A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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EAF-FOAMY SLAG IN STAINLESS STEEL PRODUCTION NEW EXTREMELY EFFICIENT TECHNOLOGY EASY TO HANDLE AND COST-EFFICIENT

PIENIĄCY SIĘ ŻUŻEL PRZY PRODUKCJI STALI NIERDZEWNEJ W PIECU ŁUKOWYM NOWA NIEZWYKLE SKUTECZNA TECHNOLOGIA ŁATWA W OBSŁUDZE I OPŁACALNA

Economy of the electric arc furnace technology is strongly dependent on the efficiency of electrical energy introduced into the metal bath. Slag foaming practice for carbon steel grades has since long time its daily application but for stainless steels not successfully yet. Production cost lowering is achieved by improved thermal efficiency and operation conditions by stabilizing of the arc activity. In consequence of such technology the refractory and electrode consumption as well as noise level is perceptible decreased.

All these effects can be now achieved at the stainless steel production thanks a new patented technology of SMS Demag AG / Germany developed in common work with the AGH-University of Science and Technology in Krakow /Poland and tested industrially by Acesita S.A./ Brazil.

The new technology distinguishes fundamentally in comparison with all known applied and trialled technologies working on the basis of injection procedure. The special prepared briquettes are used as reacting agent on the slag and metal phase boundary forming carbon monoxide and dioxide necessary for the foaming effect. This idea was first tested in laboratory at EAF conditions. Suitable viscosity of the slag was tested according to the normal production conditions.

Controlled high foaming level covering completly the electric arc allows application highest transformer taps resulting in longer electric arcs and high temperature gradient in the range of 13–14 K/min.

Keywords: EAF-stainless steel, foamy slag, briquettes, foaming control

Ekonomia technologii wytapiania stali w elektrycznym piecu łukowym silnie zależy od wydajności energii elektrycznej dostarczonej do kąpieli metalowej. Praktyka pienienia żużla dla stali węglowych jest stosowana od dłuższego czasu, natomiast dla stali nierdzewnych jeszcze nie. Zmniejszenie kosztów produkcji osiągane jest poprzez polepszenie sprawności cieplnej i warunków sterowania przez stabilizacje aktywności łuku. W konsekwencji tej technologii zużycie elektrod i wyłożenia ogniotrwałego, jak i poziom hałasu jest dostrzegalnie zmniejszone.

Wszystkie te efekty mogą być teraz osiągnięte przy produkcji stali nierdzewnej, dzięki nowo opatentowanej technologii SMS Demag AG przy współpracy z Akademią Górniczo – Hutniczą w Krakowie i przemysłowo przetestowanej w Acesita S.A. w Brazylii.

Nowa technologia różni się zasadniczo od znanych stosowanych i próbnych technologii, bazujących na procesie wdmuchiwania. Specjalnie przygotowane brykiety są stosowane jako czynnik reagujący na granicy fazowej metalu i żużla, tworząc tlenek i dwutlenek węgla, konieczne do efektu pienienia. Pomysł ten najpierw był testowany w laboratoryjnym piecu łukowym. Odpowiednia lepkość żużla była testowana z uwzględnieniem warunków produkcji.

Kontrolowany poziom wysokości pienienia całkowicie przykrywającego łuk pozwala na stosowanie wyższych zaczepów transformatora w rezultacie zwiększając długości łuku i gradient temperatury w przedziale 13–14 K/min.

1. Introduction

Since many years the foaming slag practice in the EAF is well established in low alloyed steel production. It improves thermal efficiency of the melting, lowers refractory and electrode consumptions, and provides a stable arcing at lower noise level. Good foaming effect is

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attainable by suitable slag viscosity strongly affected by iron oxide content in the slag as well as permanent iron oxidation and iron oxide reduction by injected oxygen and carbon into the metal bath and slag, respectively. In case of high alloyed steels with high chromium content the preconditions for slag foaming effect are diametrically different. Oxygen injected into the steel produces mainly chromium oxide with totally different properties in comparison with iron oxide, it changes significantly the slag viscosity. The solubility of chromium oxide in the slag is considerable weaker in comparison with that of iron oxide at the same thermal and basicity conditions. Also the reduction of chromium oxide by carbon does not attain such intensity as the reduction of iron oxide. The gas generation is poor. The oxygen/carbon injection technique in the high chromium alloyed steel production is due to the chemical and physical conditions evidently hazardous and difficult in operation. The risk of uncontrolled oxidation of chromium is pronounced, resulting in high chromium losses and poor foaming.

In common development of the SMS Demag AG / Germany, Acesita S.A. / Brazil and the AGH-University of Science and Technology in Krakow / Poland a new sophisticated technology of foaming slag has been invented and laboratory as well as industrially successfully tested. Further application found place latest at the EAF of SMS II Jindal Stainless Ltd./ Hisar, India.

The novel technology distinguishes principally from the conventional one, which uses injection of oxygen and carbon via manipulator lances. The new technique bases on the reduction of iron and chromium oxide by carbon as well as on the thermal dissociation of lime stone contained in small briquettes. Specific density of briquettes is assorted to have value between slag and metal. Introduction into the melt causes placing exactly on the slag and metal boundary - optimal place for the requested gas generation.

The aim of this project was to establish adequate forms and chemical compositions of materials for effective slag foaming with high chromium oxide content as well as to define optimal slag conditions. The supposed materials contain iron oxide scales, carbon carriers, and high-carbon alloys typical for stainless steel production. As ballast, for the purpose of briquette density control, iron alloys or scrap as well as possible calcium carbonate or fluorite combined with some binding agents were taken into consideration. Besides of these features different sizes of briquettes or pellets were considered.

2. Sophisticated idea of slag foaming formation

Two factors define the foamy slag formation: the foaming material with the corresponding reacting components, which produce gaseous products, and the slag viscosity dependent on the chemistry and temperature. A liquid slag is for the foam formation a prerequisite.

The principal reaction that creates gas bubbles in the slag is the reduction of iron and chromium oxides according to the reactions:

$$(\mathrm{FeO}) + C_{particle-or-dissolved} = [\mathrm{Fe}] + \{\mathrm{CO}\} \quad (1)$$

$$(\mathrm{Cr_2O_3}) + 3C_{particle-or-dissolved} = 2[\mathrm{Cr}] + 3\{\mathrm{CO}\} \quad (2)$$

The reaction (1) is the principle in carbon steelmaking and iron oxide is the major component in the slag. When the slag viscosity is suitable for sustaining foam, then the simple carbon injection into the slag causes the foaming effect. Other situation is in case of stainless steel slag. The major components are CaO, SiO_2 and Cr_2O_3. The SiO_2 is a fluxing component, while the Cr_2O_3 stiffens the slag. Due to the higher chromium affinity to oxygen the Cr_2O_3 generation takes place preferentially in comparison with FeO. Therefore it is important to control the chromium oxide content and the slag basicity, responsible for the viscosity, which constrains gas bubbles to temporary detainment in the slag layer.

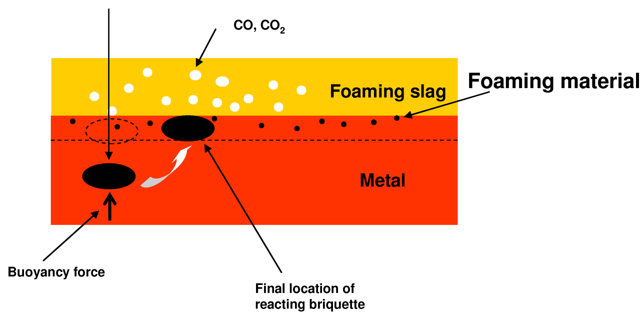

Fig. 1. Principle of foaming slag formation by briquette

The bubble forming phenomenon is a process of formation new surface area by the mechanical force resolved by reaction gas. In the presented technology this gas is an effect of the reduction reaction of metal oxides by carbon taking place in a briquette or pellet introduced into the metal bath. Buoyancy forces of bubbles crack the slag surface saturating temporarily the top layer and create the foam. With a sustained gas flow coming from the reacting briquettes the population of the bubble aggregation as foam continues to grow. As a consequence of it, the height of the foam layer increases. Important for such mechanism is the optimal placing of the briquettes to get the maximum foaming effectiveness. It is the boundary between the slag layer and liquid metal. With the control of the briquette density, corresponding to the range between that of slag and metal (3–7 m^3/t)

such placing is always reachable. The foam height increases with the increase of the gas flow rate; it is directly proportional to the foaming material rate. Figure 1 illustrates the principle of the slag foaming.

3. Theoretical considerations. Laboratory test. Results

The aim of this laboratory experiment was to establish adequate forms and chemical compositions of the materials for effective foaming of high chromium oxide slag. The materials were supposed to contain iron oxide scales, carbon carriers, and high-carbon ferrochromium as weighting agent as well as possibly calcium carbonate as additional producer of gas for foaming process. As to the form of the foaming materials either briquettes or pellets of different sizes were considered. Furthermore, the research study was carried out by making laboratory heats, sampling metal and slag phases for chemical analysis in order to optimize the foam ability.

In the first stage of the work, the most promising materials for foaming were the subject of theoretical considerations. A model for computation of the specific densities of the foaming mixtures was applied.

In the second stage of the work, the foaming mixtures were prepared in forms of briquettes and pellets of different sizes. A number of 40 heats were performed in a laboratory arc furnace to investigate the impact of various parameters on the height and stability of the generated foams.

In the third stage, the obtained experimentally results were analysed and the final conclusions and technological recommendations as to the optimal conditions for the slag foaming were established.

Figure 2 illustrates the test stand consisting of a single-electrode EAF with conductive bottom. The furnace was powered by a transformer, 75 kVA rated power, supplied by a voltage of 380 V. The total melt capacity was 5kg. Tested metal was prepared from about 1.5 kg of AISI 304 scrap. After the scrap melting, an industrial slag of defined composition and weight, approx. 3 kg, was added and melted accompanied by samplings for metal and slag chemistry, s. Table 1. The temperature was controlled close to 1600°C, the initial height of the slag recorded and the foaming mixture in small batches added into the furnace; Since the foaming initiation until the cease of the foam, the slag height and the foaming duration were being measured. The measurement was done by immersion of a tungsten bar until it got the crucible bottom. After taking out the bar, the height of the solidified slag was read out; the reading was supposed to be equal to the foamed slag height.

Fig. 2. Laboratory EAF – Test stand

TABLE 1

Chemical composition of the slag

Chemical composition, %						
CaO	SiO_2	FeO	MnO	MgO	Al_2O_3	Cr_2o_3
40.33	30.21	5.11	5.44	7.80	8.42	11.86

The total duration time of the foaming process after slag melting was within 7 to 14 minutes range. When the foaming process was over, sampling of the slag was done again and the metal with slag was tapped into a mould. After their solidification the metal as well as slag was weighed.

Two forms of foaming material were applied: briquettes and pellets. The briquettes were made by compression of a powdered charge material by means of a specially designed press device. The diameter of this way produced briquettes was 30 mm, the height was within 15– 17 mm range. They weighed within 50–70 g range. The pellets were made in a drum by pelletizing powdered materials with added molasses as binding agent. Two kinds of the pellets (2–5 mm and 8–10 mm) were sorted and further applied in tests.

The investigations were performed for the foaming additions composed of stoichiometric amounts of Fe_2O_3 and C-graphite. The specific density of this foaming material component is presented in the Table 2.

TABLE 2

Calculated specific densities of the foaming materials

Foaming material	Material
Foaming material composition	7-18%C- 30–40% Fe_2O_3
Specific density, [g/cm^3]	3.8–4.2

The results of the slag foamability dependent on the kind of used material are illustrated in diagram, Fig. 3.

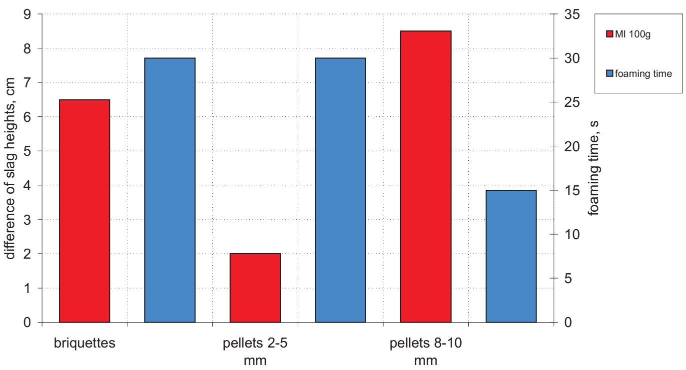

Fig. 3. Differences of slag heights for different forms of foaming material

Results indicate that one gets the highest foamability for the pellets of a 8–10 mm diameter, while the lowest one for those of a 2–5 mm diameter. The effect is due to the fact that small pellets do not sink in the slag layer but float up to the slag surface. The phenomenon is caused by the interfacial tension forces at the pellet/liquid slag boundary. While floating on the slag surface, the bubbles formed in the pellets do not go into the slag layer but they go into the ambient atmosphere. For pellets the foaming time was lower than this for briquettes. It can be explained by the kind of their structure. Briquettes are compressed materials, of lower porosity. Decreased contact surface with liquid slag causes slower heat transfer slower reduction of the iron oxides in the briquettes and in consequence lower gas rate. Only briquettes were selected for industrial examination.

4. Industrial test by Acesita S.A. Procedure. Results

On the base of the above described laboratory test ACESITA S.A. and SMS Demag AG have agreed a common industrial test of foamy slag at high Cr-oxide in an EAF to prove its industrial functionality as well as viability. The test was carried out in the EAF #3 in the steel plant in Timoteo / Brazil. The EAF-AC with the capacity between 25-35t and transformer of 32 MVA is designed for pre-metal production of austenitic and ferritic steel grades in common operation with the down stream operating 80t AOD-L and MRP-L converters.

The test, integrated with the current production consisted of 45 austenitic and 15 ferritic steel heats. 40 heats were tested corresponding to the technological variant 1, s. Fig. 4. The variant 1 distinguishes from the normal operation, where oxygen is blown during the whole super-heating period. The reason of such procedure was to separate the oxygen effect on the carbon and metal oxidation, additional generation of CO bubbles, as well as impact effect of the gas stream. The residual heats were tested under normal operational conditions by variant 2.

The EAF #3 works with a power divided into 9 taps. The tap 28 with arc length between 15.5–21.5 cm allows work with the maximal power and is used generally in the first melting stage only. Because intensive energy radiation on the furnace walls during the super-heating period, where metal bath is flat, a protected operation is requested e.g. short electric arcs. In operational standards the lowest taps between 20 and 23 with the arc length of 10–16.6 cm are applied. High level of foaming slag, above the electrode tips, allows operations with higher taps shorting the tap to tap time. The real temperature growth rate was estimated at approx. 12–14 K/min at the tap 28 against 6–7 K/min at the tap 23, 24.

As foaming material briquettes with changed composition in comparison with the laboratory test were used. The ballast function of FeCrHC was substituted by fine shredded steel scrap. The briquettes were made from mixtures consisting materials shown in Table 3 while its size is shown in Fig. 5.

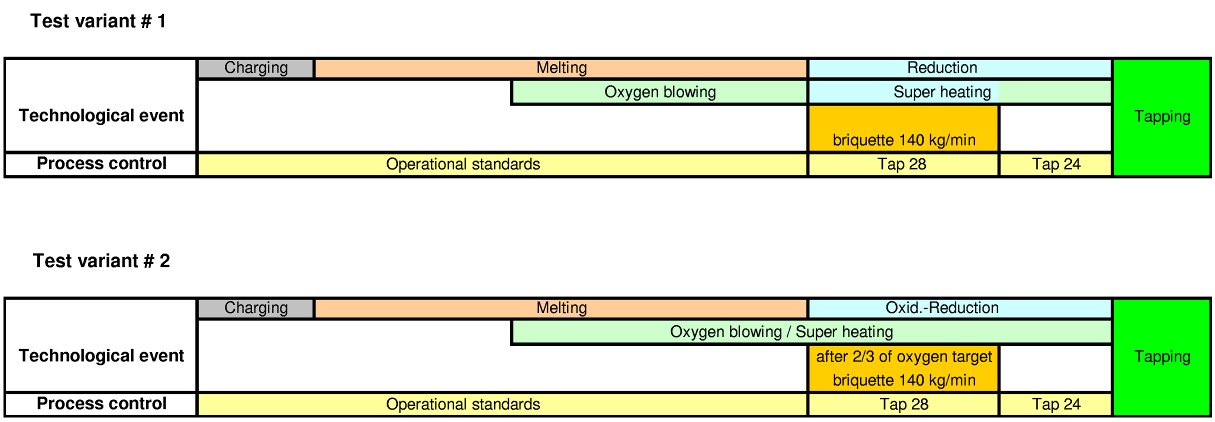

Fig. 4. Scheme of test variants

TABLE 3

Briquette compounds

Material
Scall CCM
Coke
Limestone
Fine scrap
Binder
Real density 3.8–4.2 t/m^3

Fig. 5. Briquette size

Briquettes were added into the furnace via 5th hole with controlled addition speed. Each test heat was recorded by video camera and documented by metal and slag analysis before briquette additions and at the tapping. Simultaneously to the metal sampling the temperature were measured. For the purpose of noise measurement developed during the foaming period and comparison with standard operations some heats were recorded continuously by a portable sonic measuring device. Besides these measurements each heat was characterized by voltage, current, energy consumption, power, cos ϕ and by the tap number. Figure 6 illustrates the observation stand in the front of the EAF #3. As the test results show, the foaming of a Cr_2O_3 rich EAF slag is a difficult but under controlled slag conditions possible task. Results of this industrial test confirm the correct recipe of the foaming material and the optimal reacting place of the briquettes. Further experiences of the test show also dependences between the initial slag amount and its foamability. Intensive gas development in combination with the slag mass and the desired low viscosity allows slag generations with sufficient height for complete cover of the electric arcs. The optimal initial slag amount fluctuates in the range 68–72 kg/t$_{steel}$. Figure 7 illustrates areas of slag composition after briquette additions. It can be seen, that most of slags were well reduced. The average residual Cr_2O_3 in the slag was indicated by 4.2%. Also the basicity in the range 1.3–1.35 was established as optimal. This part of the slag system must be considered to be the optimum area. The viscosity in this part is low, however, partly undissolved lime and higher Cr_2O_3 content increases the viscosity. Figure 8 illustrates a typical slag height development of a AISI 304 heat. The slag heights were measured with a reference to the electrode diameter.

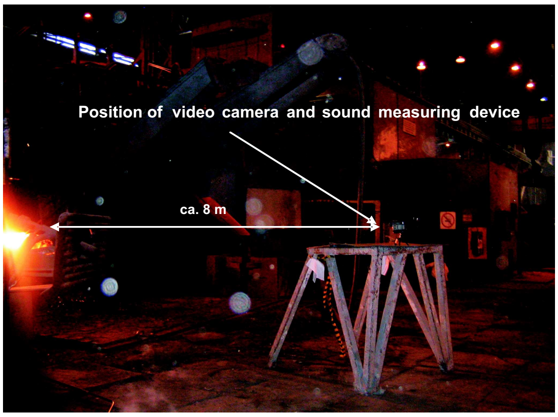

Fig. 6. Test observation stand

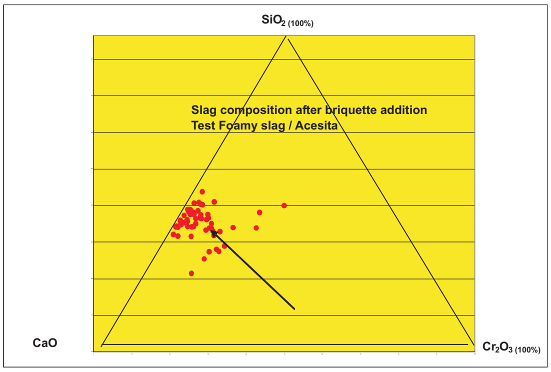

Fig. 7. Standardized slag diagram

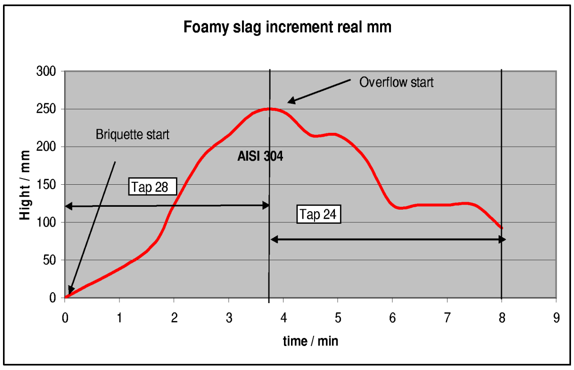

Fig. 8. Slag height course

As the curve shows, after approx. 2 minutes the slag reached the adequate height suitable for the electric arc cover. During the next 4 minutes this level was established, leaving the required range after 4–5 minutes. It should be mentioned, that since the 3.5 minutes an overflow of the slag through the furnace door was observed. The slag mass was relating to this continuously reduced until a stable level was reached. It was observed in other tests with oxygen blowing, that the oxygen stream support in the receipt of the foaming layer. In view on the electrode consumption the foamy slag has an undisputed significance. Figure 9 illustrates by secondary voltage the electric arc behaviour in a standard operation and in the presence of foaming slag operation. Small signal fluctuations, low level of amplitudes lowers mechanical and thermal electrical tensions. In consequence of such courses the level of noise generation is also significantly lowered.

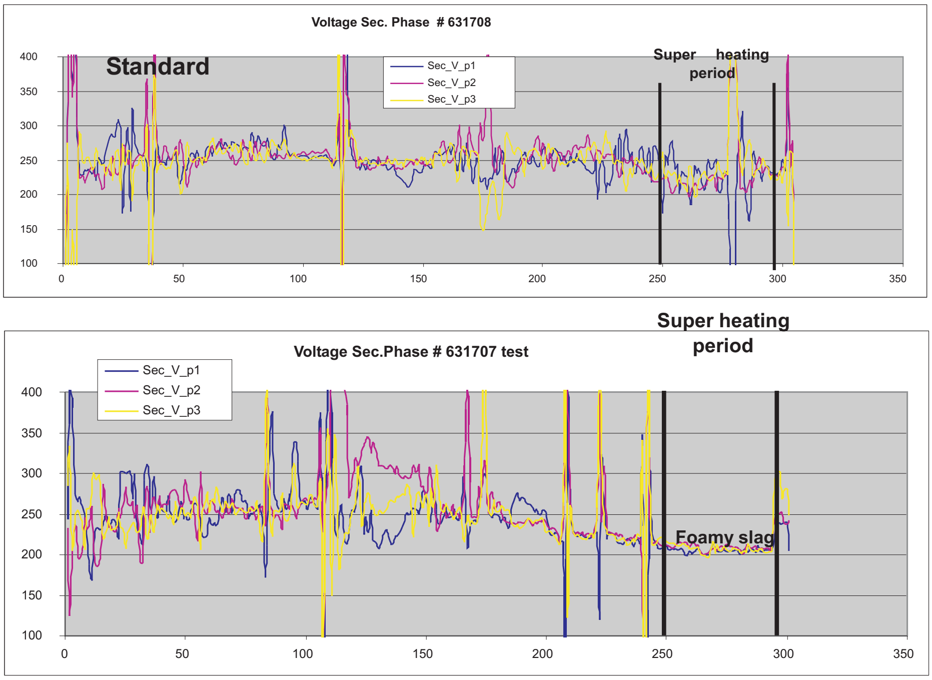

Fig. 9. Dynamic of electric arc in standard and foamy slag presence

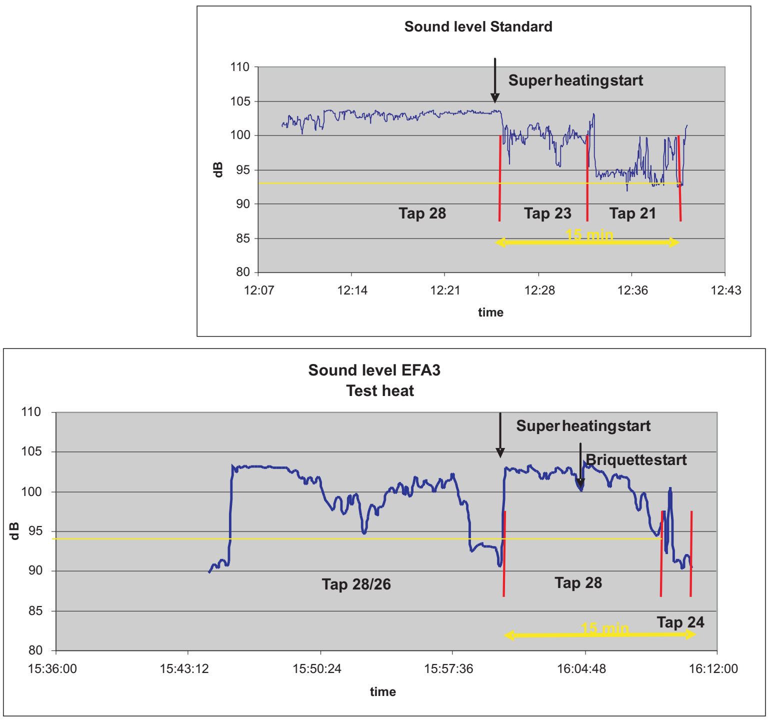

Fig. 10. Sound development during super heating

Figure 10 shows a comparison of the noise development in case of a standard and foamy slag treated heat. It can be seen, that the standard heat is operated in the super-heating period with a decided lower transformer tap 23 and 21 and generates a noise level between 100 and 95 dB accordingly. Test heats show an exact correlation between the foamy slag development, means covering of the electric arcs by foam, and the noise level. The impact of the foam damping can be seen explicitly in the final period, where the noise level decreases from the approx. 95 to 90 dB at a transformer tap 24, Fig. 10 below. Tested heats were generally observed in view on the briquette components, their density, addition speed control, slag conditions and technology. Evaluations of metallurgical parameters show improvement trend in almost all aspects. In scope of charge materials, chromium, manganese and metal yield the improvement is approx. 2%. The shortening of the super-heating period by operation with higher transformer taps has a high potential in increasing of the plant production. However, due to the relative low number of the test heats (60) a final comparison will be made after longer campaign. Especially long impact effects like electrode consumption, refractory life, electrical maintenance of switch transformer contacts and dust emission are of high significance in the process economy.

5. Conclusions

All tests demonstrate that the new foaming slag technology for stainless steelmaking in EAF carried out by foaming materials containing scale, carbon and ballast materials, introduced into the furnace in briquettes form with a special defined density and in combination with a controlled slag viscosity implicates sufficient foaming quality and its height. The slag height is controllable by intensity and duration of additions. In details it can be concluded, that:

– Briquettes with FeCrHC or steel scrap fulfil requirements of density.
– Limestone improves the gas formation.
– Briquettes with density higher than 3.5 t/m^3 assure the placing directly under the slag.
– Good slag foaming is dependent on the slag viscosity controlled by the temperature and basicity. Lower temperatures (1500–1550°C) correspond to lower basicity (lime not completely dissolved), higher temperatures (1600–1650°C) correspond to higher basicity (lime completely solved). Both factors work in contrary to each other.
– High foaming effect requires a sufficient level of original slag e.g. initial slag volume.
– High foaming slag stabilizes thermal and mechanical conditions on the operating electrodes tips.
– Covering of the electric arcs by foaming slag causes lowering of noise level.

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REFERENCES

[1] M. Karbowniczek, A. Michaliszyn, E. Kawecka-Cebula, K. Pytel, P. Migas, Material and conditions effecting foamy slag at high Cr-oxide concentration, unpublished report, AGH-University of Science and Technology, Krakow, (2005).

[2] H. Tavernier et. al., Foaming of the slag and recycling of stainless steel dusts by injection into the electric arc furnace for stainless steels, Technical Steel Research European Commission, Luxemburg, (2004).

[3] B. Vidacak, I. Arvanitidis, P.G. Jönsson, P. Sjöberg, Observation on foaming of EAF slags in the production of stainless steel, Scandinavian Journal of Metallurgy, (2002).

[4] M. Peter, K. Koch, J. Lamut, M. Juhrat, Schäumverhalten von Schlacken des Elektrolichbogenofen-Prozesses, Stahl und Eisen **119**, 10, (1999).

[5] E.B. Pretorius, R.C. Nunnington, Stainless steel slag fundamentals: from furnace to tundish, Iron and Steelmaking, **29**, 2, (2002).

[6] J. Kerr, R. Fruehan, Foamibility of stainless Steelmaking slags in EAF, Iron & Steelmaker, 4, (2002).

[7] M. Karbowniczek, Slag foaming in steelmaking processes, AGH-University of Science and Technology, Krakow, Poland 1999.