ENHANCED PERFORMANCE OF BOF HOOD IN STEEL MILLS WITH COMPOSITE TUBE TECHNOLOGY *

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Abstract
Brazil is the largest producer of crude steel in the Americas by BOF process and many challenges come along with the increasing market demand. In the BOF, a tubular wall hood structure has been showing premature failures related to the overlay welded tube technology placed in the hood wall. The main root causes were: thermal fatigue at 1800°C, hot spot formation, high heat-affected zone (HAZ) leading to susceptibility of stress cracking, carburizing corrosion and superficial wearing. Based on that, co-extruded tube technology (named composite tube by Sandvik) was the alternative chosen to enhance hood performance without compromising BOF process. In order to rises safety and productivity, composite tube has 100% metallurgical bond assuring stable expansion, high heat exchange efficiency, better corrosion resistance and less rough surface finishing. It was highly suggested to many others mills due to similar and already existing reported cases.

Keywords: BOF Hood; Co-extruded tube; Composite tube.

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1 INTRODUCTION

According to Worldsteel Association annual report 2018 [1], Brazil is the third largest producer of crude steel by blowing oxygen furnace (BOF) process without considering China production chain.

The volume stated in table 1 considers crude steel production by BOF, which promotes the steel conversion removing carbon content by oxygen blowing technique. Brazil is placed behind Russia, Germany and slightly over United States capacity (Table 1). China leads the steel market roughly 16 times higher than the top country stated in the table ranking. In the Americas, Brazil is the largest producer and consequently plays an important role in the steel making market.

Table 1. Worldwide production

Crude steel	
Country	**Production (ton$_x$10^3)**
Russia	47 800
Germany	30 290
Brazil	26 654
United States	25 788
China	754 140

Source: Worldsteel Association 2018.

Brazilian crude steel production has increased 2,6% compared to the last year [2]. It is expected that internal market rises continuously from its crises faced in 2016 and new investments in technologies are accomplishing to take place in steel mills to support crude steel demand.

1.1 BOF

Steel refining is crucial to add value in the finishing product and one of the main process used in primary steel refining in Brazil is based on BOF, which is a vessel in the primary refining area aiming to convert molten pig iron into crude steel. It enables an efficient decrease in carbon (C) content level in the iron chemical composition based on a sequence of thermodynamic events that take place in the BOF.

Firstly, the ladle is pre-charged with qualified steel scrap. Then, molten pig iron from previous ore reduction process is poured inside the furnace. After charging, as a second stage, oxygen (O_2) is blown through a water-cooled lance from the top to promote oxidation of certain chemical elements in the pig iron composition, i.e. silicon (Si), carbon (C), manganese (Mn), sulphur (S) and phosphorus (P). At the same time, it is also injected argon (Ar) and nitrogen (N_2) gas to increase interaction mainly between C and O in the molten iron. These gases are injected to better reduce C content in the pig iron and convert it to crude steel by carrying %C as fume gases according to the equation (1).

The BOF principle generates mainly CO_2 gas that is conveyed through a hood.

$$C_{(\text{diluted in iron})} + O2_{(g)} \rightarrow CO_{2(g)} \qquad (1)$$

As a result of the increasing production demand, steel mills have pushed the production capacity to higher levels and consequently new incidents came along with

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its growth. Several unplanned shutdowns have happened in the hood tubular walls structure that is placed above the BOF.

The unsatisfactory performance has not to deal with BOF principle but with the technology used to manufacture tubes used in the hood structure. It basically consists of overlay welding technology to make a clad of stainless steel in the tubes surface.

The harsh environment is located at the hood higher temperature region where the overlay welded tubes are placed.

To better understand the premature failure, the following chapter will make an overview about the exhaustion process usually found in the steel mills.

1.2 Hood challenge

The reduction process results in an effective slag formation and high fume gases volume during the blowing time. The fume gas is then conveyed throughout the hood indicated as “Fume collection hood” in the figure 1.

For the entire blowing step, the ladle is placed underneath this hood to guarantee that fume gases (mainly CO and CO_2) and solid oxidized particles (FeM) are carefully carried outside the ladle. The hood structure is made of tubular walls to decrease the temperature of the fume gas by the heat exchange concept within cooling water circulating inside the tube.

The higher temperature experienced in the hood structure is located closer to the ladle. It reaches roughly 1800°C and it is where the overlay welded tubes are installed to withstand the failure mechanisms during blowing time.

Usually hoods structures are mainly made by wall tubes in low alloyed carbon steel placed in the upper region of the equipment and overlay welded tube with layer in alloy 625 (UNS N06625) placed closer to vessel.

The operators challenge come across with the premature cracks found in the overlay welded tubes due to some hypothesis, such as thermal fatigue, hot spot formation, high heat-affected zone (HAZ) and the corrosive gases with abrasive particles over tubes surface.

Despite safety concerns during operation, the investment on the respective overlay welded technology has been high but not efficiently relative to the performance target and expected by the operators. This study case aims to offer a much reliable technology to mitigate the failures found.

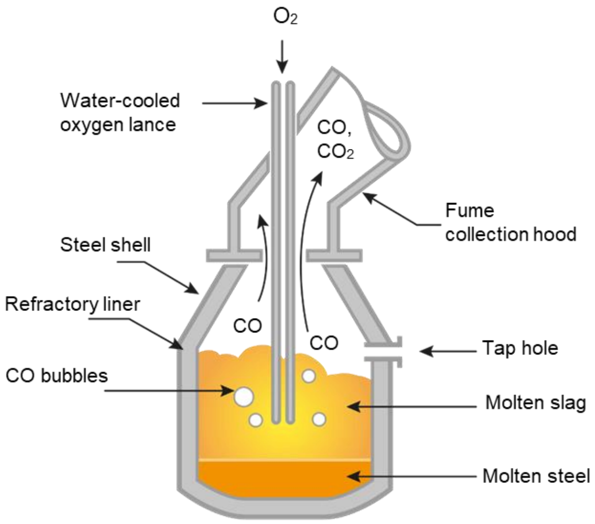

Figure 1. BOF oxygen blowing scheme (Author, 2019).

2 STUDY CASE

The hood structure made of overlay welded tube (alloy 625 – UNS N06625) was studied in a Brazilian steel mill which operated in the conditions listed below.

a) Tube temperature: ~290°C
b) Fume gas inlet temperature: 1800°C
c) Fume gas outlet temperature: 725°C
d) Water inlet temperature: 80-90°C
e) Water outlet temperature: 135-140°C
f) Overlay welded tube life expectancy: 10 years
g) First failure observed (overlay welded tube): 3 years, then every 1-year operation
h) Inspection plan: twice a year
i) Fume charc.: 71% CO, 16% N2, 12% CO2, 0,7% H2, 0,3% O2
j) Particles charc.: 67,1% FeM, 12,9% CaO, 6,41% SiO2, 13,59% MgO and others

After engineering fluid dynamics analysis (figure 2), some hypotheses were highlighted to explain these failures in the higher temperature area, at 1800°C. It was important to evaluate that the risks involving the process are high enough to start an emergency shutdown in the area, once there is cooling water circulating in the structure and a tiny leakage may cause explosions when water meets molten iron.

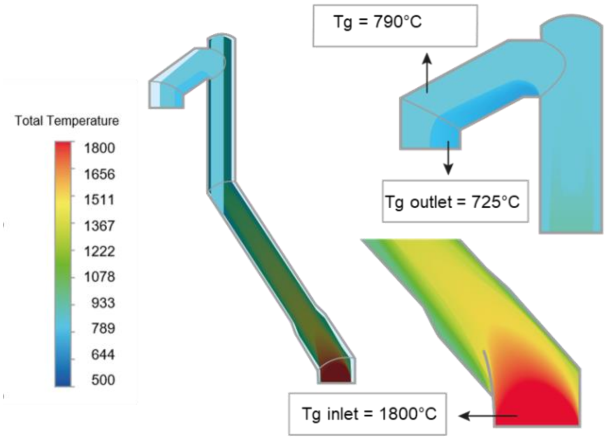

Figure 2. Hood CFD analysis (Author, 2019).

Once again, the investment on the respective overlay welding technology has been high and not efficiently relative to the expected by the operators. In that case, it did not justify such investment on an unreliable technology which demands high maintenance cost and resources to replace tubes after 3 years installation and continuously requiring inspection every semester.

2.1 Failures

Due to the characteristics of the area, the following topics guided us to evaluated some of the root causes. In figure 3, it can be seen the overlay welded tube before and after installation in (a) and (b), and the tube wall microstructure as a result of the overlay welding technique in (c).

a) Thermal fatigue was likely to take place due to intermittent blowing cycles
b) Corrosive oxidizing and carburizing gases together and abrasive particles wearing tube surfaces
c) Superficial imperfection and inclusion leading to hot-spot formation
d) High heat-affected zone during overlay welding coating increasing susceptibility to stress cracking
e) Steam side cracks because of chloride contamination and low-alloyed carbon steel with no chromium (Cr) in its chemical composition.

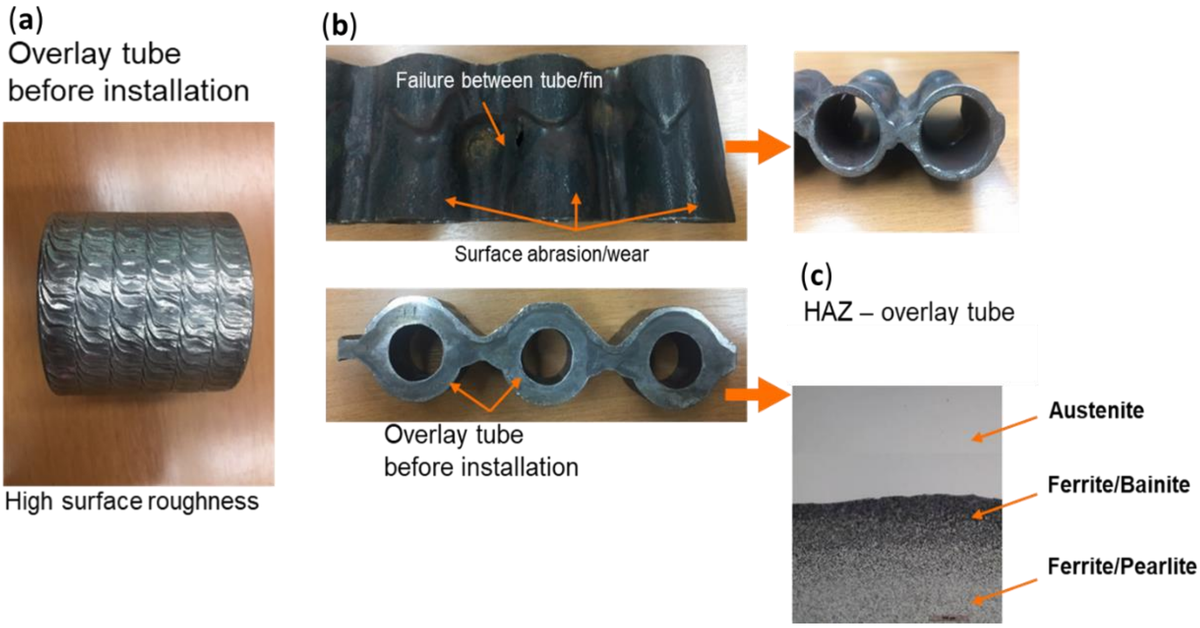

Figure 3. Images of the (a) rough overlay welded tube surface before installation; (b) its wearing surface after installation; (c) its 3 different microstructures because of overlay welding technology (Author, 2019).

3 CO-EXTRUDED TUBE TECHNOLOGY

Co-extruded tube technology was developed in the 70s due to increasing pressure of chemical recovery boilers and higher power efficiency. It is commercially called as *composite tubes* by Sandvik Company and are suitable for applications which the external and internal condition of the tubes requires different properties that cannot be met by only a single material.

The co-extruded technology consists of two different alloys metallurgically bonded to ensure good thermal transfer property. The nickel-based alloys or stainless-steel alloys are selected to resist corrosion over the external surface, while carbon steels are approved for use in pressure vessels and special structure stability.

The following diagram (figure 4) shows the production route of Sandvik technology in which the component in orange is the stainless steel clad and blue component represents the carbon steel alloy (1). After matching proper sizes and alloys, the billet with the 2 components is hot co-extruded through the extrusion matrix in the step (2), resulting in the composite tube hollow.

After co-extrusion, the outer stainless layer is cold pilgered in step (3) to reduce its thickness and reaches its wall tolerance level according to the customer need. Before final testing, the tubes are heat treated to re-establish its mechanical properties and meet ASME BPVC requirements. At the final step (4), Sandvik guarantees its metallurgical bond integrity by performing a non-destructive test (ultrasonic test) in 100% tube section.

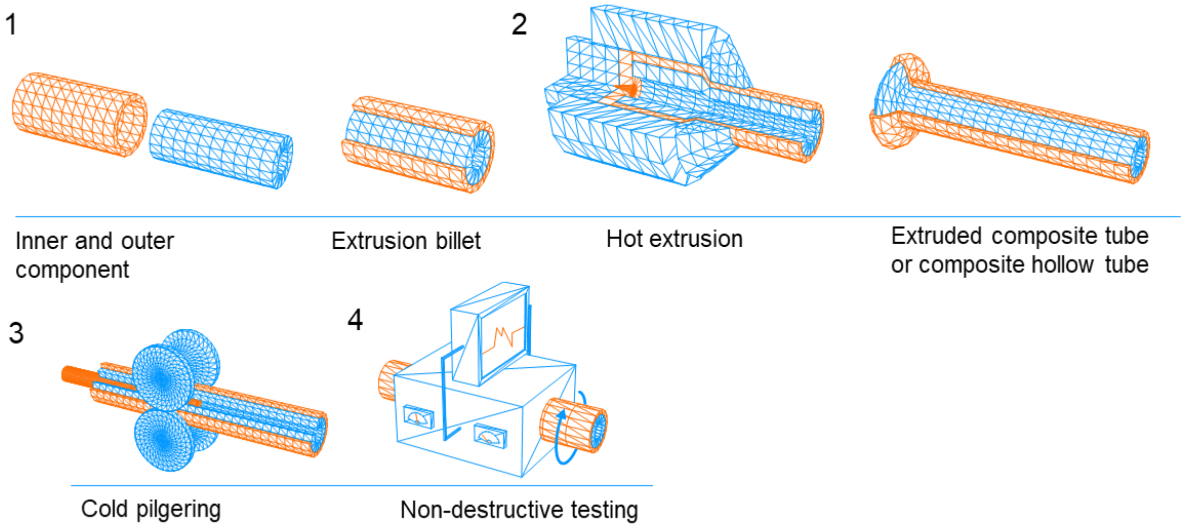

Figure 4. Sandvik production route diagram: co-extruded composite tube technology (Author, 2019).

As a result of the cold finishing surface, the final product has a smooth surface within easy cleaning and less risk of deposit over the tube. In fact, the ultrasonic test verifies the metallurgical bond, the absence of inside defects between layers, the absence of outside defects over its surfaces and it also measures the thickness of the inner and outer components. On the application point of view, the co-extruded tube presents better thermal transfer compared to overlay welding technology. The co-extrusion process results in very limited diffusion of chemical content and lower alloy dilution in the bonding area.

The bonding zone is the main reason of such great worldwide performance along many years, as recorded by Sandvik.

In the microstructures (figure 5), it is able to compare both bonding zone of the two different technologies. On the left (figure 5 (a)), the overlay welded tube microstructure presents many unbonded areas between the deposition of stainless layer and carbon steel component. Besides, there is a layer in light grey color between both materials corresponding to high dillution of chemical elements during weld deposition. This area can be considered as a third microstructure, with different properties along the tube length. It usually happens because of high heat input set to build up the stainless layer during overlay welding procedure.

For all these reasons, overlay welded tube technology would preferably affects the product performance.

On the other hand, co-extruded composite tube technology (Figure 5 (b)) is 100% ultrasonic tested to ensure that any voids and unbonded zone is found between layers. As it does not involve any steel melting, the co-extruded technology presents very limited dilution during its manufacturing.

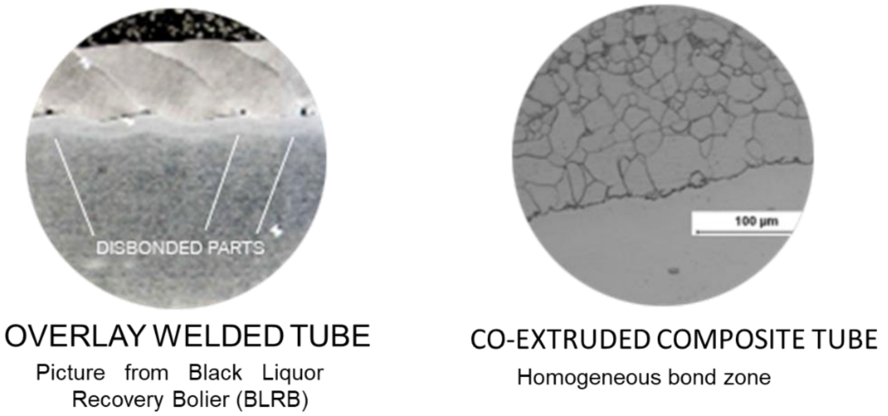

Figure 5. Comparison between bonding zone of overlay welded tube and co-extruded composite tube technology (Author, 2019).

Besides the previous analysis, it can be seen in figure 6 (a) the uneven layer of overlay welding over the carbon steel and the surface finishing. It helps to promote hot spot formation along the tube surface, which is described as one of the main root causes of hood failures.

The uneven layer may affect the thermal conductivity and promotes an unbalanced thermal expansion due to the thickness difference in carbon and stainless steel. Risks of stress cracking may also increase because of distinct stress behavior of each material.

As a contrast, the figure 6 (b) shows a consequence of no melting, low diffusion and mixing of alloys. Sandvik co-extrusion process results in a straight, continuous and cohesive layer, overcoming all negative effects created by overlay welding technology.

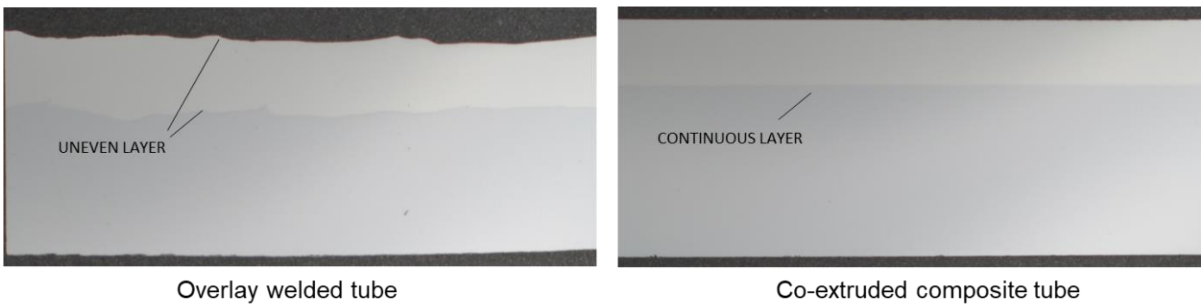

Figure 6. In (a) Overlay welded tube layer and (b) Sandvik co-extruded composite tube (Author, 2019

Based on the hood failures, the next chapter covers the alloy selection and proposal to withstand the mechanisms described as root cause induced by overlay welding technology.

4 MATERIAL SELECTION

Firstly, it was checked the carbon steel component comparing with the carbon steel already used in the steel mill. The table 2 shows the chemical composition of the seamless carbon steel tube in use (DIN 14175 St35.8) and other three different seamless carbon steel tubes (ASTM SA210-A1, ASTM A213-T22 and ASTM A213-T91) as options to replace the already existing grade.

As the process does not generates high stress due to steam pressure inside the tube, the selection of the carbon steel layer was guided by the chromium (Cr) and molybdenum (Mo) content aiming to face corrosion attack on the steam side. Cr and Mo are the most important chemical elements capable to increase halogens corrosion resistance and specially increase the resistance of chloride contamination in the steam/water. In table 2, the grades A213-T22 and A213-T91 were the proper candidates to be alternatives to this application.

Table 2. Nominal chemical composition of carbon steel grades

Carbon steel grade	C	Si	Mn	P (max)	S (max)	Cr	Ni (max)	Mo	Others
DIN 14175 St 35.8	≤0,17	0,1-0,35	0,4-0,8	0,04	0,040	-	-	-	-
SA210-A1	0,21	0,3	0,7	0,03	0,015	-	-	-	-
A213-T22	0,10	0,3	0,5	0,02	0,020	**2,3**	-	**1,0**	-
A213-T91	0,10	0,4	0,5	0,02	0,010	**8,5**	0,4	**1,0**	V, Nb, N

Source: ASME BPVC II Part B, 2017 [3].

In terms of high stainless steel performance, it was compared the chemical composition of alloy 625 (UNS N06625) with Sandvik Sanicro 67 (UNS N06690) in the table 3. The same chain of thought was adopted to choose the grade, aiming to face corrosion mechanism with higher Cr in its chemical composition.

Sanicro 67 (UNS N06690) with 30% Cr was selected to increase corrosion resistance against the oxidizing and carburizing gases [4].

Table 3. Nominal chemical composition of stainless steel grades

Stainless steel grade	C	Si	Mn	P	S	Cr	Ni	Fe	Nb
Alloy 625 (UNS N06625)	0,0025	0,2	0,15	≤0,015	≤0,015	21,5	61	4	3,5
Sanicro 67 (UNS N06690)	0,0200	≤0,5	≤0,5	≤0,020	≤0,015	30,0	60 (bal)	10	-

Source: ASTM A312, 2017 [5].

Most of the cracks found in the interface tube-fins showed in figure 3 (b) were also related to the tube physical properties and its behavior within the intermittent cycles.

Sandvik co-extruded composite tube behaves like one single material granted by the metallurgical bonding strength. The diagram on the left (figure 7 (a)) shows carbon steel 4L7 (SA210-A1) in grey with better structural stability compared to stainless steel Sanicro 67 (UNS N06690) in blue line, as expected. However, when both alloys are bonded by co-extrusion, the tube acts like unique product with intermediate profile and closer to carbon steel curve (orange curve). It means that in terms of thermal expansion, co-extruded tube has great resistance to stress cracking mechanism by not compromising the entire fin-tube hood design within its controlled expansion.

In diagram on the right (Figure 7 (b)), the same intermediate behavior is seen but now in terms of conductivity. It can be read as the higher the curve is, the better thermal conductivity is reached. During the BOF operation, it is aimed to lower the gases temperature during the blowing cycle, so good heat exchange is needed and can be achieved by co-extruded technology.

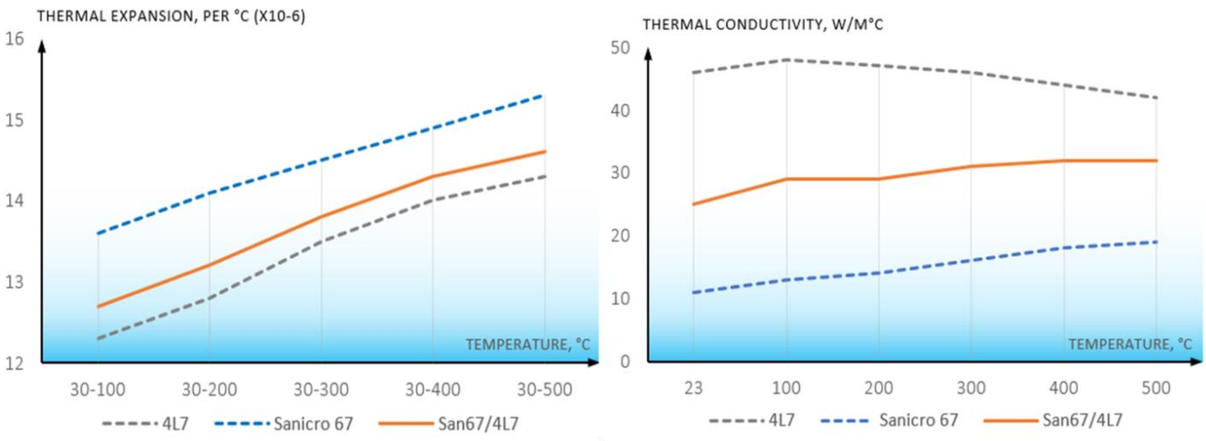

Figure 7. Sandvik co-extruded tubes performance regards (a) lower thermal expansion behavior and (b) good thermal conductivity (Author, 2019).

Composite tube in Sanicro 67 (UNS N06690) with 4L7 (SA210-A1) will be installed in the current steel mill studied to increase safety and equipment performance. It is highly suggested to many others mills due to already existing reported cases with the same premature failure.

5 CONCLUSION

In the Americas, Brazil was shown as the largest producer of crude steel by BOF process. As a result of the increased demand of steel, premature failures have appeared in the overlay welded tube placed in the hood structure.

Overlay welded tube was shown as a significant cost technology to be implemented with no satisfactory performance to what was expected in terms of lifecycle. Besides, safety concerns were one of the key highlights from the operators, in which any leakage would result in explosions and emergency shutdown. In this paper, the root causes related to the overlay welding technology were: thermal fatigue, hot spot formation, high heat-affected zone (HAZ), carburizing corrosion and superficial wearing.

Co-extruded tube technology (Composite Tube) was the alternative chosen to enhance hood performance without compromising BOF process. This technology consisted in a very high-quality product guaranteed by its early success in boilers applications since 70s. It was assured by the production route of Sandvik, the great resource of extended lifecycle in the market encouraged this technology implementation in the hood structure.

Composite tube showed a smooth surface finishing tube, high controlled metallurgical bond verification by UT test in 100% of the tubes and its structural stability. Based on the application requirements, this paper proposed composite tube technology in Sanicro 67 (UNS N06690) stainless steel layer and 3 different options of carbon steel component to be chosen depending on the process characteristic.

Overall, composite tube was higly recommended to this application aiming to increase operator’s safety, higher BOF productivity and rise equipment efficiency to continuosly meet market demand.

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