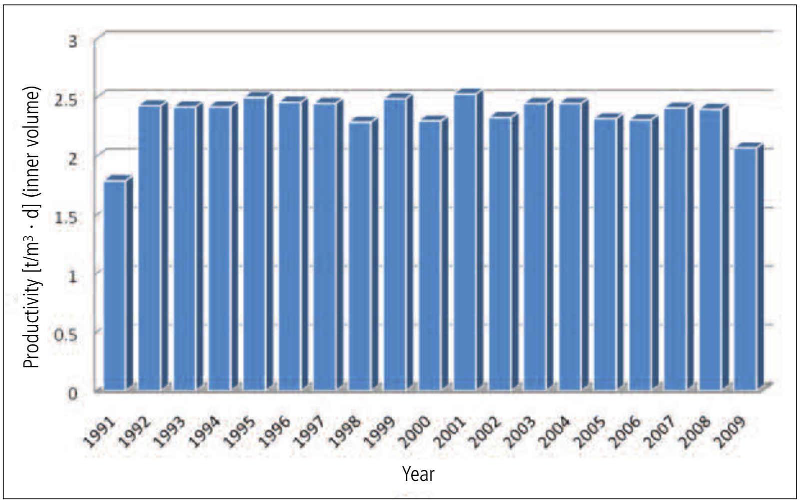

Fig. 1 Productivity of CSN BF2 5th campaign

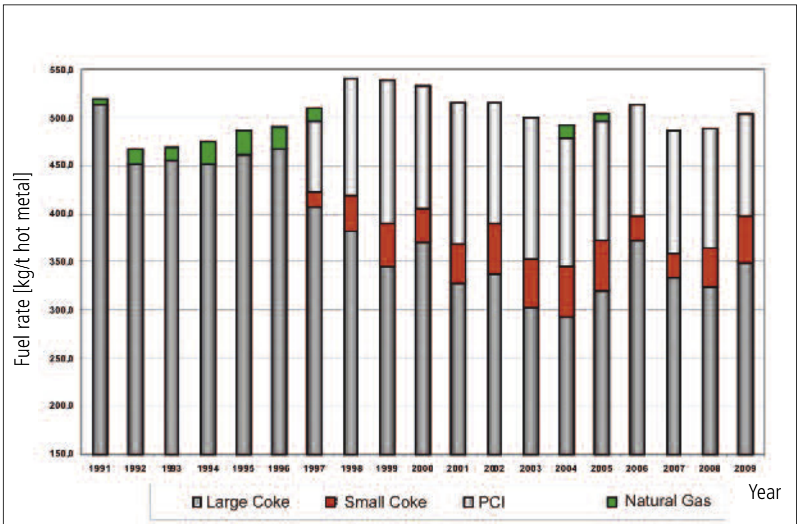

Fig. 2 Fuel rate of CSN BF2

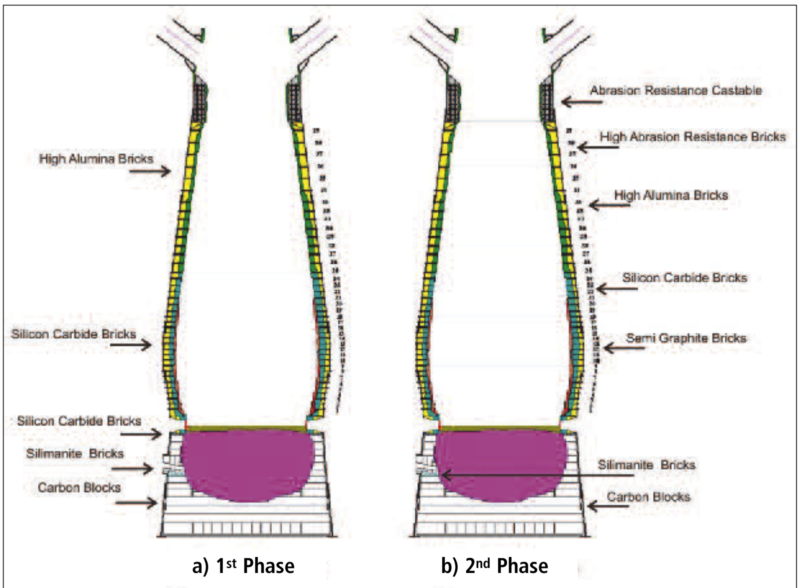

Fig. 3 Refractory lining design before and after 2000 partial repair

ner volume). Fig. 3 shows schematically the refractory lining designs related to the 1st and 2nd campaign phases. For the sake of protecting the metallic shell, a minimum 390 mm residual thickness for the refractory lining was established, so as to keep the last brick layer close to the shell, thereby preventing brickwork from collapsing through a knock-on effect and formation of hot spots.

As of 1997, after the PCI Plant came on stream, skull started to build up in lower stack and belly, negatively impacting operational results [1], which called for the development and implementation of special operational procedures, so that burden might descend more smoothly while removing skull stuck on refractory lining. Removing skull had its adverse effects, leading to premature wear, as by trying to remove it part of refractory lining comes off too.

In the 1997 to 2000 time span, end of the 1st campaign phase, the maintenance strategy consisted of annual repairs by manually applying refractory castable (cold manual gunning) from top down to tuyeres. For a repair of this nature, the rebound level was not decisive, as the whole rebounded material might be removed through tuyere openings. Tab. 3 shows the main features of cold gunning involving such repairs.

In the 2nd phase of the campaign, 2003 to 2006, the maintenance strategy consisted of robotically applying refractory castable every six months (hot robotic gunning) from top down to lower stack. The areas comprising belly, bosh and tuyeres, lined with semi-graphite bricks of high thermal conductivity, thermal solution [2], and wear profile virtually stabilized did not require any repairs. This kind of repair does not allow for removal of rebounded material made up of high alumina concentration, Al_2O_3, and high melting point. As a result, the rebounded material index becomes a crucial issue, thus limiting the maximum amount of material to be applied due to inherent risks to which BF is exposed when it comes to resuming operations.

On the assumption that 80 t of refractory material is applied, with 60 % alumina, and 15 % rebound index, the ensuing Al_2O_3 deposition upon BF burden will be 7,2 t. Furthermore, the decision on the robotic technology to be used took primarily into account personnel safety, leading to unmanned services inside BF, because of the

Tab. 3 Main features involving cold manual gunning of CSN BF2, 1997 to 2000 time frame

Repaired area	Period	Duration	Remarks
Top down to tuyeres	April 1997	9 days	without tapping salamander
Top down to tuyeres	April 1998	15 days	without tapping salamander

Tab. 4 Main features of hot robotic gunning used at CSN BF2 between 2003 and 2006

Year	2003		2004	2005		2006
Month	Apr.	Nov.	Jul.	Aug.	Nov.	Jul.
Applied material [t]	40	77	81	87	83	45
Application rate [t/h[	3,51	3,85	4,26	4,95	3,95	4,09
Rebound index [%]	18	17	15	16	18	16

possible risks of CO and high temperatures. However, as good thermal insulation on BF burden is, such hazards must still be reckoned with.

Tab. 4 shows the main features of repairs using hot robotic gunning. In 2005 with the economy on the upturn and a robust market, the company's policy in place toward servicing the lining every six months was discontinued. Following a 13-month break from the last application, the wear profile in critical shape with residual thicknesses of < 390 mm, required that huge amounts of material be applied – something like 120 t – to fully salvage lining.

Nevertheless, the high rebound index of the technology used (hot robotic gunning) ranging from 10 % to 15 %, limited the maximum amount of material to be applied, due to slagging difficulty of the alumina deposited upon BF burden.

As a result, BF shutdowns became more frequent, so that material could be applied for lining through restoration – applications August to November 2005 and July 2006 (Tab. 4).

Fig. 4 shows the wear profile behaviour in the 2003 to 2006 time frame, taking as a reference the upper stack, row elevation 35 of cooling plates. The wear in this area had a negative impact on burden distribution. In this connection, the shotcreting technology, which is widely used in North America, Europe and Asia [3], fit perfectly into CSN's specific needs.

On Tab. 5 a comparison is drawn between gunning and shotcreting technologies.

2 Objective

With the economy on the upturn and a robust market, the mounting production losses, arising out of BF outages to apply refractory castable, with ensuing interruption to business, prompted CSN to implement shotcreting technology aiming at:

- restoring the refractory lining without operational risks when BF resumes operation – low rebound index; and
- prolonging BF campaign by scaling back shutdown frequency for refractory maintenaince thus minimizing production losses.

3 Methodology

3.1 Evaluation of technical and economic feasibility of shotcreting

The very first step toward conducting a preliminary evaluation was to visit *Magneco-Metrel*/USA, the manufacturer of colloidal-silica-bonded refractory castable, to be applied through shotcreting in order to gain insight into this new technology and to ascertain the required facilities, material performance, etc., and witness its use in large-sized BF.

In terms of South America, that was the first time ever that colloidal-silica-bonded refractory castable using this technology was supposed to be employed in large-sized BFs.

To make this project possible, a partnership was formed between Magneco-Metrel/USA, manufacturer of this material and holder of the technology, and *Calorisol*/BR, a company providing erection and refractory services.

Investments made by Calorisol included the import of 2 pumping machines (Allentown, model 3300), of proven efficiency, and 2 robots assembled in Brazil, according to Mag-

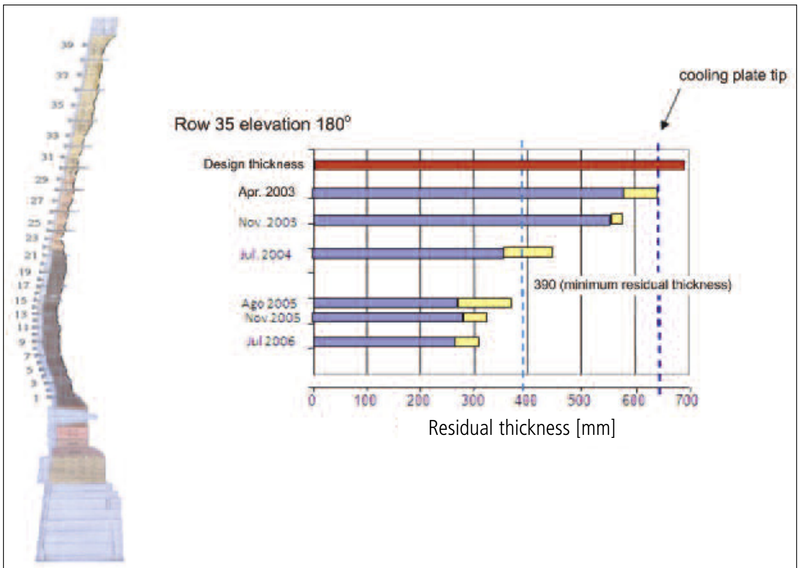

Fig. 4 Wear profile behaviour of refractory lining of upper stack at row 35 cooling plates elevation (ref.: 2003 – 2006 time frame)

Tab. 5 Comparing technologies gunning/shotcreting in BFs

Assessment parameters	Gunning	Shotcreting
Cost of application equipment	low (simpler)	high (more robust)
Pumping of material	dry	wet
Rebound index [%]	10–15	3–5
Application rate [t/h]	3–4	8–12
Material performance [months]	6–12	12–18

Tab. 6 Products of hydration reaction of calcium aluminate cement [4]

Curing temperature [°C]	Hydration products
< 21	$CAH_{10} + Al_2O_3$ gel
21 – 35	$C_2AH_8 + AH_3$ gel*
35	$C_4AH_6 + AH_3$ crystalline

*Gel crystallizes between 27 °C and 32 °C

Tab. 7 Main physico-chemical properties of refractory castables used at CSN BF2

Properties	Applied area (stacks)	
	lower & mid	upper
Chemical analysis [mass-%]		
Al_2O_3	73,9	64,6
SiC	17,4	–
SiO_2	6,3	32,6
Fe_2O_3	0,3	0,7
TiO_2	2,0	1,4
CaO	0,1	0,1
Alkali	–	0,4
Physical properties (after curing at 110 °C):		
Specific apparent mass [g/cm³]	2,76 – 2,84	2,39 – 2,50
Apparent porosity [%]	16,6 – 19,7	12,8 – 17,0
Modulus of rupture [MPa]	4,1 – 7,2	5,5 – 10,0
Cold crushing resistance [MPa]	22,1 – 29,7	24,8 – 44,8
(after burning at 1400 °C):		
Permanent linear variation [%]	0,0 – 0,4	-0,2 – 0,3

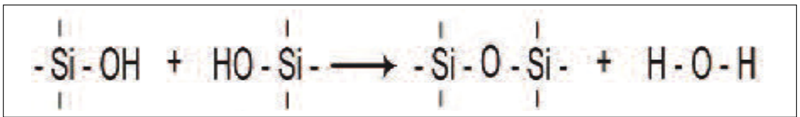

Fig. 5 Condensation reaction producing Si-O-Si bonds [4]

neco-Metrel design, with all critical components being imported. Upon fabrication, functional and performance cold runs were conducted.

3.2 Refractory materials

The technology of colloidal-silica-bonded refractory castable is based upon the elimination of calcium aluminate cement in the mix as well as the use of sol-gel technology.

3.2.1 Cement-bonded concrete

The bulk of refractory castables and ramming mixes uses calcium aluminate cement as aggregate binder (CAC). The amount of CAC may vary from rather low portions to 10 % or more, depending on manufacturer and product. The presence of CAC can be seen from CaO content in the chemical analysis of the material. For most of products which are CAC bonded, the CaO content ranges from 0,8 to 3,0 %. Water is added to such refractory castables and ramming mixes at an appropriate consistency. The added water reacts with CAC, forming hydrated phases, which prompt material to bond at low temperatures. These formed phases depend on curing temperature (Tab. 6).

At low temperatures, CAC bonded castable is quite dense and permeability is very low. As hydrated phases are decomposed and chemically bounded water is eliminated, binding resistance declines while material permeability and porosity rise, till the whole water is removed.

3.2.2 Colloidal-silica-bonded pumpable refractory castables

Pumpable refractory castables, based on sol-gel bonding technology, are without calcium aluminate. These castables use a colloidal silica binder without water, which is added on the job site, prior to application, with a MgO based set accelerator additive. This additive turns pumpable castable into gel and causes material to set at a controllable rate. Transformation into gel occurs because of condensation reaction (Fig. 5), which involves water being released. Unlike CAC bond, which involves the formation of chemically bound water, colloidal-silica-bonded materials give off water. Therefore, silica bond involves a chemical bonding that is not broken when material is dehydrated under heat. As water is not chemically bound, the bulk of it in gel structure is free to be released at very low temperatures (100 °C). However, a small portion of water in form of hydroxyl groups may still be released at quite high temperatures. Water release, though barely detectable, results in the formation of further Si-O-Si bonds, hence adding to resistance.

For industrial application at CSN BF2, pumpable refractory castables were selected. They consisted of a alumina- and colloidal-silica sol-gel based bonding system, with set accelerator free of alkali and compatible with the use of colloidal-silica-bonded products. Application was conducted by shotcreting. Tab. 7 shows the main physico-chemical properties of refractory castables used at CSN BF2.

3.2.3 Alkali corrosion

Colloidal silica has been used in alumina castables, because of its effectiveness when it comes to packing, rheology, its size and round shape as well as the possible in-situ mullite formation through alumina reaction [5]. When mullite is formed in-situ, an increased corrosion resistance and an excellent resistance to damage caused by thermal shock in refractory castables are built [6]. From a technology standpoint, it is interesting to notice mullite formation at temperatures below those usually observed, close to 1400 °C, by using precursors as nano-particles, and therefore more reactive.

Formation of mullite is desirable from the aspect of alkaline-corrosion prevention. According to literature [7], it is particularly through free silica that alkali and zinc are incorporated into BF refractory lining. Alkali and zinc deposits are basically formed in the area near the 800-°C isotherm as a result of the condensation phenomenon involving alkali and zinc vapours. Alkali corrosion is particularly important at the BF mid and lower stacks, where temperatures range between 700 °C and 1100 °C. Alkali and zinc react with alumina and silica contained in the material, leading to the formation of aluminosilicates, phases of low density and low melting point:

$K_2O_{(s,l)} + Al_2O_{3(s)} + 2\,SiO_{2(s)} \rightarrow K_2O \cdot Al_2O_3 \cdot 2\,SiO_{2(l)}$ (kaliophilite)

$K_2O \cdot Al_2O_3 \cdot 2\,SiO_{2(l)} + 2\,SiO_{2(s)} \rightarrow K_2O \cdot Al_2O_3 \cdot 4\,SiO_{2(l)}$ (leucite)

$ZnO_{(s,l)} + Al_2O_{3(s)} \rightarrow ZnAl_2O_{4(l)}$ (zinc aluminate)

$ZnO_{(s,l)} + SiO_{2(s)} \rightarrow ZnSiO_{3(l)}$ (zinc silicate)

The high volume of formed liquid phase, close to the 800-°C isotherm, causes the material microstructure to collapse due to structural spalling, resulting in its full disintegration, making it powder like (brittle zone).
The materials to be used at CSN BF2 (Tab. 7) are applied simultaneously with an MgO-based setting accelerator additive in suspension with water (30 mass-%).
The castable binder concerned consists of aqueous colloidal silica. In suspension, the colloidal silica represents 40 mass-%.
For the purpose of investigation of in-situ alumina formation, mixtures of superfine fractions (of less 45 µm) were prepared (325 mesh screen), using mid and lower stack castables (Tab. 5) with 12 mass-% binder and 1 mass-% setting accelerator. During preparation, the mixtures were treated at 800 °C, 900 °C, 1000 °C, 1100 °C, 1200 °C and 1300 °C and analyzed by XRD.

3.3 Evaluation of material application

The evaluation of material application consisted of measuring the application rate [t/h] and rebound index [%].
Rebound index was determined by means of alumina mass balance, taking into account the combination of elements given below:
- the 3 last burdens prior to BF blow-out
- the banking burden added prior to BF blow-out
- refractory castable used (rebound)
- the first 3 burdens after applying refractory material
- slag of first casts upon BF resuming operations, till normalization (Al_2O_3 < 13 %).

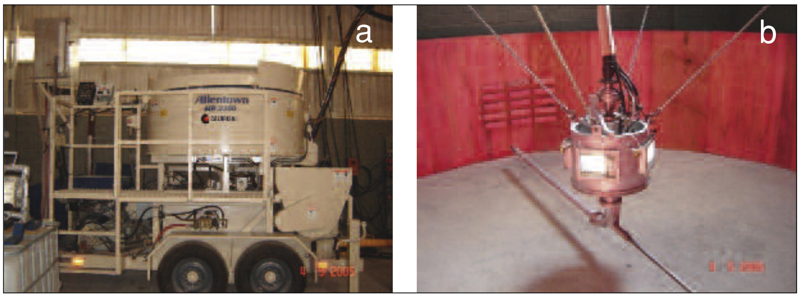

Fig. 6 Robots cold performance test: a) pumping machine; b) robot

4 Results and discussion

4.1 Robots functional and performance testing

Cold runs to evaluate how robots performed (Fig. 6) consisted of applying castable onto wooden mock-up, thereby simulating industrial application in BFs running on cooling plates. Robots' performance, material application rate and the rebound level found in these tests were considered fairly satisfactory.

4.2 Robotic shotcreting

Tab. 8 shows a history of robotic shotcreting at CSN BF2 at the end of the 2nd phase of campaign 2006 to 2009.
In the first application back in September 2006, despite the high amount of castable applied (101 t), there were a number of problems which jeopardized its ultimate performance:
- low application rate (5,53 t/h); pumping machines stopping quite frequently as a result of filters becoming clogged, due to the use of combustible fuel, contaminated with impurities
- high rebound index (13,2 %); additive pumping machine running on inverted connection, suction, in the first 2 h of application and failure to exchange robot lance, later, in upper stack.

As the learning process went on, application performance became better and better. In July 2008 (4th application), the results attained were comparable with the best obtained in the world and compatible with the technology used: application rate 12,0 t/h and rebound index 3,75 %.

Tab. 8 History of shotcreting at CSN BF2 (2006 – 2008 time frame)

Year	2006	2007		2008
Month	Sep.	Aug.	Oct.	Jul.
Applied material [t]	101	60	36	102
Application rate [t/h]	5,53	7,50	6,00	12,00
Rebound index [%]	13,02	6,74	6,40	3,75
Burden descend [m]	19	19	7	19
Thickness of applied material [mm]:				
maximum	177	100	200	225
average	74	71	118	142
minimum	27	28	34	81

Tab. 9 Behaviour of refractory lining wear rate of CSN BF 2 (2006 – 2008 time span)

Impact of using pellet	Period					
	Sep. 06 Aug. 07	Aug. 07 Oct. 07	Oct. 07 Dec. 07	Dec. 07 Feb. 08	Feb. 08 May 08	May 08 Jul. 08
Shotcreting	Sep. 06	Aug. 07	Oct. 07			Jul. 08
Wear rate x 10^{-5} [mm/t hot metal]	6,84		27,23	7,47	16,97	7,69
Pellet in burden	Yes		No	Yes	No	Yes

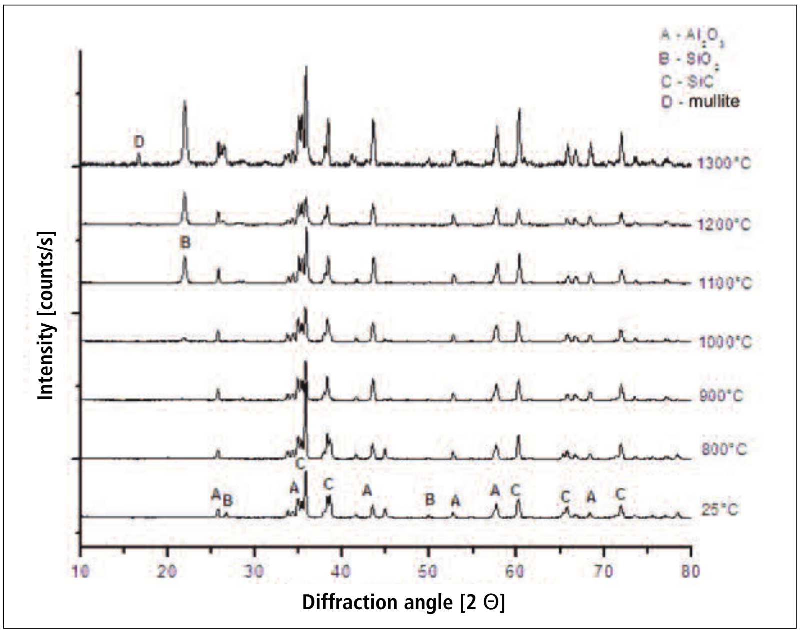

Fig. 7 **XRD of castable super fine fraction mixture used in lower and mid stacks with 12 mass-% binder and 1 mass-% setting accelerator after heat treatment**

4.3 Monitoring wear profile

Usually CSN BF2 runs on 12 % pellet in the burden to prevent skull build-up. Nevertheless, from October to December 2007 and February to May 2008, no pellet was added. Hence, there was an increase in formation frequency and removal of inactive burden, adhered to refractory lining, which prompted wear rate to ramp up. Tab. 9 shows the impact of not having added pellet to BF burden on the wear rate of refractory lining.

4.4 In-situ mullite formation

Fig. 7 shows the X-ray diffractogramme of super-fine mixture castable used in lower and mid stacks with 12 mass-% binder and 1 mass-% setting accelerator after heat treatment. In-situ mullite formation only occurs when temperatures of around 1300 °C.

These results are corroborated by studies conducted by *Gerotto* et al. [8]. As alkali and zinc settle into BF refractory lining in the isotherm of approx. 800 °C, then the whole free silica in the material will continue on for reactions involving alkaline and zinc corrosion. Paradoxically, the material used at CSN BF2 performed fairly satisfactorily, with an approximate 12-month service life. This may be ascribed to the following:

- deposition of alkali and zinc into BF refractory lining is a long-term phenomenon
- the 800-°C isotherm shifts toward the cold face, in direction of residual lining, as wear of the applied material moves on.

4.5 Economic feasibility study

Tab. 10 shows the assumptions considered for comparison purposes, from an economic standpoint, using shotcreting and gunning technologies to extend CSN BF2 campaign. The net present value (NPV) resulting from the cash flow difference between the above-mentioned technologies in the years 2004 to 2009 is approximately USD 870 000 in favour of shotcreting. The higher application rate substantially reduces production losses, and therefore interruption to business, the main component of the cost matrix. This is particularly true when the market is robust.

Tab. 10 **Assumptions considered for economic comparison purposes of shotcreting and gunning technologies to prolong CSN BF campaign**

Assumptions	Gunning	Shotcreting
Material performance [months]	6	12
Number of material application / year	2	1
Material amount [t]	80 (2 x 40)	80 (1 x 80)
Application rate [t/h]	4	8

5 Conclusion

The implementation of robotic shotcreting technology to preserve the integrity of CSN BF2 refractory lining, instead of gunning, proved to be technically and economically feasible for the following reasons:

- high application rate: 8 – 12 t/h
- low rebound index: 3 – 5 %
- better material performance: 12 – 18 months
- decrease in refractory maintenance costs totalling USD 870 000 (NPV) in the 2004 to 2009 time frame.

Acknowledgements

Special thanks to all companies and individuals, whose valuable inputs made this project possible: Magneco-Metrel/USA, Calorisol and CSN/Brazil.

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