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# A Refractory Wear Predictive Model Developed for BOF Converters

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**Original Research Article**

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**Abstract:** In order to contribute to the experience of the BOF operators, related with the wear of the refractory lining, a Wear Predictive Model (WPM) was developed. It is based on the database of many measurements made using a laser scanner. Not only this WPM model could be consider as a tool that supports decision such as doing a gunning repair or not, but also as guide to analyze changes in the initial refractory lining that led to a performance increase or cost reduction, for instance. The wear rate of MgO-C refractory lining depends on the material itself and the different erosive and corrosive agents present during the process. This WPM was developed in a BOF that do not operates with sub-lance, therefore the areas have been defined as the most critical ones are: barrel (B), tapping area (T), slag lines (horizontal ($SL_h$), vertical ($SL_v$) and the crossing of both ($SL_c$)) and trunnions (T). The results obtained after several scans along many lining campaigns have been tabulated for a subsequent analysis. As output of this statistic WPM, curves with minimum and maximum thickness have been drawn. These curves show two main areas: secure work (WS) operation area and risky work (WR) operation area. It is possible to define the impact of different operating parameters as well.
**Keywords:** Converter, refractory, wear, predictive model.

## INTRODUCTION

One of the most applied refining process of hot metal in the steelmaking is carried out in converters [1-3]. Hanna *et al.*, in [4], comment that over 350 BOF are in operation worldwide. In an environment of World over-capacity and low selling prices, survival of many steel plants has meant significant philosophical changes.

Reducing costs have been the only way the steel makers have been able to compete. The operating maintenance strategies applied vary depending on different points: regional trends, raw material quality, the plant layout, availability of secondary metallurgy facilities and the requirements of finished product.

In this paper, the three converters studied present a combination of top and bottom blowing, which is called combined blowing technology. A multi-hole lance inducing several spreading supersonic oxygen jets produces the top blowing. Simultaneously, inert gas (Ar, $N_2$) is blown through porous plugs (cooled/uncooled) in the bottom-lining to achieve stirring.

For BOF working lining, mainly affected by slag and metal corrosion, MgO-C refractory with about 18% carbon is used. Higher carbon reduces the strength but for such applications, corrosion is most important than strength [5].

However, strength is important for the charge pad of BOF where the liquid metal and all other steelmaking batch materials fall from height. An MgO-C brick with 9% or 10% of C is used in this bottom zone. Once the charging is completed, these refractories will be covered with the metal bath and protected respect slag corrosion. Low carbon results in relatively lower corrosion resistance, but in the bottom zone the slag attack is rare. The whole BOF hanging through metallic supports and effect of stresses due to the hanging condition occurred in the trunnion area (T). The stresses increase due to the vasculation movement of the BOF during steelmaking process [6]. For this reason refractories in these areas require strength and flexibility and the bricks used are MgO-C with 12% - 15% of carbon content. In the taphole area, the refractories are under the tremendous movement of molten metal during tapping. Corrosion resistance and mechanical strength are important in these areas and strong refractories containing 10%-12% of carbon are used for these application [6, 9].

The wear mechanisms of each zone of the BOF are complex and are caused by the combination of different factors: chemical attack, erosion, abrasion, effects of joint conditions and friction force caused by thermal stress (mainly in the zones of the barrel and cone of the converter). Some lining zones suffer wear faster than others do and therefore maintenance practice constitutes a relevant factor to prolong the BOF life.

Different maintenance practices with slag are carried out: slag splashing (which protects all the zones of the BOF), slag foaming (promotes the wall zone protection) and build up (that protects the bottom zone). In addition, various refractory products are applied. Gunning is a common practice for refractory lining maintenance, and it is considered very effective. However it is expensive [4-12].

A refractory mass with different size fractions and additives is forced under pneumatic pressure and placed on the desired area, using special equipment involving/with a mixer machine and gun. Control of where to gun and how much to gun is critical in controlling costs.

Laser scan is a very useful tool to evaluate the refractory lining evolution. To support the BOF operators, in relation with the wear of the refractory lining, a Wear Predictive Model (WPM), was developed. The model is based on historic measurements made using a laser scanner on the refractory lining of three BOF converters. This WPM model, is not only considered a tool that supports decision of when it is necessary to carry out/perform the gunning repair, it also constitutes a guide to analyze changes in the initial refractory lining that result in a performance increase or cost reduction, for instance. The wear rate of an MgO-C refractory lining depends on the material itself and the different erosive and corrosive agents present during the process. This model was developed considering BOF converters that do not operate with sub-lance. Five different zones have been defined as the most critical wear ones: barrel (B), tapping area ($T_a$), slag lines(horizontal ($SL_h$), vertical ($SL_v$) and the crossingof both ($SL_c$) and trunnions (T).Measurements results collected by laser scans along many lining campaigns were considered in the statistical analysis for the model development.

As output of this statistic WPM model, the curves with minimum lining thickness have been drawn. These curves can show to the operator two main areas in real time: secure work operation area (WS) and risky work operation area (WR).In addition, it is possible to observe the evolution of the lining during the campaign, to evaluate the wear rate ($W_{rate}$) at each zone of the lining, to control and decide the type of maintenance reparation necessary. It is possible to define the impact of different operating parameters as well.

## MATERIALS AND METHODS

The hanging of the BOF through metallic supports produces stresses concentration and causes damage in the trunnions area (T). The stresses increase due to the vasculation movement of the BOF during steelmaking process. For this reason, refractories in these area requires good mechanical strength and flexibility. One of the type of bricks that are extensively used in the trunnion area is MgO-C, with 12% -15% of carbon content.

In the taphole area, the refractories are under the tremendous movement of molten metal during tapping. Corrosion resistance and mechanical strength are important in these areas and strong refractories containing 10%-12% of carbon are used for these application [10].

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This model was developed considering BOF converters that do not operates with sub-lance. Five different zones have been defined as the most critical wear ones: barrel (B), tapping area ($T_a$), slag lines (horizontal ($SL_h$), vertical ($SL_v$) and the crossing of both ($SL_c$) and trunnions (T). Measurements results collected by laser scans along many lining campaigns were considered in the statistical analysis for the model development.

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The WPM model was developed for three BOF converters that operate with combined blown. The lining thicknesses are determined in different zones of the converters based on measurements made with a laser scanner at different time during the course of fifty campaigns. Nowadays, laser measurements constitute an important tool to control the MgO-C converter lining evolution and for operators it is a tool to decide the repair practice demands. However, the historic information collected is useful to predict the evolution of the refractory lining, to avoid the risk of infiltration and improve the maintenance practices program. Figure -1, shows the scheme of the measurements practice with the laser scanner equipment described in [13].

Currently measuring with laser equipment is the most used method to quantify the wear inside a converter. The method consists of using calibrated reference points and measured before starting up a rebuilt BOF. In a period established along the campaign the lining thickness is measured and compared with the original points values, corresponding to the refractory lining. Each point represents, in fact, an area portion of the inner surface of the furnace of about $0.2m^2$.

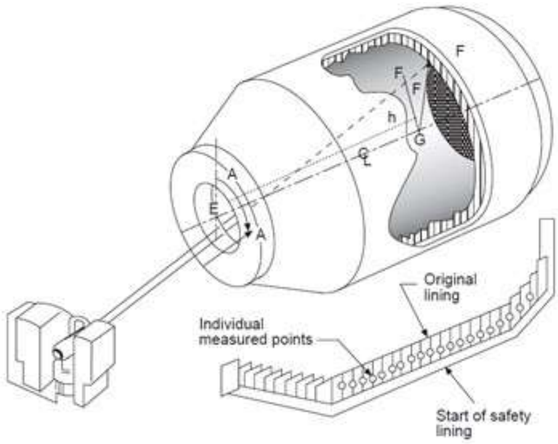


**Fig-1: Scheme of the measurements practice with the laser scanner equipment [8]**

Then, using a software, the results are analyzed to obtain the remaining thickness of refractory material in the area corresponding to each point. Once the measurement process is completed, a thickness map of the entire internal surface of the converter is obtained.

In this study, data of measurements carried out during fifty campaigns (around three operation years) of the three BOF converters were collected. The information was systematized according to a specific criterion and considering different zones of the converters that are assumed as critical because they suffer the worst wear conditions within the BOF and present specific wear mechanisms. Also, the industrial operation variables are take into account. For simplicity only results of the barrel (B) and the trunnions (T) zones are discussed in this paper.

During the converter charging period, a localized area of the barrel (load side) suffer the impact of the scrap and the hot metal, causing damage. However, wear also is present during tapping, because the slag cause corrosion, erosion and abrasion, on both the barrel and in the cone zone.

The four trunnions zones considered in this paper are: $TE_{SLh}$ (horizontal slag line of the engine side trunnion), $TE_{SLc}$ (crossing slag line of the engine side trunnion), $TC_{SLh}$ (conductive trunnion horizontal slag line) and $TC_{SLc}$ (conductive trunnion crossing slag line). In all the mentioned trunnion zones the wear mechanisms involve different factors such as oxidant atmosphere, corrosion and slag/metal erosion.

During blowing the turbulence caused by gases and metal also affect the refractory of the side walls. The slag constitutes a chemical corrosive agent that produces damage during all the conversion process.

**RESULTS AND DISCUSSION**

Converter is one kind of key equipment in steelmaking plant, the mass of a large capacity converter could over 2000t [6]. Converter work reliability decides the security and economy of steel production. To ensure the quality and yield of the steel, first of all ensure the safe operation of the converter equipment, especially the tilting part of the converter, it is not only the focus of the design converter and also the difficulty. The slag influent the converter deeply when the converter is tapping and sampling. The slag not only erodes the mouth of the converter, also different zones are damaged. The slag is a long distance from the trunnion centerline of the converter which has a great influence to the dumping moment. However, the slag is an important consideration when we design and operates the converter [7].

The end point control for converter steelmaking is important operation in converter smelting later stage, and the end point control level directly affects the production efficiency and product quality [8]. If the end point control not accurate, so smelting time will be extended, and the life of furnace lining will reduce, metal consumption will increase, steel quality will be affected. For this reason it is relevant to develop a tool to predict the end point and to control the converter evolution during the campaign. The WPM model constitutes one alternative.

**WPM model**

From the database of the wear critic zones selected for this study (barrel and trunnions) all the lining thickness values are mapped and evaluated. Applying a specific algorithm developed for this model, the minimum values registered are selected. For this purpose, an interval of 100 taps was considered. With the values obtained the minimum lining thickness curve is constructed applying a polynomial fit function and the accuracy is established by the determination coefficient ($R^2$).

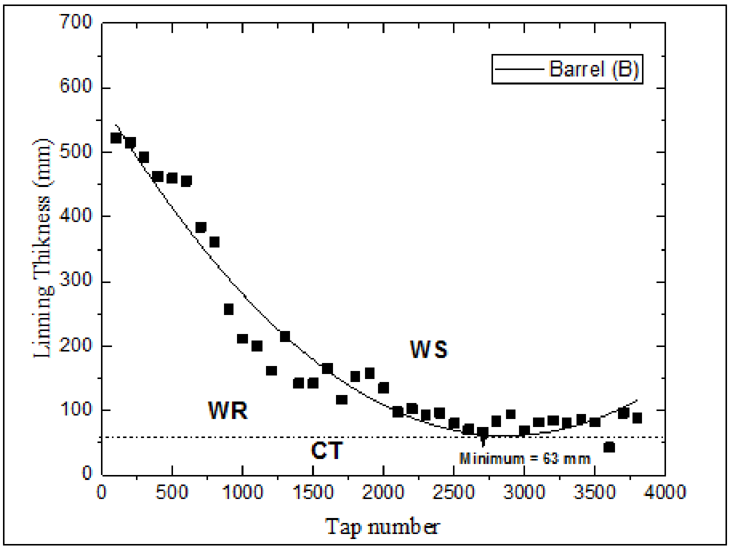


**Fig-2: Minimum lining thickness curve of the barrel zone (B)**

In Figure-2, an example of the minimum lining thickness curve pertaining to the barrel zone (B) is observed. The graph considers the thickness of refractory lining as a function of the number of taps. Similar curves are obtained for each zone of the converter.

The historic starting lining thickness in the barrel (B) of the BOF converters studied is around 700 mm. It is noticeable that the highest wear rate is produced up to ~ 2000 taps. The WPM model shows that the minimum historic lining thickness value of the barrel was 63 mm. This value also was also registered as the minimum lining thickness value of all the zones of the converters.

This value is assumed as a critic lining thickness value (CT) of the refractory lining that introduces the converter in a very risky operation condition. For security, the ~ 10% of the initial lining thickness is assumed as the BOF thickness lining operative limit (TOL). This value indicates the operators that a maintenance practice (such as gunning or slag foaming) is required.

It is important to mention that the curve obtained present a good fit and the statistic determination coefficient ($R^2$) includes > 97 % of the lining thickness values determined. The area above the curve could be defined as a secure work zone (WS). On the contrary, under the curve it is possible to establish a risky operation zone (WR). The operational risk increases as the thickness of the refractory lining approaches the critical value (CT).

In the case of the four trunnions zones, the minimum lining thickness curves are shown in Figure - 3. All of them, present a starting lining thickness value around 700 mm. The wear curves present a similar behaviour respect to barrel B.

It is observed that in the crossing slag line trunnions zones, the minimum values of thickness reached in the refractory lining are: 284 mm ($TE_{SLC}$) and 243 mm ($TC_{SLC}$). The crossing slag line trunnions, always present critic localized wear areas and they are frequently repaired. In the case of the horizontal slag line trunnions zones ($TE_{SLH}$ and $TC_{SLH}$), the minimum lining thickness values achieved are lower than the crossing slag line trunnions zones: 76 mm and 70 mm respectively.

If the predicted curve is shown "on line", the operators could easily check the lining evolution of the running campaign, to control the thickness of the refractory lining and to program the maintenance practices whenever it is necessary, avoiding the unnecessary risk of infiltration or the projection (gunning). In Figure -4: an example of one campaign evolution related to the barrel zone together with minimum lining thickness curve (predicted by the WPM model) is observed.

It is observed that in the campaign, the wear lining thickness evolution is under the predictable behaviour, the minimum lining thickness reached 93 mm at ~ 2926 taps. Maintenance practices was mainly carried out from the tap 2926 up to the end of the campaign (4145 taps) in order to avoid the lining thickness to decrease at lower thickness than the historic CT value. For higher safety, the operators decide the repair when the lining thickness is around the 10 % of the original lining thickness. The BOF operation is carried out in the WS zone of the curve, through all the campaign.

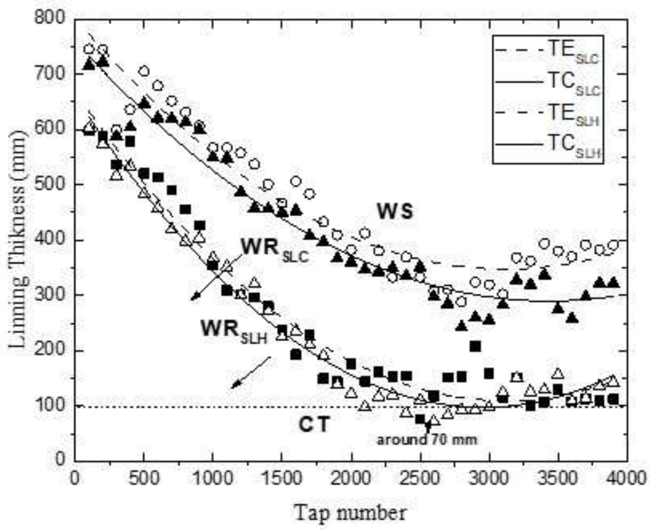


**Fig- 3: Minimum lining thickness curves of the trunnions zones**

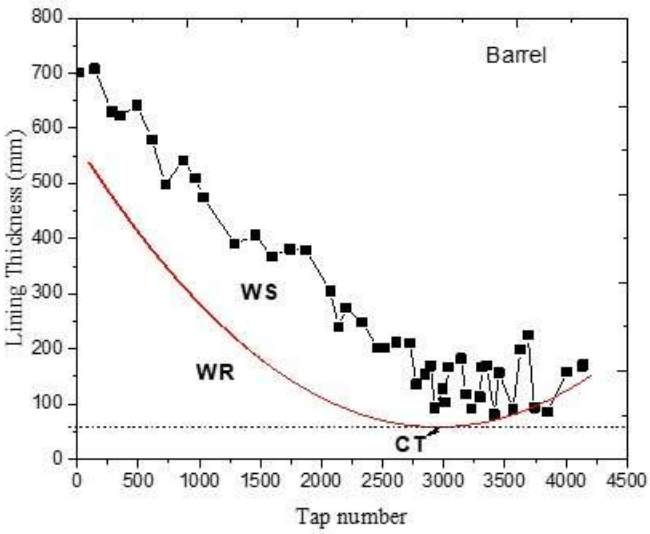


**Fig-4: Barrel lining thickness evolution during a running campaign**

The model also allows to predict the volumetric capacity variation of the converter. An excessive build up practice or gunning applied, results in a decrease of the converter volumetric capacity and in consequence a loss of performance is caused.

The wear rate also constitutes a good information to predict the lining thickness evolution. This value is particular for each zone of the converter. On the base of the thickness values and the tap number the wear rate ($W_{rate}$) in each zone, is established:

$$W_{rate} = \frac{dT_{min}}{dn} \quad (1)$$

where: $W_{rate}$= wear rate, $T_{min}$= historic minimum thickness and n= tap number.

The WPM model also predict the optimum wear rate in order to achieve the objective tap number, in the industrial plant. When the model is operating on line, all the converters critic zones could be observed simultaneously in the screen and the information provide the possibility to control the evolution of the lining thickness. In Figure -5, the information of the barrel, $TE_{SLH}$ and $TC_{SLH}$ evolution of the lining thickness is visualized. It is important to identify also the critical zone that is in the worst state, the $W_{rate}$ in each zone and the details of the repairs. Both trunnion zones ($TE_{SLH}$ and $TC_{SLH}$), present higher $W_{rate}$ than the barrel. In the trunnions, the repairs were carried out in the tap ~ 1500. However, the barrel was repaired around the tap ~ 2500.

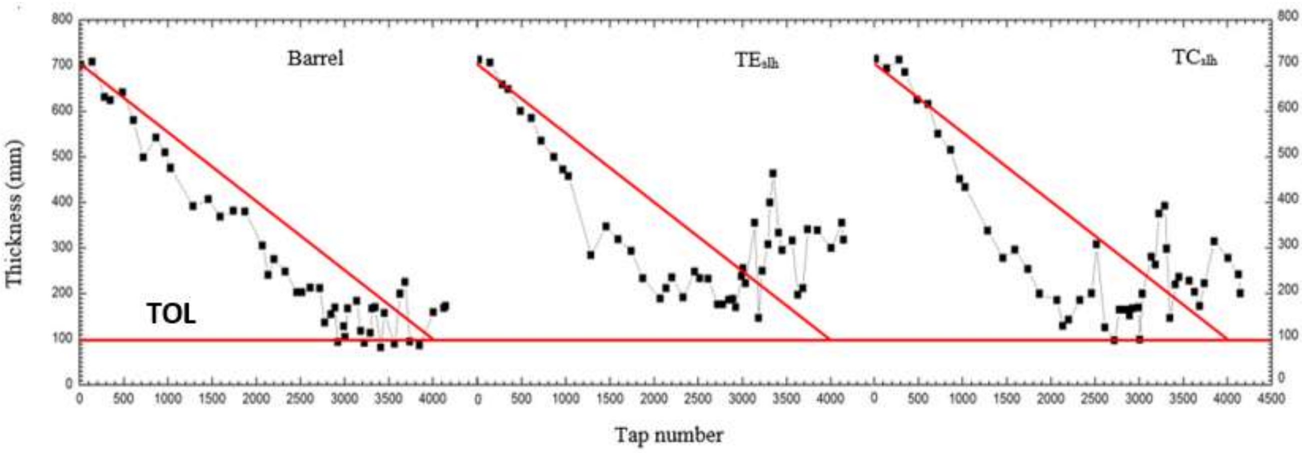


**Fig-5: Screen example that shows the evolution of the Barrel, $TE_{SLH}$ and $TC_{SLH}$ lining thickness**

The comparison of the lining thickness evolution allows to observe that in all the critic zones, the thickness values are above the critic thickness CT and the 10% of the original lining thickness. It is relevant to comment that in order to estimate the life of the refractory lining it is necessary to consider all the information obtained during the periodic measurements.

On the base of the initial thickness and historic evolution, the WPM model defines a BOF lining thickness operative limit (TOL). The information is introduced into the graph of "Thickness vs. Tap number". The intersection of the fit line with the critical thickness (CT) provides a "Tap number" that represents the refractory lining life expectancy ($L_E$) of the BOF converter. The life expectancy ($L_E$) could be predicted with and without repairs consideration. In (Table-1) the values without repairs ($L_E$), increment of life expectancy by repairs ($L_{ER}$) and total life expectancy ($L_{ET}$) are obtained for one campaign are observed.

**Table-1: Predictive life values of the BOF converter lining**

| CT (mm) | $W_{rate}$ (mm/tap) | % $R^2$ | $L_E$ (Tap Nº) | $L_{ER}$ (Taps) | $L_{ET}$ (Tap Nº) | $L_R$ (Tap Nº) | $e_{\%}$ |
|---|---|---|---|---|---|---|---|
| 70 | - 0.198 | 97% | 3027 | 1197 | 4224 | 4145 | 2 |

In this case, the estimated wear rate in the barrel is 0.198 mm/tap. Including the information of the repairs, WPM model predicts a total life expectancy: $L_{ET}$ = 4224 taps with e% = 2. It is observed that the real life ($L_{R)}$ of the converter during the campaign is 4145 taps. The end of this campaign was 79 taps prior the WPM prediction.

## CONCLUSIONS

The WPM model, based on historical laser scanning measurements carried out on three BOF along more than 50 campaigns, represents an important tool for the steelmaking operation, because it allows to control the wear in all the critic zones simultaneously. The visualization of the information “on line” allows the operators: to program the repairs whenever they are necessary, to evaluate the wear rate $W_{rate}$ in each zone of the BOF during all the campaign, to control the volume capacity of the converter to maximize the efficiency, to estimate the life expectancy $L_E$ of the BOF at the beginning of the campaign with a good precision ($e_{\%}$=2 and a determination coefficient $R^2$ that represent > 97% of the measurements).

The WPM model establishes two operation zones: a security work zone (WS) above the minimum lining thickness curve and a risky operation zone (WR) under the mentioned curve. It also determines the critic lining thickness (CT) that is the minimum thickness achieved in each zone historically. To avoid operation risks a BOF lining thickness operative limit (TOL), regarding the original lining thickness of each zone is defined.

The representation through graphs or tables facilitates the monitoring of the evolution of the life of the BOF converter and constitutes an intuitive tool, easy to use, that can be online during all production and can be displayed on any computer or mobile device.

Concepts such as wear rate ($W_{rate}$), critical thickness (CT), the lining life expectancy $L_E$ are relevant to plan and anticipate actions or decision making about the repairs. The information is provided by the model at the beginning of the campaign.

The model is quite accurate with a very low error $e_{\%}$= 2. It is for this reason that this tool provides an opportunity to improve the efficiency in the control of the wear of the refractory lining and contributes to the general control over the process in order to reduce the consumption of materials and energy.

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