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Analysis of Thermal Interactions in the Slag Pots for Transporting Copper Slags

Adam Szklarz[1], Adam W. Bydałek[2*], Piotr Migas[3], Andrzej Pytel[4], Krzysztof Jaśkowiec[4], Adam Bitka[4], Michał Wójcicki[4], Stanisław Pysz[4], Robert Żuczek[4]

[1] KGHM, the Copper Smelter in Głogów, Żukowicka 1, Głogów 67-200, Poland
[2] University of Zielona Góra, University of Zielona Góra, Zielona Góra 65-516, Poland
[3] AGH University of Science and Technology, Al. Mickiewicza 30, Kraków 30-059, Poland
[4] Foundry Research Institute in Kraków, Zakopiańska 73, Kraków 30-418, Poland

Corresponding Author Email: a.bydalek@iimb.uz.zgora.pl

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ABSTRACT

During the processes of copper production, post-reaction slags are formed and must be transported to storage sites as waste. The working conditions of the slag ladles are extreme, incl. due to the high reactivity of copper slag and the cyclicality of the operation of the slag ladles. The material of the vat walls is exposed to intense factors: chemical in the form of a liquid phase and temperature in the form of high gradients (thermal shocks). Which leads to a reduction in the campaign length of a single vat. The paper discusses the issues related to the operation of smelting slag pots depending on the insulating material. The aim of the work is to analyze the thermal interactions during the filling of the pots. The conclusions from the presented research are a proposal of actions aimed at extending the working time of the slag pots between repairs related to operation, as well as in terms of the total working time. The analyzes of thermal decomposition on the external and internal surfaces of slag pots with "artificially compressed" calcium milk $Ca(OH)_2$ on the entire surface of the slag pots, which were carried out in the presented work, gave very similar results as during the modeling of steel slag pot. The use of a heat-resistant concrete layer at the bottom of the pots significantly reduces the damage zone and extends the working time.

1. INTRODUCTION

The main products of the process in copper smelters by removing slag from the flash furnace in the electric furnace are Cu-Pb-Fe alloy (69-81% Cu), which is further processed in the smelter and copper slag (less than 0.7% Cu), waste managed by other companies.

In the process of copper removal, copper slags are transported from the electric furnace to ladles with a capacity of V = 16.5 m^3, which are part of wagons, commonly known as [1, 2]. Other products, such as a copper blister from the flash furnace, slag from the flash furnace, Cu-Pb-Fe alloy from the electric furnace, copper blister from the blister furnaces and anode slag [3-5] are transported in an additionally in smaller ones - V = 8 m^3 slag pots. It is common practice to pour a new batch of slag into the ladle previously filled with the liquid slag. Such treatment is aimed at reducing the temperature gradient in the walls of the slag pots [6, 7]. It is a very wasteful operation, hence the more favorable orientation is to cover the slag pots with protective (garnished) coatings [8-10].

The simplest parameter reflecting the influence of the liquid slag inside the slag pots is the temperature determined at the assumed boundary between the wall of the slag pots and the slag. The pouring temperature of the slag pots content fits, determined by slag solidification, is approx. Ts = 800°C. For the slag pots immediately after its pouring at a temperature of approx. 1200°C, it means a sudden temperature increase in the tank and on its internal surface. The contact temperature T_w is part of the solution to the problem of heat transfer to the environment. With regard to the remaining surfaces of the ladle, the general boundary condition is the transfer of thermal radiation to the environment, and the above value of e should be treated as a whole (Lambert heater), defined by the Stefan Boltzmann law [11, 12]:

$$k_{(s,l)}\nabla_{n,o} T = e\chi(T_{w,o}^4 - T_{ref}^4),\quad \chi = 5.670373*10^{-8}\ W/(m^2K^4) \tag{1}$$

Despite many methods of solving the signaled problems, due to the complexity of problems caused by phase changes in the analyzed system, analytical solutions are obtained only for one-dimensional cases. Therefore, the study decided to limit the mathematical and numerical analyzes to the assessment of the estimated temperature in individual transverse layers of slag in the ladle with the use of the FactSage program [13, 14].

Research on extending the slag ladle campaign in technology focused on identifying the ladle shear temperature fields and types of corrosion, and the possibility of influencing the ladle operation time. As the basic element of the research, a comparative analysis of the vat's behavior (taking into account the temperature fields inside the vat) with and without lime milk was planned. The aim of the work is to define the methodology of conduct in the processes of smelting slag pots filling and transport in terms of operation in order to ensure the longest use of smelting slag pots. The scope of work includes technological activities related to thermal shock occurring during operation.

The work contains analysis of the literature on the operation of ladles transporting slags, especially in terms of the method of their protection against thermal shocks. The material used in the work and the research methodology were indicated. The results of the research, especially the thermal analysis of the ladle, are presented. The work ends with discussion of the results, summary and conclusions.

2. ANALYSIS OF WORK, EXPLOITATION OF LADLES AND SLAG POTS, RESULTING DAMAGES

2.1 Analysis of the operation of the slag pots

Numerous studies are conducted [1, 2, 6-10] aimed at determining the optimal working conditions for ladles transporting liquid slag. The subject of these works is the assessment of the ladle wear and proposals for extending the time of their failure-free operation. The simultaneous analyzes of numerical modeling are aimed [1, 7] at indicating the extremely working areas in the vats. These indicated areas are protected by coating with protective layers [8-10]. Before starting work, the slag pot is bleached. The surfaces of 16.5 m^3 tanks and 8 m^3 tanks are coated with $Ca(OH)_2$ emulsion by injection. The slag pouring process into the slag pots takes place cyclically every 8 hours and lasts about 2 hours. The temperature of the slag during tapping is approx. 1380-1450°C, the height of the slag pot charging is 6.5 m (measured from the edge of the pouring gutter to the bottom of the slag pots). The entire operation takes approximately 4 hours.

In continuous use, the pots are also not only bleached, but also cleaned. Cleaning the slag pot (knocking out) consists in repeatedly hitting the hanging slag pot against the slag pot attached to the ground until the build-up is completely detached from the walls of the cleaned slag pot. The activities related to the cleaning of the slag pots located on the pots also consist in breaking the clots remaining on the walls and bottom after pouring out the slag.

2.2 Operation - bleaching of ladle cars

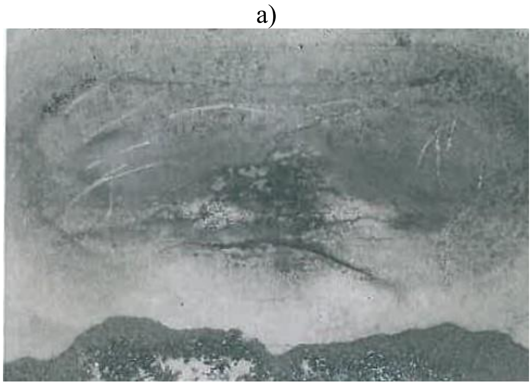
Bleaching is carried out with the use of lime milk with a concentration of 20%. The demand of $Ca(OH)_2$ for one wagon of slag boilers is 20 dm^3, which for 18 dm^3 of such machines is 360 dm^3. However, this amount does not guarantee rapid wear of the cats and it was considered appropriate to make an adjustment also at this stage of the coating process. In the case of bleaching of slag boilers V = 8 m^3, their inner surface is whitened with a layer of lime emulsion using a spraying device. Bleaching cannot be performed in hot slag boilers. Hence, in practice, it is often used in larger amounts, even up to 560 dm^3 (re-bleaching - 10 times). Correct use of lime milk will imply an extension of the duration of the slag ladle campaign, which in turn will reduce the unit costs of copper production.

2.3 Analysis of the formation of thermal defects

During the operation of the slag pots V = 16.5 m^3, defects (Figures 1-3) arising as a result of thermal stresses were observed, which appear in the form of:

- microcracks,
- a network of cracks, the so-called spider's web,
- melting at the bottom of the pots,
- cracks on the bottom surface,
- washing at the bottom of the slag pots,
- pitting at the bottom of the pots,
- internal blisters and discontinuities in the wall material.

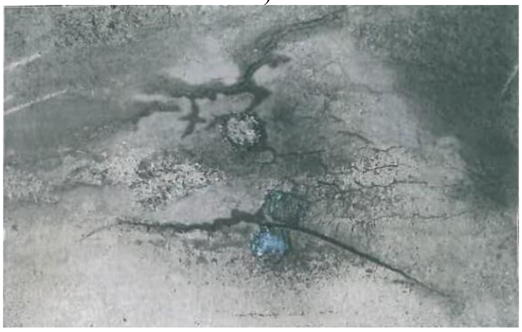
a)



b)

Figure 1. a) Wash out, and microcracks on the bottom of the slag pots V = 16.5 m^3, b) a network of cracks and fractures a "spider web" on the bottom of the slag pots V = 16.5 m^3

a)

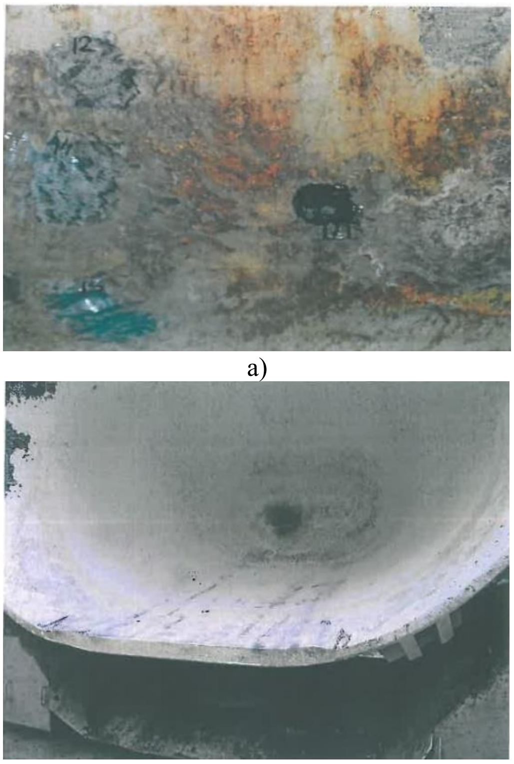


b)

Figure 2. a) Melting at the bottom of the slag pots V = 16.5 m^3, b) spreading cracks along with a grid of cracks in the slag pots V = 16.5 m^3

The cracks in the slag pots differ from each other in dimensions, and their highest crack value is even 500 mm.

Cracks differences are:
- Cracks at the bottom of the slag pots up to 500 mm long,
- Cracks with a depth of 17 mm to 42 mm,
- Cracks from 6.2 mm to 11.5 mm thick.


a)

b)

Figure 3. a) Pitting on the bottom of the slag pots V = 16.5 m^3, b) Small cracks and rinsed bottom of the slag pots V = 16.5 m^3

3. RESEARCH MATERIAL AND METHODOLOGY

3.1 Material

A slag pots with a total capacity of 16.5 m^3 and a weight of approx. 22,500 kg, made of cast steel 230-450 W (ferritic stainless steel). Usable capacity is 14.3 m^3. The slag pot with a total capacity of V = 8 m^3 and weight of approx. 17 700 kg is made of cast steel with the designation 230-450 W. The usable capacity is V = 6.5 m^3. The indicated materials used for the production of slag pots are characterized by high resistance to thermal stress due to high plasticity and good elongation values. Their sensitivity to excessive stresses resulting from uneven thermal slag pots is low.

3.2 Research methodology

The tests were carried out for 8 m^3 slag pots, assuming that the obtained results will also allow for use in 16.5 m^3 tanks. The tests were carried out on 8 slag pots, 7 of which were covered with the traditional method, taking into account only the different coating times, while one slag pot was covered with a special refractory concrete developed for own needs.

The surfaces of the 16.5 m^3 slag pot and the 8 m^3 slag pot were covered (bleached) with a $Ca(OH)_2$ emulsion by injection. At 20 liters, an emulsion with a concentration of 20% per tube was used. In the tests, a special heat-resistant concrete was also used (forming the so-called garnisage in the slag pot), which was used in the amount of 10 dm^3 per slag pot.

The measurements were made with the FLIR SR600 thermal imaging camera with the emissivity $\varepsilon = 0.92$ (Figure 4). The aim of the research was to present the temperature distribution on the ladle surface. The tests were carried out at the charging slag pots with slag, during emptying the slag pots from slag and when the slag pot was empty - immediately after pouring out.

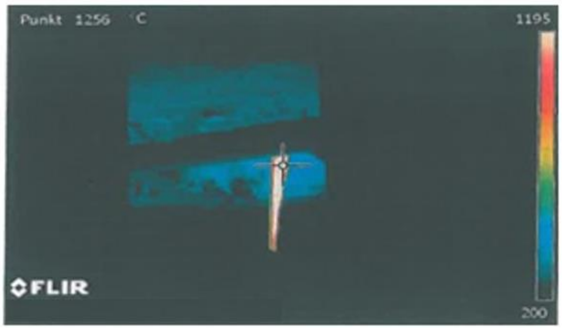


Figure 4. Temperature measurement of the slag stream made with a FLIR SR600 infrared camera

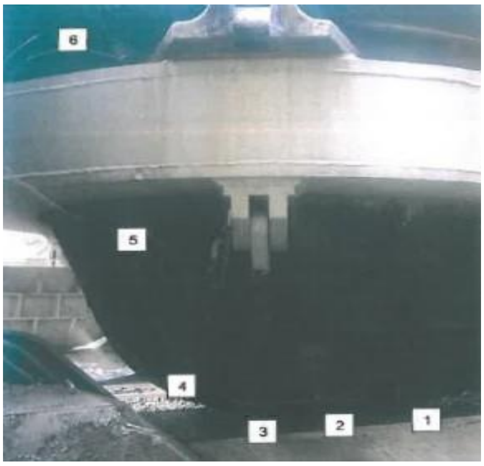
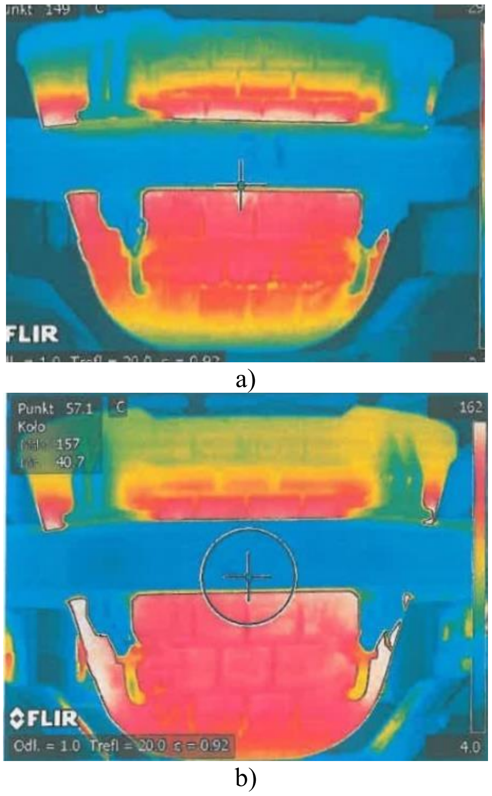


Figure 5. Placement of thermocouples on the ladle V = 16.5 m^3

Measurements with sheathed thermocouples using the MRac15 recorder and thermocouples allowed to control the temperature change on the outer layer of the slag pots. The thermocouples were positioned as follows: thermocouples numbered 1, 2, 3, 4 are located at the bottom surface (Figure 5). Measurements were made with a LPH lance with disposable Pt-PtRh sensors. Thermocouple number 5 was placed near the middle zone, and thermocouple number 6 was placed in the highest region. The whole process lasted about 20 hours, i.e. it was carried out in a period of incomplete three cycles.

4. RESULTS OF THERMAL ANALYZES AND RESEARCH

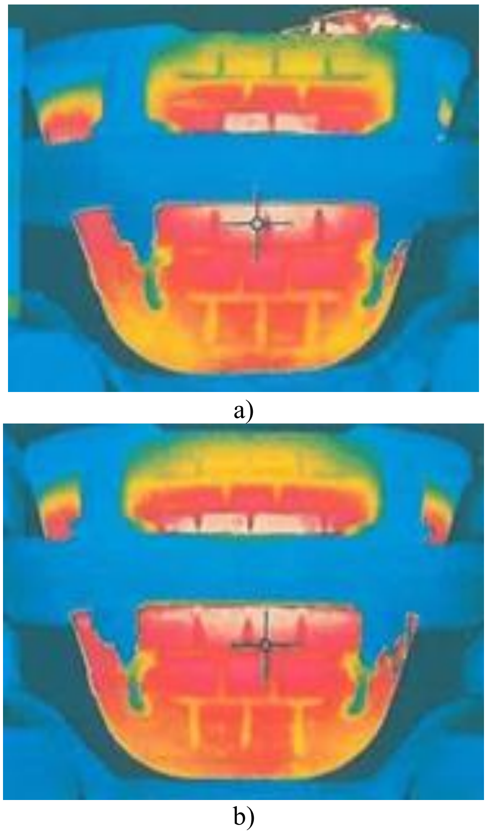
During the tapping of the slag from the electric furnace, temperature measurements were made, which correspond to the three cycles of copper slag removal in the electric furnace (Figures 6-9). Figures 6-9 show the recorded overheating temperatures of boilers depending on the coating technology used. The analysis of slag temperatures shows that the temperature of the slag pots poured in subsequent measurements ranges from 1270°C to 1300°C.



a)

b)

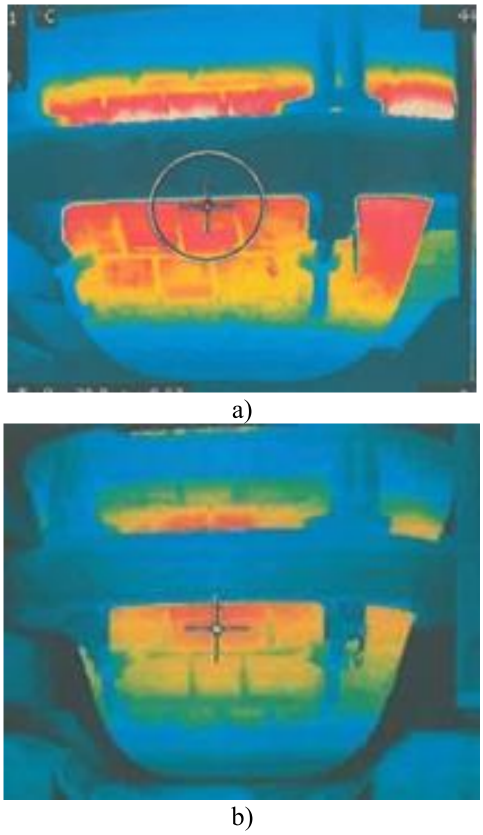
Figure 6. The slag pots without garnishes filled with slag: a) covered with milky calcareous $Ca(OH)_2$, b) without cover



a)

b)

Figure 7. The slag pots without a garland after pouring the slag: a) covered with milky calcareous $Ca(OH)_2$, b) without coating



a)

b)

Figure 8. The slag pots with a heat-resistant concrete garland: a) filled with slag, b) after pouring the slag

- The first cycle of research

The first period of the research was characterized by each vat being covered with lime milk (whitening). The initial temperature of the bottom of the slag pot (points 1, 2, 3), just before pouring, oscillated between 200 and 220°C. The temperature measured at the other elements was 150 - 175°C. After the slag pot was poured with slag, the external surfaces were heated to a temperature of 300 to 450°C. The upper temperature limit fluctuates in the upper part of the slag pot due to the small wall thickness. Further measurements showed that during the emptying of the slag from the slag pot, the internal surface temperature was from 870 to 940°C.

The upper zones inside the slag pots, immediately after pouring it, indicated a temperature ranging from 460 to 480°C. At the time of its discharge, a slow decrease in the temperature in the bottom of the slag pots (points 1 and 4) by 50°C per minute was noted - to the temperature before the next flooding - 200-220°C.

- Second cycle of research

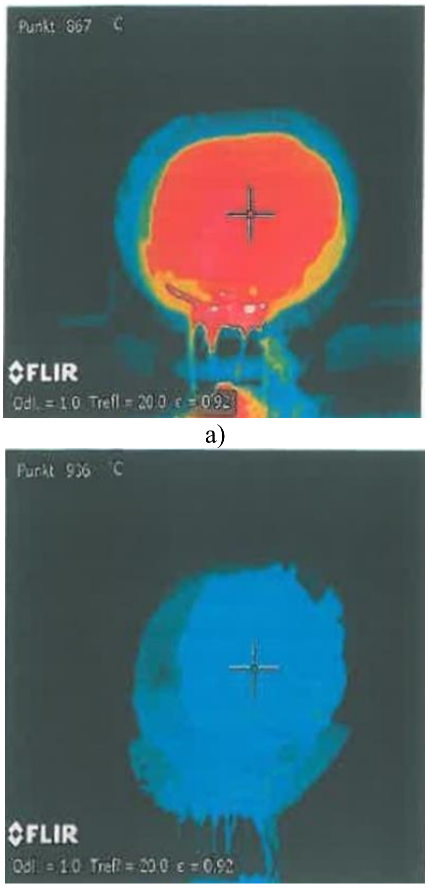
In the next measurement period, the slag pots was not re-coated with lime milk (in the previous production, coatings are applied every third - fifth flooding cycle), and as a result the temperature was lower within the range of 100-150°C (points 1, 2, 3). The temperature measured at the other elements was 120-140°C. After the slag pot was poured with slag, the external surfaces were heated to the temperature from 410 to 530°C. The upper temperature limit fluctuates in the upper part of the slag pots due to the small wall thickness. Further measurements indicated that during the emptying of the slag pot from the slag, the internal surface temperature was from 920 to 1030°C.

The upper zones inside the slag pots, immediately after pouring it, showed a temperature ranging from 490 to 550°C. At the time of emptying the slag pot, a rapid decrease in the temperature in the bottom of the slag pot (points 1 and 4) by 100°C per minute was noted - down to the temperature before the next pouring -100 - 150°C.

- The third cycle of research

The third test cycle was each covered with refractory concrete (garage). The initial temperature at the bottom of the slag pots (points 1, 2, 3), just before pouring out, oscillated between 250 and 320°C. The temperature measured on the other elements was 250-275°C. After the slag pot was poured with slag, the external surfaces reached the temperature of 280 to 400°C. The upper temperature limit varied at the top of the slag pot due to the small wall thickness. Further measurements showed that during the emptying of the slag from the slag pot, the internal surface temperature was 750-800°C.

The upper zones inside the slag pot, just after it was poured out, showed a temperature in the range of 360 to 400°C. At the time of its discharge, a slow drop in temperature at the bottom of the slag pot (points 1 and 4) by 30°C per minute was noted - to the temperature before the next flooding - 250 to 320°C.



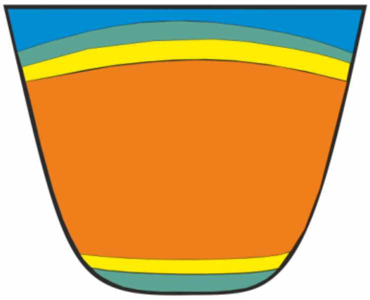
a)

b)

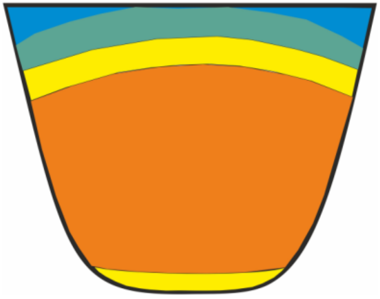
Figure 9. The interior of the slag pots 3, before (a) and after pouring the slag (b)

5. DISCUSSION OF RESULTS, SUMMARY AND CONCLUSIONS

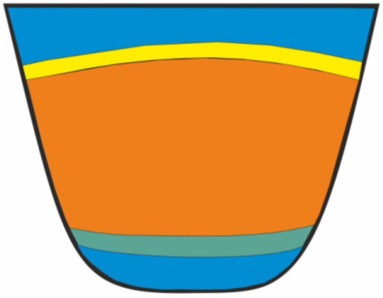
Summarizing the three ranges of sheathed thermocouple tests, it can be noted that during the first cycle, where the slag pots had a cover each time applied in the form of lime milk, the temperature, after filling, gradually increased in the lower part of the slag pots and then decreased within the range of 100 -150°C. In the second research period, when the tank was stripped of its cover, which resulted in an increase in temperature in the lower zone of the bottom by about 150 - 200°C. The third period was characterized by a much lower temperature increase and decrease than in the first cycle, within 50°C. Figure 10 presents a graphical overview of the thermal effects obtained during measurements, assuming the temperature of the filled slag pots at the time of pouring it with slag and the emptying temperature before the slag pots is poured again.



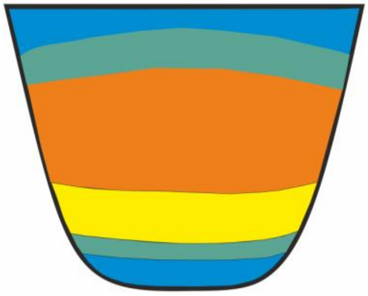
a) slag pot without cover or with $Ca(OH)_2$ cover after pouring slag



b) without cover or with $Ca(OH)_2$ cover after pouring the slag



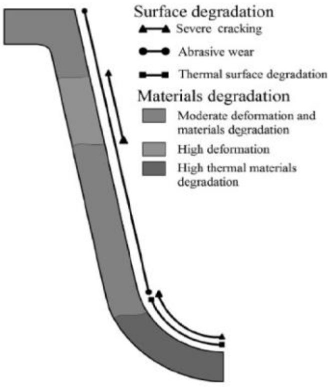
c) slag pot with refractory concrete lining after slag flooding



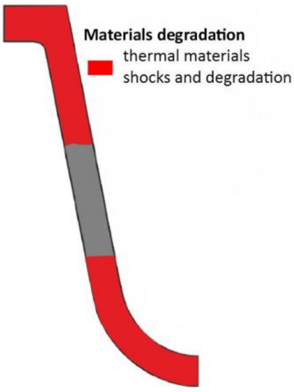
d) slag pot with refractory concrete lining after emptying the slag

🟦 up to 150°C, … from 150 - 250°C, … from 250 - 350°C, … above 350°C

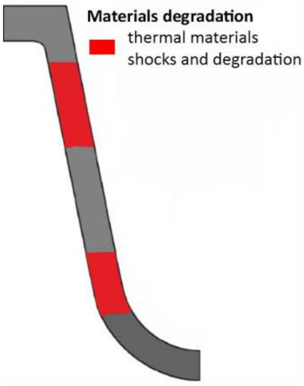
Figure 10. Schematic description of the thermal effects in the analyzed slag pots



a) graphical illustration of degradation mechanisms steelmaking slag pot [1, 7]



b) graphical illustration of degradation mechanisms copper slag pot with $Ca(OH)_2$



c) graphical illustration of degradation mechanisms copper slag pot with the garnisage lining

Figure 11. Comparison of selected zone wear mechanisms for different slag pots

A greater degree of damage to the slag pot material due to stresses and thermal shocks was also observed when pouring a slag pot without a garnisage than when pouring a slag pots having a garnisage. The arising surface cracks of the slag pots and their enlargement is the result of the occurrence of large temperature gradients during the pouring of the slag pots with slag in the copper smelting processes. The unpublished studies of the authors also show that subjecting the slag pots to whitewashing at elevated temperatures may also be the source of cracks. According to the authors, the heated internal surface of the slag pots covered with liquid lime causes stresses, which in turn will lead to the initiation of cracks. The analysis of the results shows that the slag pots with a concrete layer in the lower part is protected against rapid cooling of the entire slag pots, which gives a better possibility of protection against thermal shocks.

Based on studies similar to those presented in [1, 7], where the erosive effects of steel slag pots were presented, the authors proposed a numerical model of wear of the surface of slag pots in copper processes. The simulations performed showed the places of wall wear in the slag pots and the corresponding mechanisms, as shown in Figure 11.

The analyzes of thermal decomposition on the external and internal surfaces of slag pots with "artificially compressed" calcium milk $Ca(OH)_2$ on the entire surface of the slag pots, which were carried out in the presented work, gave very similar results as during the modeling of steel slag pot. On the other hand, the use of a heat-resistant concrete layer at the bottom of the slag pots significantly reduces the damage zone. The tests carried out with the use of a cement coating on the bottom of the slag pots allowed the following conclusions to be drawn:

- it allowed to avoid repeated hitting of the ladle against the surface
- the slag can be easily removed from the slag pots covered with concrete,
- an extension of the slag pots operation time between repairs from 3-5 cycles to 8-10 cycles was noted,
- the total working time of the slag pots has more than tripled,
- a 50% reduction in the cost of using the insulation layer in the form of cement was noted compared to the traditional whitewashing of calcium milk with $Ca(OH)_2$.

The results of the tests and analyzes indicate that the correct use of lime milk, and in particular its placement in the appropriate places of the ladle, will imply an extension of the duration of the slag ladle campaign. This will reduce the unit costs of copper production.

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