Saint-Gobain's Ceramic Cup: an update

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Glossary of definitions and abbreviations: BF = Blast Furnace; CC = Ceramic Cup which includes hearth wall and pad linings; GRW = Global Refractory Wall which includes carbon and ceramic linings; CW = Ceramic Wall made of Coranit or Coranit Al materials.

ABSTRACT

Saint-Gobain has pioneered and developed innovative refractory solutions for the blast-furnace for many years. From the first Ceramic Cup in the early 1980's to date, new materials have been designed and developed and still today new products are being created. For the hearth, the Ceramic Cup in Coranit Al bricks has become globally accepted.
However, a large number of alternative Ceramic Cup solutions, supplied by other companies, have emerged over the years with often reduced performance. Saint-Gobain's name is still closely linked with the one of Ceramic Cup. As a consequence, after several years of operation, where possible, data has been gathered and analysed to evaluate the wear profile evolution of the Saint-Gobain Sialon bonded Ceramic Cup.

INTRODUCTION

Saint-Gobain High Performance Refractories design, manufacture and supply refractory lining solutions and services used in several applications for the iron and steel industry. The Ceramic Cup concept was created and promoted by Saint-Gobain in the 80's to protect the carbon lining inside BF crucible (Figure 2). The ceramic wall plays a major role in this philosophy, forming the stable layer that protects the carbon lining [1, 2]. Saint-Gobain's Ceramic Cup has been supplied and installed in almost 100 blast furnaces worldwide making the company become the reference for this technology. To withstand the severe conditions existing inside BF hearth, refractory solutions moved originally from large pre-cast blocks in Chrome-Alumina to Brown-fused alumina then finally today to small Sialon-bonded corundum brick. Two generations of Sialon bonded material were developed consecutively: Coranit and Coranit Al.

The following advantages are generally admitted to Sialon bonded wall in front of carbon lining:
- No dissolution by carbon unsaturated iron
- Very good corrosion resistance to slag and melting iron at high temperature (1400°C – 1600°C)
- Very good stability to chemical attack especially alkali and zinc attack
- Very good oxidation resistance in case of water leakage
- Excellent thermo-mechanical properties
- Low thermal conductivity leading to heat/energy and coke savings

The wear of hearth refractories is widely recognized as the main limitation for a long BF campaign. As a result, the choice of the following three pillars respectively ceramic cup design, refractory materials and their installation is being recognized as the critical decision for customers during reline [3].

Wear mechanisms involved in the blast furnace hearth are mainly:

- Chemical reactions and corrosion/erosion between refractory materials and melting iron and slags liquids
- Thermo-mechanical stresses

Inside the hearth, the fluid flow alone may cause wear to the refractory lining but a combination of this with particles abrasion and thermal stresses may cause inescapably more significant wear which could decrease drastically the campaign life [4].

In this paper, ceramic cup performances designed with both qualities (Coranit or Coranit Al) will be discussed through several examples:

- Arcelor-Mittal blast furnace number 4 in Dunkerque
- Arcelor-Mittal blast furnaces number 1 and 2 in Fos-sur-Mer
- ThyssenKrupp Steel Europe blast furnace number 2 in Duisburg

		Arcelor-Mittal - Dunkerque	Arcelor-Mittal – Fos-sur-Mer		ThyssenKrupp - Duisburg
		BF4	BF1	BF2	Schwelgern 2
Blow-in date		2001	2008	2011	1993
Hearth Ø (m)		14	12,3	12,3	14,9
Shell ext. Ø (m)		18,1	14,8	14,8	22
Number of taphole		4	2	2	4
Tap hole angle		6°	9°	9°	3°
Number of tuyeres		40	32	32	42
Hearth design		Ceramic cup			
Global Refractory Wall		Carbon + Ceramic			
Ceramic Wall	All along BF elevation	400 mm CORANIT	400 mm CORANIT Al	400 mm CORANIT Al	400 mm CORANIT
	Elephant foot area (if different)		500 mm CORANIT Al	500 mm CORANIT Al	

Figure 1: Some characteristics of BF designs studied in the paper

For these blast furnaces, real field data were gathered and analysed to investigate the ceramic cup wear evolution throughout the BF campaign. Indeed, the global refractory wall wear is mapped thanks to the different sensors positioned on several blast furnace cross-sections.

The aim is to assess and better understand how the refractory lining wear profile has evolved over time in order to increase our knowledge and identify the next line of development for our forthcoming innovation strategy (quality material and hearth design).

METHODOLOGY USED TO COLLECT DATA DURING BF OPERATING

Hearth lining materials

All the blast furnaces studied are built with a Ceramic Cup design made up of several refractory layers (Figure 2):
- The ceramic bottom consisting of an upper layer of white ceramic materials, enjoying a high resistance to mechanical wear, crack occurrence and optimal jointing to limit liquid iron penetration/solidification inside the lining while at the same time avoiding too high thermo-mechanical load.
- The tap-hole area, a critical zone where no clear philosophy for lining optimization on the material quality or design (brick, block, monolithics…) has emerged so far [5].
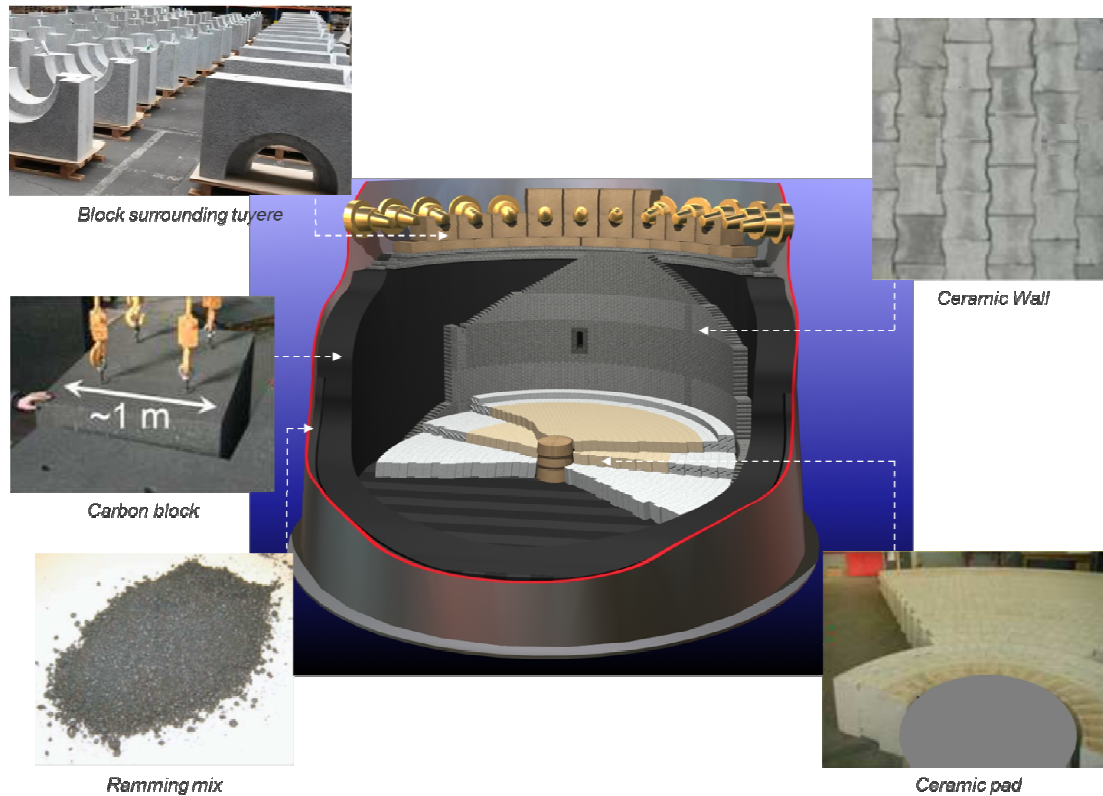

Figure 2: Saint-Gobain's Ceramic Cup hearth design

- The global refractory wall is designed with five different types of materials:
  o A sacrificial layer of low quality brick generally made of fireclay, used to avoid significant thermal shock during start-up and the very first contact with molten iron.
  o The ceramic wall made of Sialon bonded corundum bricks resistent to molten iron and slag and protecting the carbon behind from dissolution. Moreover, the 800°C-900°C isotherm is moved inside the ceramic, helping the cup extend the hearth lifetime [6]. Acting as the very first barrier against corrosive agents, the wear evolution of this layer will be investigated in detail in this paper.
  o A specific concrete refractory used between the ceramic and the carbon layer.
  o The carbon lining generally composed of large blocks. It is normally characterized by a high thermal conductivity and low pore size diameter. Its role is to keep the inner wall at a low temperature and to prevent any liquid iron from reaching the shell. As the carbon saturation of pig iron cannot always be guaranteed, it is important to lower the contact between the carbon and the liquid metal to avoid rapid carbon loss by promotion of a stable protection layer which is difficult.
  o The ramming mix installed between the steel shell and the carbon walls used for both to reduce the global thermo-mechanical stress after blow-in stage and to ensure a good thermal contact between the steel shell and the carbon.
- The external steel shell of the blast furnace.

Monitoring of temperature and data analysis

Today, the best way to monitor the wear inside the BF is via well placed thermocouples using a modern software programme. It is important that the programme is "on-line" and calibrated before BF blow-in prior to any wear taking place thereby giving high confidence in the results. Each hearth lining is equipped with thermocouples to monitor the temperature profile inside the hearth layers during the entire BF campaign. The permanently installed thermocouples are directly set-up inside the refractory lining in precise locations to record constantly the local temperature.

These probes are located all around the circumferential lining and their position (x = radial position, y = BF elevation), and number are specific to each blast furnace (Figure 3).
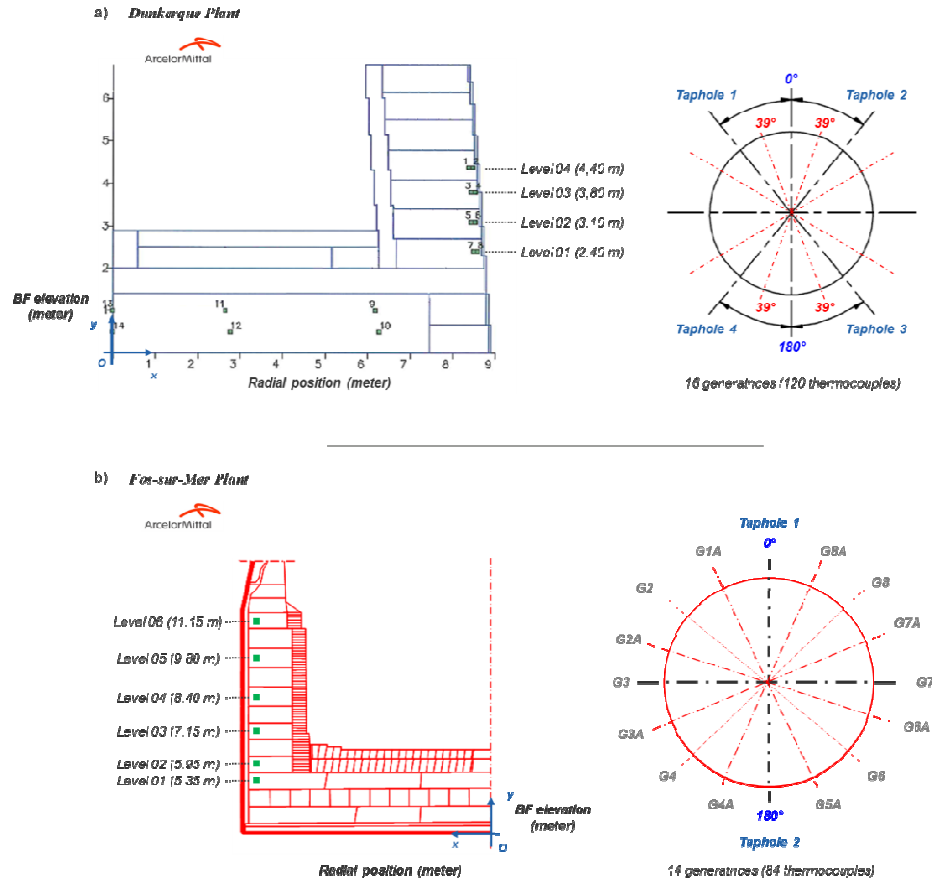

Figure 3: Hearth walls – thermocouples instrumentation (Arcelor-Mittal) respectively for
a) Dunkerque BF n°4 and b) Fos-sur-Mer BF n°1 and n°2

The software program (Mothus) has been developed by Arcelor-Mittal in recent years to model the wear profile with now a very good accuracy between real/theoretical data [7]. For Thyssen, similar software named "Thybas" is used to monitor hearth wear. Based on this data over the years, we have access to the wear evolution profile of the hearth lining.

For example, thanks to this methodology, Arcelor-Mittal regularly report internally the actual "age" of the full BF taking into account the calculated age for each BF part including tap-holes, staves and hearth lining. These data are compared against the expected wear pattern required to achieve the desired campaign lifetime [8]. The current report shows the only area of concern is the copper staves, but repair of this section is much easier than in the hearth.

It seems logical that wear evolution may be uneven around the lining, for many reasons such as tap-hole asymmetry, localized accidents resulting from BF operating actions, BF stoppage and restart, tuyere leakage, local ilmenite injection, etc.

As a consequence, a "weak point" could be eventually detected and measured in a specific location of the crucible (worst scenario). However, whatever the origin of this issue and even if this weak point is localized and not representative of the global ceramic cup erosion profile on all the circumferential BF part, this weakest point will be used to determine the real lifetime of the ceramic cup walls inside the blast furnace.

The main data and results of Sialon bonded lining performances in real conditions will be discussed hereafter. For Arcelor-Mittal, a deeper investigation will be performed based on in-situ data and for Thyssen Krupp results already reported by Rüther and al. 2015 [3].

RESULTS

Arcelor Mittal Dunkerque BF n°4

In this blast furnace, a Coranit wall was installed with a brick initial thickness of 400 mm (Figure 3, Figure 4). Thermocouples are installed regularly all around the refractory hearth for elevations ranging from 2.4 m to 4.4 m height, below the tap-hole area. Data communicated for this blast furnace were covering the first 9 years after blow-in (2001-2010) and results up to this date were clear enough to closely and accurately monitor the wearing process on the Ceramic Cup.

Since blow-in stage on 22nd November 2001, operating parameters analysis has highlighted that the ceramic cup wall was still inside after 7.5 years of operation (Figure 4). Residual Coranit brick thickness average was estimated to be around 100 mm.
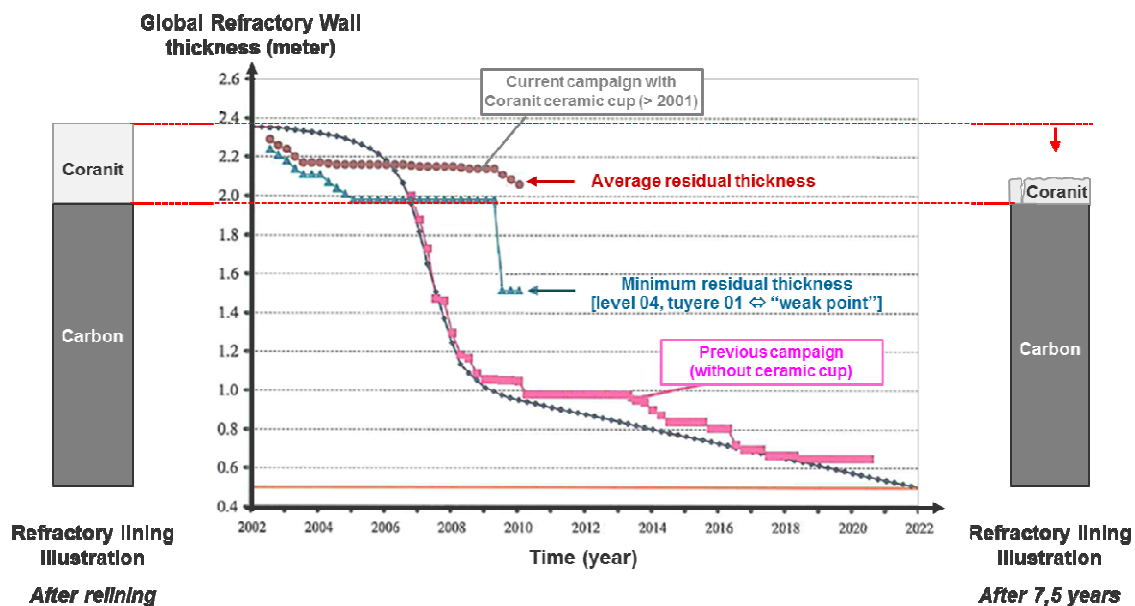

**Figure 4: Wear profile of ceramic cup made with Coranit bricks
(Dunkerque Arcelor-Mittal – blast furnace n°4)**

Here, the global wear of brick lining is regular on all blast furnace cross-sections except for one measure detected at level 04 below the tuyere n°1. Based on this weak point, the ceramic cup wall lifetime has been reduced to 7.5 years even though residual thickness of Coranit brick is measured on the rest of the entire hearth circumference after more than 8 years (Figure 4).

Unfortunately, it was not possible to identify clearly blast furnace operating events to explain the wear below tuyere 1 level 4. However, some abnormal events occurred soon after blast furnace blow-in were reported by the user:
- Immediately after blow-in, some hot spots with gas leakage within one tap-hole area and propagating in the interstitial space between the carbon lining and the steel shell were detected. This issue was stabilized by numerous grout injections from the outside in various shell locations.

- In 2003, tap-hole n°1 was blocked during several weeks. Significant operations were performed using oxygen lance through the emergency tap-hole to reconnect the tuyere/tap-hole. This is the most likely hypothesis mentioned for the user.
- Difficulties observed on each tap-hole leading finally to a general stoppage for full tap-hole repair in April 2016 as illustrated Figure 5.
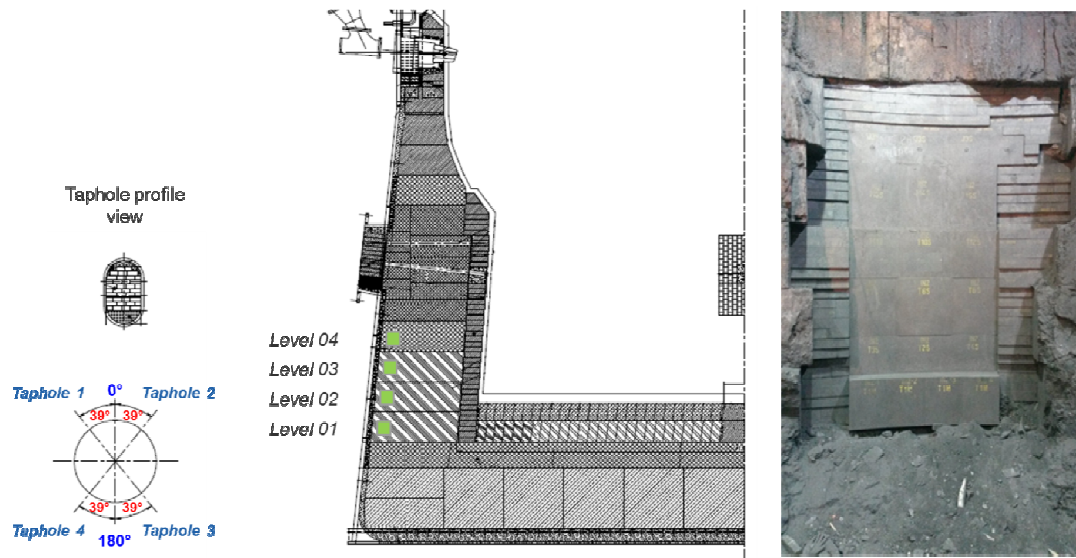
Figure 5: Illustration of tap-hole repair – April 2016
(Dunkerque Arcelor-Mittal – blast furnace n°4)

It seems reasonable to believe that these repairs (grout injection amount and property, local additional stress, etc.) or operational procedures would impact the lining stability and could certainly explain the weak point occurrence.

The refractory corrosion rate increases consistently with the BF elevation (Figure 6) putting forward the existence of an erosion gradient in this BF below the tap-hole to the bottom.

BF n°4 level	BF elevation (meter)	GRW thickness (meter)		Average wear evolution (%)	
		Initial	Average in-situ measure	GRW	CW (Coranit)
01	2.40	2.42	2.68[*]	≈ 0%	≈ 0%
02	3.10	2.40	2.47[*]	≈ 0%	≈ 0%
03	3.80	2.38	2.16	9%	54%
04	4.38	2.35	2.06	13%	74%

Figure 6: Average wear profile data measured 8 years after BF n°4 blow-in

A large number of modelling studies reported that heat flow distribution in the hearth and temperature distribution in the hot metal and in refractories [9, 10, 11, 12, 13] are significantly influenced by several often dependent factors, which are principally:
- The fluid flow resulting from daily tap-hole tapping [14]. In this process, significant local flow behavior in blast furnace hearth, especially in the coke free region, occurring also when all tap-holes are closed [15] and known to be responsible for refractory material erosion [16, 17];
- Dead man position and characteristics (porosity, permeability, saturation) [15, 17, 18]
- Hot iron fluid characteristics: temperature, density and viscosity, fluid tilt during taping [19].
- Carbon dissolution impact, maximum in the high-speed zone near and around tap-hole [14].

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[*] It will be considered that a lining thickness superior to initial will be the result of iron pig solidification on brick surface (iron gangue). As a result the wear rate will be considered to be close to 0%.

Monitoring was accurate enough to detect when rapid wear occurred local to the tap-hole below tuyere 1 level 4 (Figure 5). It can be seen that the remaining Cup suddenly disappeared towards the end of 2009. In addition, over 400 mm of carbon rapidly disappeared at this time also (Figure 4); this rapid carbon wear characteristic has been already reported [20].
This was the start of a more local monitoring of the tap-hole areas which eventually led to the repair outage in 2016 for repairs. The repairs made in 2016 (almost 15 years after blow-in the Cup had eventually worn away) highlighted that the carbon thickness was generally close to original thickness. This can be seen in the photo of the repaired tap-hole (Figure 5).

Blast furnace operators of the Ceramic Cup concept should note once more the importance of the rapid carbon wear that was experienced on Dunkerque BF4 once the Cup disappeared. Even during periods of accelerated wear, such rapid loss was never experienced by the Ceramic Cup, only the carbon. This proves once again the protecting and attenuating aspect of the Cup during periods of BF operational instability.

Arcelor-Mittal – Fos- sur- Mer

In both blast furnaces (BF n°1 and BF n°2), a Coranit Al brick wall of 400 mm was installed. Thermocouples were installed regularly around the hearth with positions ranging from 5.3 m to 11.2 m (Figure 3). The design of both furnaces is rigorously the same.

BF n°1
No issues were detected over the first 8 years after blow-in (10th January 2008). Using Mothus wear profile model, Coranit Al brick wall remained inside the blast furnace on the entire circumference with no reported weak point (Figure 7).

BF n°1 level	BF elevation (meter)	GRW thickness (meter)		Average wear evolution (%)	
		Initial	Average in-situ measure	GRW	CW (Coranit Al)
01	5.35	1.83	1.83	≈ 0%	≈ 0%
02	5.95	1.83	1.80	1%	5%
03	7.15	1.73	1.58	9%	37%
04	8.40	1.73	1.60	7%	31%
05	9.80	1.73	1.59	8%	35%
06	11.15	1.58	1.39	12%	48%

Figure 7: Wear profile data measured 8 years after BF n°1 blow-in (Arcelor-Mittal – Fos-sur-Mer)

If we consider the most corroded parts (level 03 to 06), 62% of initial Coranit Al thickness is still inside the hearth corresponding to a residual brick thickness around 248 mm.

The corrosion profile is quite regular all along the blast furnace elevation (Figure 8). However, a slightly more pronounced corrosion could be noticed, located just below the tuyere area (level 11.15 m). The wear profile is also regular all along the blast furnace circumferential part, without any local "weak point" occurring during blast furnace operation.
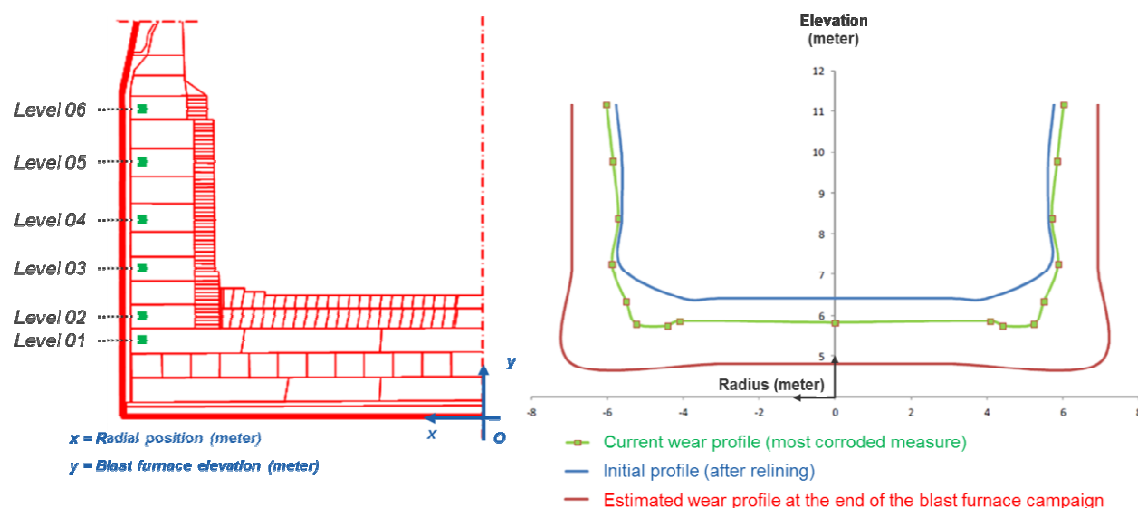
Figure 8: Wear profile after 8 years
(Fos-sur-Mer - Arcelor-Mittal – blast furnace n°1)

For example, compared to the average data listed in Figure 7, maximum GRW erosion rates found are 17% both at tuyere (level 06) and pad/bottom intersection (level 03).

These observations and measures prove that Coranit Al lining is still present all along the hearth elevation and on the entire circumference with a regular wear profile. This conclusion is also fully validated by the user, considering that after at least 8 years, Coranit Al wall continues to protect actively the carbon lining, thus contributing to increase blast furnace lifetime.
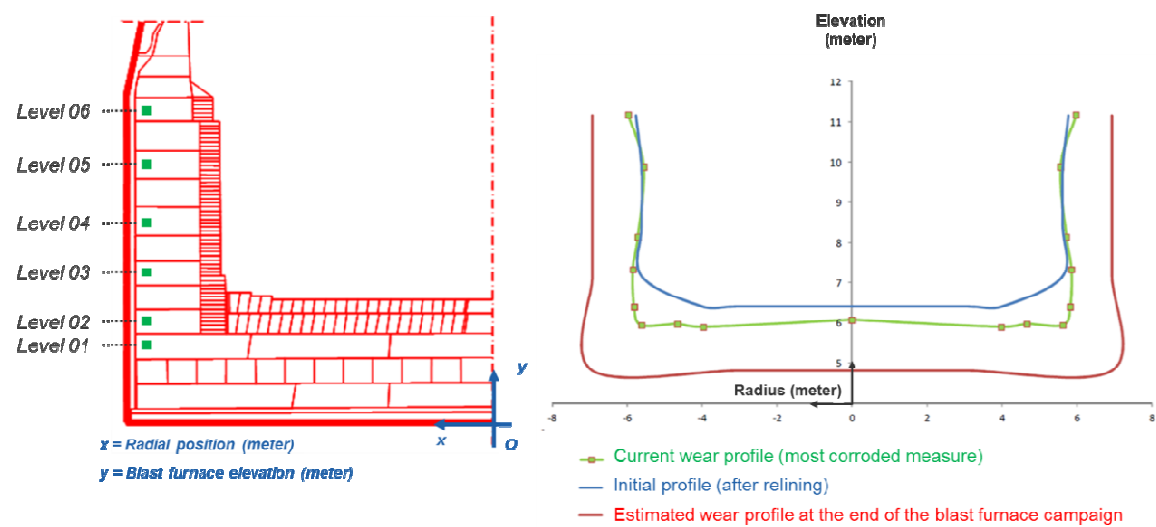
BF n°2

For this blast furnace, the blow-in was performed on 19th September 2011. After 4.5 years, it is not surprising to find that Sialon bonded lining is still present inside BF hearth. If we consider the most corroded parts (level 03 to 06), the residual average Coranit Al brick thickness is measured around 257 mm.

BF n°2 level	BF elevation (meter)	GRW thickness (meter)		Average wear evolution (%)	
		Initial	Average in-situ measure	GRW	CW (Coranit Al)
01	5.35	1.83	1.80	1%	5%
02	5.95	1.83	1.80	1%	5%
03	7.15	1.73	1.56	10%	41%
04	8.40	1.73	1.59	8%	33%
05	9.80	1.73	1.60	7%	31%
06	11.15	1.58	1.43	10%	38%

Figure 9: Wear profile data measured 4.5 years after BF n°2 blow-in (Arcelor-Mittal – Fos-sur-Mer)

For this blast furnace, same observations were made as for BF n°1 with a wear profile homogeneous all along the BF elevation (Figure 10) and a regular profile all along the BF circumferential part.

Figure 10: Wear profile after 4.5 years
(Fos-sur-Mer - Arcelor-Mittal – blast furnace n°2)

For example, for the highest corroded point measured in the elephant foot zone, the GRW residual thickness is measured around 1.43 m, corresponding to a wear rate of 17% (vs. 10% for the average).

Comparative study between BF n°1 and BF n°2

The comparison between the 2 blast furnaces within a same period of time of 4.5 years is given in Figure 11. Both wear profiles are similar even if it appears that a higher erosion rate is measured for BF n°2 in the elephant foot zone (Figure 11).

BF level	BF elevation (meter)	Average in-situ measure for GRW (meter)		Average wear evolution for GRW (%)		Average wear evolution for CW (Coranit Al) (%)	
		BF n°1	BF n°2	BF n°1	BF n°2	BF n°1	BF n°2
01	5.35	1.83	1.80	≈ 0%	1%	≈ 0%	5%
02	5.95	1.83	1.80	≈ 0%	1%	≈ 0%	5%
03	7.15	1.67	1.56	3%	10%	13%	41%
04	8.40	1.61	1.59	7%	8%	30%	33%
05	9.80	1.61	1.60	7%	7%	30%	31%
06	11.15	1.41	1.43	10%	10%	41%	38%

Figure 11: Comparative analysis of wear evolution for a same period of time of 4.5 years between BF n°1 and BF n°2 (Fos-sur-Mer - Arcelor-Mittal)

Indeed, for BF n°2, Coranit Al remaining thickness is measured around 59% in comparison to 87% found for BF n°1, making this elephant foot zone, an area to be controlled and checked regularly for BF n°2.

As additional information, the results from hearth monitoring seem consistent with in-situ stress measurements that we performed on BF n°2 steel shell during the blow-in stage in 2011. As theoretically expected [21], these in-situ measurements confirm that the elephant foot zone, which corresponds close to the pad/wall intersection [22], suffers the maximum stress after blow-in (Figure 12).
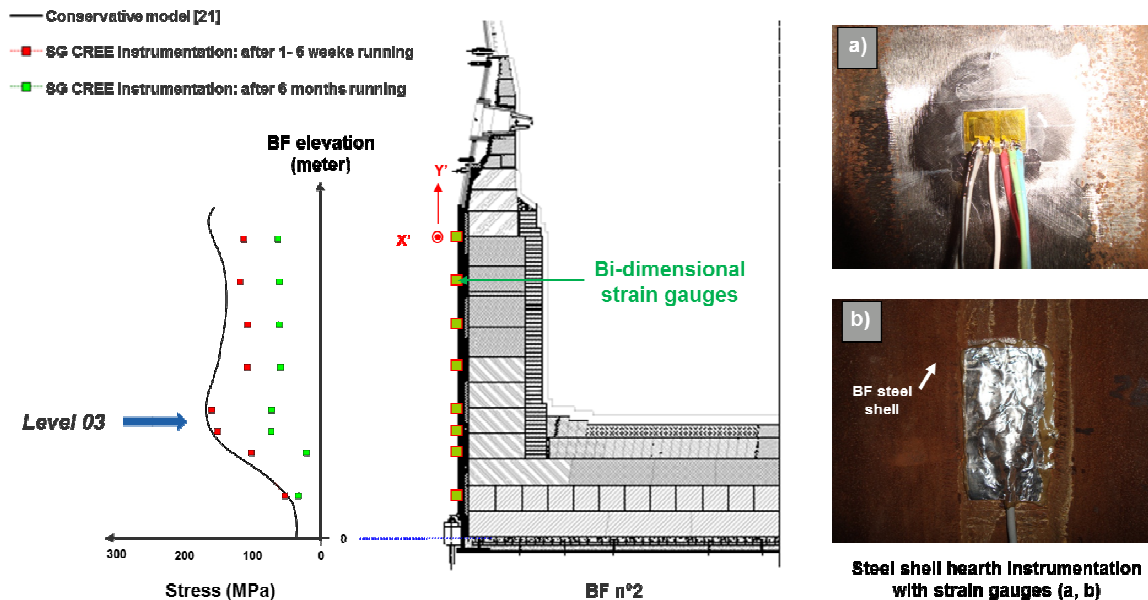
Figure 12: Stress evolution on BF n°2 steel shell after blow-in.
Illustration of maximum stress recorded for level 03 at 7.15 meters

This critical area is still the most stressed zone even after the stress relaxation which starts after 2 months. Unfortunately the same study has never been performed on BF n°1 and the level of stress could consequently not be compared.

ThyssenKrupp Steel Europe – Duisburg Schwelgern blast furnace n°2 – (Campaign 1993-2014)

In 1993, Schwelgern II one of the largest blast furnaces in the world employed a hearth equipped with a Coranit brick wall of 400 mm (Figure 130 for the first time. Refractory concept including materials choice and design is a key criterion to extend blast furnace lifetime for ThyssenKrupp. As a consequence, for this blast furnace, the combination of both a special format (small-size bricks) and an improved holding system were used within this target [3].
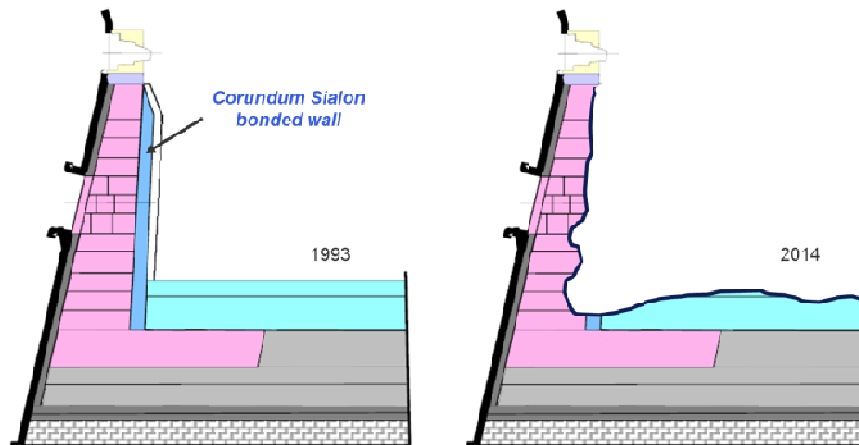

Figure 13: Wear profile evolution of the hearth lining of Schwelgern blast furnace n°2 (1993 -2014) [3]

Since blow-in on 28th October 1993, operating parameters showed that the ceramic cup wall was still inside the hearth for 9 years and further 12 additional years for the carbon lining [3]. This entire furnace campaign of 21 years was recognized to exceed by far customer's expectations (Figure 13).

Thanks to this result, it can be stated that Saint-Gobain Ceramic Cup concept was validated and a direct consequence is that it is considered in future to modify the design by increasing the ceramic side wall thickness by 50%. Under stable conditions the carbon wall, when protected can last many years. However, under unstable conditions it has been shown that rapid carbon loss can occur [20]. It is hoped that by increasing the Ceramic Cup wall thickness the lifetime can be extended on a pro-rata basis since it less affected than carbon by unstable operating conditions.

DISCUSSION

Thanks to a close collaboration with our ceramic cup customers, thermocouple and software data were collected directly from the field and analysed to evaluate the wear profile of the hearth lining. The Saint-Gobain Ceramic Cup, made of Coranit or Coranit Al walls, undergoes a regular wear from the blow-in stage throughout the BF campaign. It can be stated that the Saint-Gobain Sialon bonded lining is still present inside the blast furnace hearth over a period of time superior to 7.5 years, contrasting with the performance that could be reported for alternative ceramic linings [23, 24].

The Ceramic Cup wear is principally characterized by a regular erosion profile all along the diameter. The sensitivity and accuracy of the software programmes were able to detect localised premature wear positions. These localised wear areas reduced the overall lifetime of the whole or average ceramic wall such as observed for BF n°4 when operational difficulties were encountered. However, even during periods of operational difficulty the localised wear on the Ceramic Cup whilst worrying was not considered to be significant. Only when the Ceramic Cup wall disappeared was a really significant wearing observed (over 400 mm carbon disappeared in a few months).

The Ceramic Cup wear profile is quite homogeneous with slightly higher wear rate below the tuyere area. This is not really surprising as this area is known to be the hottest zone of the hearth in direct contact with highly corrosive slags. Less pronounced, an excess of erosion is underlined in the elephant foot zone where the mechanical stresses are the highest. This observation is common for each analysed BF and confirmed by the final Schwelgern II wear profile. It will be interesting to study the final wear characteristic after the CC has disappeared in this zone for Arcelor-Mittal blast furnaces in Fos-sur-Mer to determine whether this mechanism is more pronounced in ceramic or in carbon lining.

Based on the wear rate, it appears that the ceramic wall protects efficiently the carbon over the first 7.5 years. This observation can reasonably be attributed to the Sialon bonded ceramic properties especially its high resistance to iron and slag contact combined with excellent stability to the various chemical attacks. For the latter point, many customers reported

that the brittle layer is generally localised and visible in the residual carbon layer during a blast furnace dismantling [15, 25]. This phenomenon seems to be reduced with a ceramic wall [15] by maintaining the isothermal of alkali condensation inside the ceramic brick rather than inside the carbon layer. Our knowledge of wear profiling is increasing and is leading towards a new design with increased Ceramic Cup brick thickness to maintain the isotherms as long as possible inside the ceramic lining and benefit from the superior wear characteristics of the Sialon-bonded corundum to increase BF lifetime campaign.

CONCLUSIONS

Since Saint-Gobain started to promote the new concept of Sialon-bonded Ceramic Cup, more than 20 years of intensive collaboration were necessary to follow, track and measure the benefit of our innovation.

In this paper, the consolidated and factual data highlight the real benefit of having a Saint-Gobain designed Ceramic Cup protection in front of carbon lining. We can now reasonably state that this ceramic lining resists with its whole integrity for a period of time superior to 7.5 years inside the hearth, fully assuming its role of carbon lining protection.

These benefits, shared by most of our customers, incite the most audacious and innovative of them to henceforth envision a new design based on an increased ceramic cup thickness and to request a new material generation to even overpass the service properties of Coranit Al.

This new design combining both larger thickness and new quality is part of the Saint-Gobain High Performance Refractories' strategy to reinforce its leading position and to make our Ceramic Cup a major contributor in hearth life extension and performance.

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REFERENCES

1. Jian Liu; Weidong Wang; Yin Fang; Ruitu Xu; Rusheng He; Yongguo CaO; Rory McNally; Stefan Basista, *Analysis of Performance of Ceramic Cup and Carbon Hearth Lining used in Shagang 5800 m3 BF*, 9th India International Refractory Congress in Kolkata, 02-04/02/2012.

2. F. Roulet, E. Jorge, N. Boumahdi, R. McNally, *Latest advances in refractory for blast furnace*, METEC Insteelcon Congress - Life extension of blast furnaces, 30/06/2011.

3. Peter Rüther, Michael Peters, *Requirements for a campaign life of more than 20 years at Blast Furnace 2 of ThyssenKrupp Steel Europe*, Proceedings *METEC Congress* & 2nd ESTAD conference, Düsseldorf, Germany, 2015.

4. Desai, B., Ramna, R. V., & Dash, S. K. (2006), *Optimum coke-free space volume in blast furnace hearth by wall shear stress analysis,* ISIJ international, 46(10), pp 1396-1402.

5. Nelson, L. R., & Hundermark, R. J. (2014), *The tap-hole'-key to furnace performance*, In Furnace Tapping Conference 2014, Johannesburg: Southern African Institute of Mining and Metallurgy, pp 1-32.

6. Raipala, Kalevi, *On hearth phenomena and hot metal carbon content in blast furnace*, Helsinki University of Technology, 2003.

7. J.L. Eymond, M. Picard, M.J. Venturini, S.A. Zaimi, C. Franssen, G. Masson, J.M. Dyrda, *MOTHUS: a thermal wear model for the hearth of the blast furnace,* The international ATS Steelmaking Conference. 9-10th of December 2004.

8. Zaimi, S. A., Campos, T., Bennani, M., Lecacheux, B., Danloy, G., Pomeroy, D., & Perez-Chust, R. (2009). Blast Furnace models development and application in ArcelorMittal Group. *Revue de Metallurgie*, 106(3), pp 105-111.

9. Huang, C. E., Du, S. W., & Cheng, W. T. (2008), *Numerical investigation on hot metal flow in blast furnace hearth through CFD,* ISIJ international, *48*(9), pp 1182-1187.

10. Shibata, K., Kimura, Y., Shimizu, M., & Inaba, S. I. (1990). *Dynamics of dead-man coke and hot metal flow in a blast furnace hearth*. ISIJ International, *30*(3), pp 208-215.

11. Zhang, Y., Deshpande, R., Huang, D. F., Chaubal, P., & Zhou, C. Q. (2008), *Numerical analysis of blast furnace hearth inner profile by using CFD and heat transfer model for different time periods*, International journal of heat and mass transfer, 51(1), pp 186-197.

12. Panjkovic, V., Truelove, J. S., & Zulli, P. (2002), *Numerical modelling of iron flow and heat transfer in blast furnace hearth*, Ironmaking & steelmaking, 29(5), pp 390-400.

13. Cheng, W. T., Huang, C. N., & Du, S. W. (2005), *Three dimensional iron flow and heat transfer in the hearth of a blast furnace during tapping process*, Chemical engineering science, 60(16), pp 4485-4492.

14. Post, J.R., Peeters, T., Yang, Y., Reuter, M.A., (2003), "*Hot metal flow in the blast furnace hearth: thermal and carbon dissolution effects on buoyancy, flow and refractory wear*", Proceedings of the 3rd International Conference on Computational Fluid Dynamics in the Minerals & Process Industries, eds. P.J. Witt and M.P. Schwarz, CSIRO Australia, 10-12 December, Melbourne, pp 433-440.

15. Rodi, Reduction of iron ores. *Effect of hearth liquid level upon blast furnace operation*, Stahlinstitut VDEh, Technical steel research, 2000, pp 1-193.

16. Lei Shao, *Model-based estimation of liquid flows in the blast furnace hearth and tap-hole*, Doctoral Thesis of Thermal and Flow Engineering Laboratory, Finland 2013.

17. James R. Post, Donna Tognarelli, Jan Van Der Stel. Yongxiang Yang, Markus A. Reuter, *Hot metal flow in the hearth of a blast furnace: influence of dynamic changes in dead man porosity due to coke dissolution and coke size changes*, Paper – 5th ECIC - full paper final, 2005.

18. González, R., Barbés, M. A., Verdeja, L. F., Ruiz-Bustinza, I., Mochón, J., Duarte, M. R., ... & Migas, R. (2011), *Mechanisms knowledge of the flow and wear in the blast furnace crucible with the nodal wear model*, Metallurgy and Foundry Engineering, 37(2), pp 123-132.

19. Hong-Wei Guo, Bing-Ji Yan, Jian-Liang Zhang, He-Lan Liang and Yi-Li Liu, *Influence of Hot Metal Flow State to the Hearth Flow Field during Blast Furnace Tapping*, Research Journal of Applied Sciences, Engineering and Technology, 6(13): 2409-2414, 2013.

20. Takeda, K., Watakabe, S., Sawa, Y., Itaya, H., Kawai, T., & Matsumoto, T. (2000). Prevention of hearth brick wear by forming a stable solidified layer. Iron & steelmaker, 27(3), 79-84.

21. Brulin, J. (2010), *Modélisation thermomécanique d'un creuset de haut fourneau*, Doctoral Thesis of Orleans University.

22. Maria Swartling, *A Study of the Heat Flow in the Blast Furnace Hearth Lining*, Doctoral Thesis of Stockholm 2010,

23. Zheng-jian LIU, Jian-liang ZHANG; Hai-bin ZUO, Tian-jun YANG, *Recent Progress on Long Service Life Design of Chinese Blast Furnace Hearth*, ISIJ International, Vol. 52 (2012), No. 10, pp 1713–1723.

24. Albert J. Dzermejko, *The End of Carbonaceous Blast Furnace Hearth Working Linings?,* AISTech Conference Proceedings, 2015.

25. Silva, S. N., Vernilli, F., Justus, S. M., Marques, O. R., Mazine, A., Baldo, J. B., … & Varela, J. A. (2005). *Wear mechanism for blast furnace hearth refractory lining*, Ironmaking & steelmaking, 32(6), pp 459-467.