GEOMETRIC MODIFICATION OF THE TUNDISH IMPACT POINT AND THE ADVANCED MATERIAL FOR THIS APPLICATION

Branislav Buľko (1), Ivan Priesol (2), Peter Demeter (1), Peter Gašparovič (3)
1 Technical University of Košice, Faculty of Materials, Metallurgy and Recycling, Slovakia, branislav.bulko@tuke.sk, peter.demeter@tuke.sk
2 IPC REFRACTORIES s.r.o., Magnezitárska 11, 040 13 Košice, Slovakia , ipriesol@ipc.sk
3 Technical University of Košice, Faculty of Aviation, 042 00 Košice, Slovakia, peter.gasparovic@tuke.sk

ABSTRACT

In connection with the increasing requirements for cleanliness in conticast steel, it is necessary to develop original solutions. The tundish, as the last refractory-lined reactor, gives enough space to remove inclusions by optimizing the flow of steel. The basic component of the tundish is the impact pad, the shape of which creates a suitable flow of steel, thus making it part of the tundish metallurgy. The optimal steel flow in the tundish must avoid creating dead zone areas, or the slag "eye" phenomenon in the slag layer around the ladle shroud and is intended to create conditions for the release of inclusions by promoting reactions at the steel-slag phase interface. The flow also has to prevent excessive erosion of the tundish refractory lining. This paper compares the standard impact pad with the spherical impact pad using computational fluid dynamics (CFD) tools and physical modelling. The evaluation criteria are residence time and flow in the tundish at three different casting speeds.

Key words: continues casting, tundish, residence time, computational fluid dynamics (CFD), cement free castable, nano bond

1. INTRODUCTION

Current trends show that more than 96% of the steel produced in the world is processed by continuous casting [1]. In view of this, there is a naturally increasing pressure on producers of refractory materials used in the continuous casting process. A key part of the continuous casting plant is the tundish, which can significantly affect steel cleanliness. In connection with the constantly increasing ratio of high-grade steel in the product portfolio, development in the field of tundish metallurgy is essential. A fully operational tundish is chosen in terms of covering and refining powders and the proper slag regime. The basic requirement for a properly functioning slag system is the controlled flow of steel in the tundish so that inclusions can be released from the steel into the slag and chemical reactions have good conditions to run at the steel–slag phase interface [2]. From this perspective, the most important criterion is the geometrical adjustment of the steel impact point in the tundish. In practice, this is solved using an impact pad, which has the role of reducing the erosion of the bottom of the tundish refractory lining [3–5]. Swirl flow at the point of impact is due to the high kinetic energy of the incoming steel. The low momentum of diffusivity of the input steel causes a relatively slow transfer of fluid from the input stream with high kinetic energy to the surrounding liquid steel. In the case of a suitably shaped impact pad, a so-called “piston flow” area is created. One of the main indicators of the quality of the flow adjustment in the tundish is the residence time, which is defined as the duration of stay of steel particles in the tundish [6]. The longer the residence time, the more time inclusions have to flow from the steel into the slag.

In recent years, impact pads have undergone considerable development, especially in terms of their design, changing from simple pads through ribbed pads to the most sophisticated shapes that use the latest knowledge from mathematical and physical modelling as well.

As mentioned above, the impact pad is one of the key parts of the tundish furniture affecting the flow of liquid steel. It is mostly used with suitably selected dams, weirs, and baffles, which can significantly prolong the residence time of steel in the tundish [7–9].

In order to accurately compare the properties of the spherical impact pad with those of the standard impact pad, this article contains the results of the comparison of these impact pads without the use of other flow modifiers.

The aim of this research was to point out a new, innovative solution for the impact pad using a convex hemispherical shape. In the case of a symmetrical two-strand boat-type tundish, a more advantageous character of steel flow is assumed using a spherical impact pad.

2. EXPERIMENTAL MATERIALS AND METHODS

The “Spheric” Impact Pad

The shape of the spherical impact pad was developed in order to decrease the hydrodynamic drag force of the impinging stream of molten steel. Dimensional analysis of the drag force F provides the dependence.

$$F = \frac{1}{2} C \cdot \rho \cdot S \cdot v \qquad (1)$$

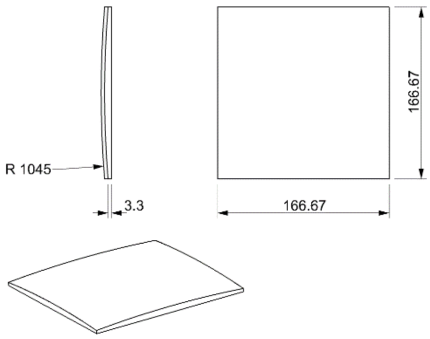
where: C—coefficient of drag, ρ —specific mass of fluid, S—size of the reference area (planform area of the pad), and v—relative velocity of impinging stream.

The coefficient C expresses the influence of the shape of the pad on the drag force. The coefficient C is a dimensionless parameter that can be assumed constant for small changes in velocity. The experimental values of the coefficient of drag of objects in a free stream are 1.17 for the square flat plate and 0.40 for the convex hemisphere [10]. The proposed spherical pad has a square planform and the upper surface shape of a large-radius hemisphere.

The shape of the spherical impact pad should, in comparison with the standard impact pad, cause less erosion of the pad surface. Smaller deflection of the stream should reduce the creation of large intensive vortices at the surface of the fluid level. Short-path flow should be suppressed by more intensive mixing at the core of the fluid volume.

Physical modelling is done in a scaled-down model of the tundish at the scale 1:3, made of transparent plastic (PMMA), with water as the fluid medium. The description of the physical model and the experimental method is given in [7,11].

The dimensions of the impact pad were calculated with respect to the scale of the tundish at the ratio 1:3, with the height of the impact pad (Figure 1) set at 9.96 mm due to its position on the bottom of the real tundish (Figure 2). The flow of steel in the tundish equipped with the “Spheric” impact pad is optimized not only for the residence time but also for the nature of the flow, so that this flow promotes the removal of inclusions into the slag and the best conditions for the slag-metal phase interface. This method of modifying the flow is given in [12, 13].



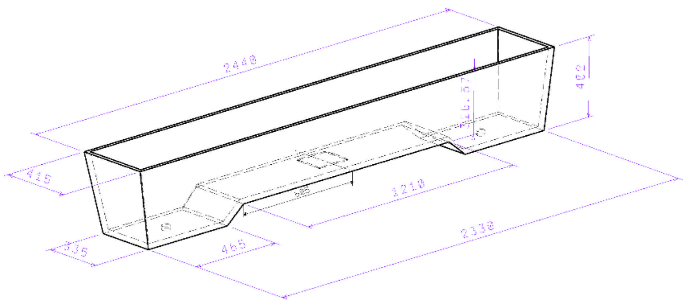


Figure 1. The “Spheric” impact pad **Figure 2.** Position of the “Spheric“ impact pad in the tundish

The Standard Impact Pad

The dimensions and position of the standard impact pad in the tundish are shown in Figure 3.

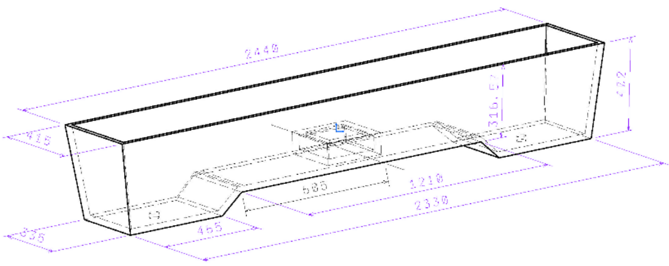


Figure 3. Position of the standard impact pad

The measurements were performed in steady-state conditions, so the steel level in the tundish was constant and the amount of steel flowing into the tundish was equal to the amount of steel flowing out from the tundish into the molds [14-20].
Measurements were performed for the tested configurations at flows corresponding to casting speeds of 0.8 m·min^{-1}, 1.2 m·min^{-1}, and 1.6 m·min^{-1} on a real continuous-casting machine. The length of the ladle shroud on the model corresponded to a real length of 1700 mm. In both configurations the same ladle shroud was used. The distance of the nose of the ladle shroud from the tundish bottom was 203 mm. Thus, when using the standard impact pad, it was 183 mm and 194 mm when the spherical impact pad was used.
Each configuration was simulated three times.
The results of our physical and mathematical simulations with spherical surfaces of impact pads in different types of tundishes led us to the realization that to produce such parts it will need a new advanced material that will meet demanding criteria. We have set these criteria in accordance with the requirements imposed on us by the current state of steel production in Europe, current European legislation and trends related to the Industry 4.0 agenda.
The basic goals of materials research were defined as:
1. Long-term exposure in the dynamic environment of liquid steel without deformation of the surfaces determining the flow control of prefabricated components, especially those used in the area of steel inflow into the tundish.

2. Preparation of the mixture for the production of prefabricated components and their production with the lowest possible energy consumption and with the lowest possible carbon footprint.

In order to fulfill these goals, we abandoned the idea of producing prefabricated components based on LCC and ULCC concrete, due to their obvious disadvantages related primarily to points 1 and 2. In our research, we focused on the preparation of cement-free mixtures using a binder prepared on the basis of the sol-gel method. The mixtures prepared in this way showed good resistance to corrosion phenomena caused by casted steel.

RESULTS AND DISCUSSION

The initial idea of the "Spheric" impact pad was verified using CFD simulation tools [21,22], (Figure 4).

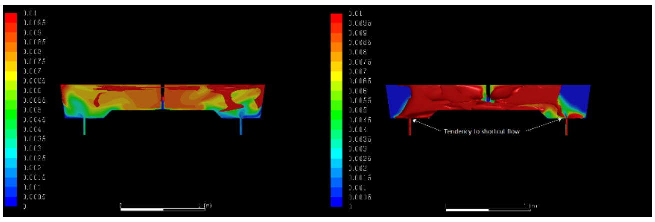


Figure 4. Comparison of fluid flow for "Spheric" impact pad and for standard impact pad at simulated casting speed 0.8 m min^{-1} - CFD simulation

Based on the results of CFD simulations, using the "Spheric" impact pad was expected to shorten the residence time compared to the standard impact pad, but on the other hand it is also expected to reduce the swirl of steel around the ladle shroud and reduce the so-called slag "eye" phenomenon. It is assumed that when using a "Spheric" impact pad the mixing area will predominate and the area of dead zones will be intensively reduced. It has also been found that the standard impact pad tends to create a shortcut flow at lower casting speeds.

The proposed impact pad was tested using the water model of the real symmetrical, two-strand boat-type tundish at scale 1:3 for the three default casting speeds. The C-curve, residence time, and visual evaluation of the flow in the tundish were selected as comparison criteria. The tracer is an water salt solution of KCl, the concentration of which is monitored by means of the conductivity measurement system, while the flow is evaluated visually using $KMnO_4$ as tracer. Figures 5 show the results of the simulations comparing the standard and Spheric impact pads. For visual flow comparison, Figure 5 show the flow of tracer at time intervals of 5, 20 and 80 s after tracer injection.

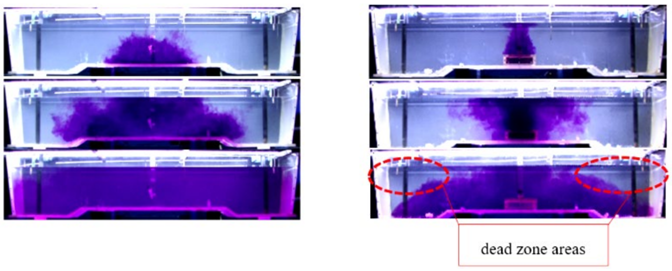


Figure 5. Visual comparison of flow for "Spheric" impact pad and for standard impact pad at simulated casting speed 0.8 m min^{-1} - physical simulation

Table 1 gives a comparison of minimum and maximum residence times for each configuration. The numbers in brackets indicate the percentage difference related to the minimum residence time of the alternative with standard impact pad under similar conditions.

Table 1. Comparison of residence times for all tested configurations.

Configuration	Casting Speed	Minimal Residence Time (s)	Maximal Residence Time (s)
Standard Impact Pad	0.8 m min^{-1}	57	98
	1.2 m min^{-1}	55	137
	1.6 m min^{-1}	39.5	119
Spheric Impact Pad	0.8 m min^{-1}	40.5 (71%)	119
	1.2 m min^{-1}	42 (76%)	127
	1.6 m min^{-1}	42 (106%)	104

The difference in flow dynamics in the impact area is shown in Figure 6, where the standard and "Spheric" impact pads are compared.

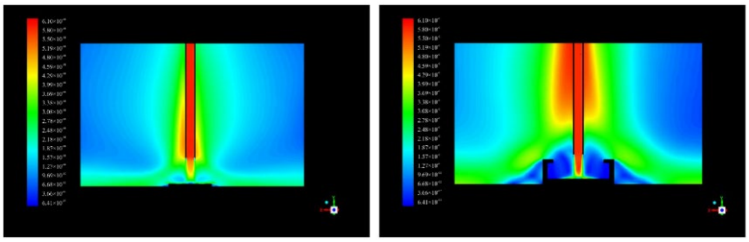


Figure 6. Comparison of velocity areas for "Spheric" and standard impact pads @ 0.8 m min^{-1}

The faster vertical circulation of steel up to the slag layer may cause the slag "eye" phenomenon, i.e., slag-free areas of steel surface open to air reoxidation and higher heat losses [23, 24].

When using a "Spheric" impact pad, the vertical velocity of the flow around the ladle shroud is significantly lower than when using a standard impact pad. Using the "Spheric" impact pad can eliminate the so-called slag "eye" around the ladle shroud in the slag layer due to the lower vertical velocity of steel flow in this area, in contrast to the standard impact pad.

In connection with the development of the own binder prepared by the sol-gel method, two types of sol-gel binders were tested. In the first case, it is a classic commercially offered colloidal silica solution, and in the second case, a silicate-aluminate colloidal solution prepared in cooperation with VŠB-TU Ostrava, CZ, which is unique not only in its composition, but also in its properties, which directly support goal 2 of our research.

The reason for using binders prepared by the sol-gel method was an effort to reduce the disadvantages of classic ceramic materials, such as their high-temperature preparation of natural raw materials or their structural instability. The use of binders prepared by the sol-gel method makes it possible to eliminate a number of these disadvantages. This method makes it possible to control the purity of the input raw materials for the formation of binders, the stability of their composition, to influence the properties of binders such as microporosity, the density of the binding grid or the resulting form of the binding xerogel by the method of preparation.

The advantage of using the sol-gel process in ceramic production is the formation of an oxide network at relatively low temperatures. This is because the reactants are dispersed by the solvent at the molecular level, with very short diffusion distances of the reacting components, which causes a fast reaction under relatively very mild conditions compared to classical ceramic materials.

The result of the research was the preparation of a mixture that uses a silicate-aluminate binder prepared by the sol-gel method and which, in addition to standard physical properties comparable to LCC/ULCC concretes of an adequate class (bauxite slag), has these properties when forming final ceramic phases such as mullite, α-corundum or cristobalite.

This binder was tested as a dried gel at different calcinating temperatures (110°C, 500°C, 800°C, 1000°C, 1200°C and 1400°C) and then the samples were analysed by DT and XRT analysis. The results of these analyses are shown in Figures 7 to 12.

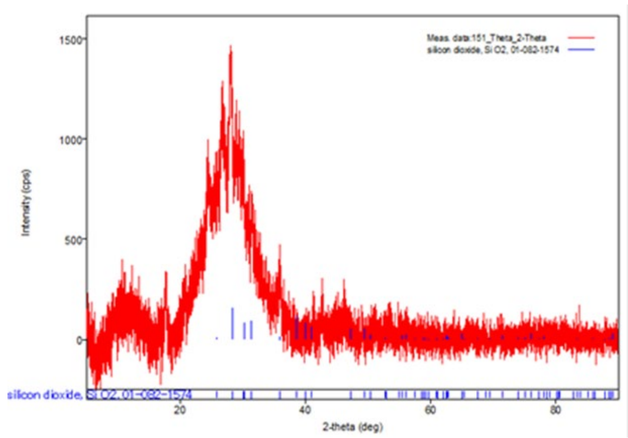


Figure 7. XRD diffractogram of gel sample dried at 110 °C – amorphous character

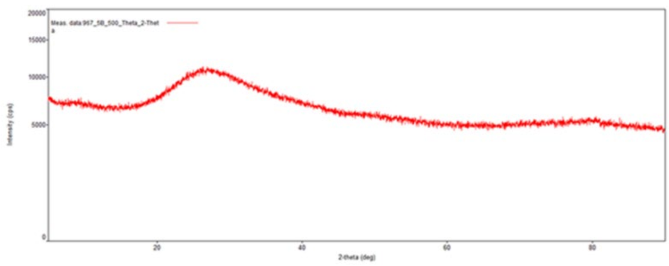


Figure 8. XRD diffractogram of sample calcined at 500 °C – amorphous character

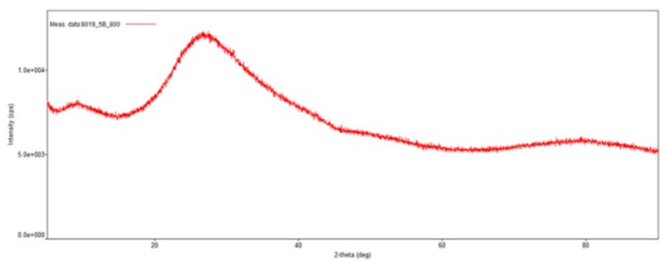


Figure 9. XRD diffractogram of sample calcined at 800 °C – amorphous character

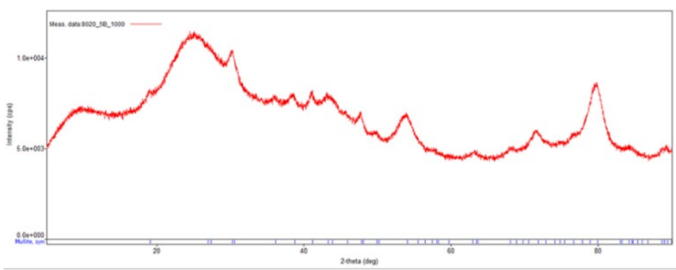


Figure 10. XRD diffractogram of sample calcined at 1000 °C – start of mullite formation

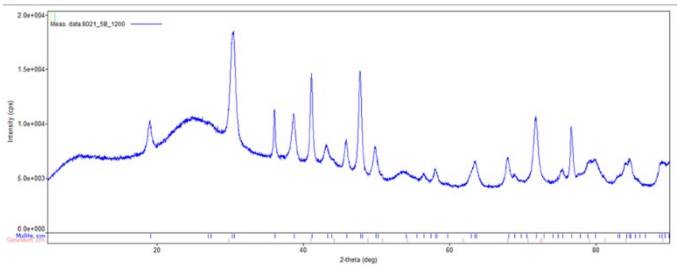


Figure 11. XRD diffractogram of sample calcined at 1200 °C – mullite, start of α-Al_2O_3 formation

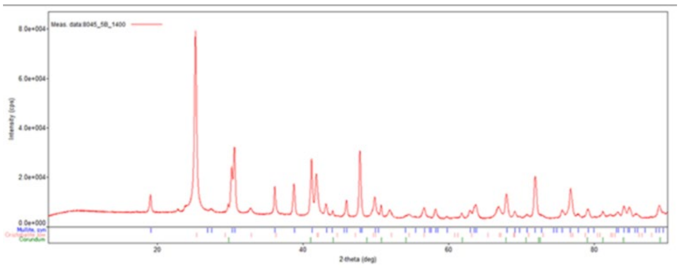


Figure 12. XRD diffractogram of sample calcined at 1400 °C – mullite, α-Al_2O_3, cristobalite

From the presented diffractograms, it is clear that the gel remained amorphous up to a temperature of 800°C. At a temperature of 1000°C, the occurrence of mullite was already recorded in the xerogel, and at a temperature of 1200°C, α-corundum also appears. With more detailed monitoring, the beginning of mullite formation was later recorded at temperatures around 950°C, and the first signs of α-corundum formation began at temperatures slightly exceeding 1100°C.

In both cases, the beginning of the formation of the final ceramic aluminate phases, mullite and α-corundum, is shifted lower by almost 100°C, which significantly contributes to the reduction of energy consumption during the final phase transformation. This fact has a significant impact on reducing the carbon footprint of both the concrete itself using the binder prepared by the sol-gel method and the products prepared from it.

After a series of experiments with the composition of the final concrete mixture for thixotropic processing, industrial tests of impact pads with a spherical surface were carried out. The composition of the mixture is shown in Table 2, and the physical properties of concrete are shown in Table 3.

Table 2. Composition of concrete mix for flow control precast

Material	%
Bauxite 0-6 mm	66
Tabular alumina	15
reactive alumina	14
Si-Al sol-gel binder	5

Table 3. Physical properties of concrete for flow control parts

Properties	Value
Bulk density drying 110°C/2h g.cm^{-3}	2,9
Bulk density firing 1200°C/5h g.cm^{-3}	2,89
PLC 110°C -ins.500°C %	-0,19
PLC 110°C -fir.1200°C %	-0,11

CCS 110°C/2h	MPa	28
CCS 1200°C/5h	MPa	122

The properties of the developed concrete mentioned above fulfilled very well the objectives of point 1, when during the practical tests they met the expectations of shape stability during the entire casting sequences. The record was the casting of 32 heats, each approximately 180 tons, in a sequence, which represents 5,760 tons of cast steel (duration of the sequence was about 30 hours) without visible damage of the spherical impact pad and without obvious deformation of its surface. The actual condition of the impact pad after the completion of the casting of the sequence of 32 heats can be seen in Figure 13. The method of applying the pad to the boat-type tundish is in Figure 14 [25].

Figure 13. Condition of Spheric impact pad after casting of 32 heats (5760 tons of steel)

Figure 14. Installation of Spheric impact pad in tundish

The tested impact pads have been subjected to thorough research. Possible formation of cracks in the depth of the material, shape and surface stability and penetration of steel into the depth of the material were investigated. Figure 15 shows the internal structure of the material at the fracture of the impact pad after it has been broken for the purposes of analysis. The image clearly shows that the material remained compact, without internal cracks. In the same way, the surface of the impact pad is without deformation even at the point of direct impact of the steel stream on the body of the pad.

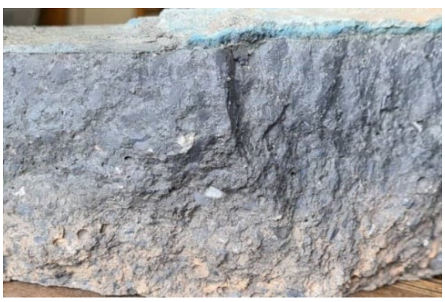


Figure 15. Break (realised in laboratory) of Spheric impact pad in area of direct impact of stream of casted steel after casting of 32 heats (5760 tons of steel)
The material of the impact pad was subjected to a detailed microscopic analysis to detect the presence of structural defects - cracks that could lead to the penetration of metal into the material, Figure 16. At the same time, a selective qualitative analysis focused on the occurrence of Fe in the material of the impact pad was performed in selected areas with the aim of determining the depth of penetration of Fe into the volume of the impact pad, Figures 17. Based on this analysis, the presence of Fe in the volume of the impact pad was determined to a depth 45-55 mm. The rate of Fe presence was a maximum of 1.8%wt. This analysis was performed with the laser unit of the Keyence VHX microscope.

Figure 16. Material structure of the impact pad after use (magnification x20)

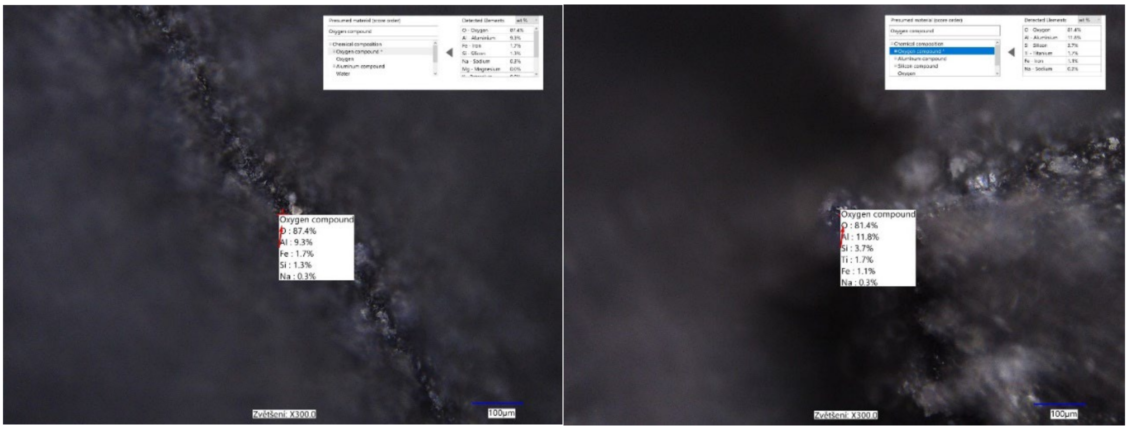


Figure 17. Point qualitative analysis confirming the presence of Fe 1.7%-left and Fe 1.1%-right (magnification x300)

Based on the analysis of the used impact pads, it can be concluded that the developed material fulfilled the number 1 goal of our assignments. The preparation of the mixture and its processing shows a significantly lower carbon footprint compared to classic LCC/ULCC concretes. This fact results from the absence, for the preparation of energy-intensive cement, and from the easier workability of the mixture using Si-Al sol gel binder. However, the main benefit is the radical saving of energy during drying, when, depending on the external conditions (mainly the temperature of the working environment), it is possible to shorten the drying time by up to 20 hours.

CONCLUSIONS

The design of the spherical impact pad with a convex surface was inspired by the differences between the flow past a flat plate and the flow past a sphere. The benefits of using „Spheric“ impact pad in symmetrical, boat type tundish are:

- Prevention of splashing of steel at the start of casting - a significantly enhanced safety factor.
- Creation of a more favourable character of the flow without the tendency to create a short-circuit flow.
- Suppresses the formation of the "red eye" phenomena in slag slayer.
- Elimination of the formation of dead zones in a tundish.

Based on the nature of the shape of the impact pad, "Spheric" is the only known system that distributes the kinetic energy of the impact stream throughout the entire volume of liquid steel - a significant benefit for the life of the refractory materials, but also the inclusions removal.

The nature and quality of the material used guarantees uniform and identical dynamic flow conditions during the entire casting process in the sequence.

The developed advanced material fulfills with a rich reserve the basic requirement that the products from it ensure the same dynamic flow conditions during the entire steel casting period.

Based on the performed measurements, it can be concluded that the “Spheric” impact pad has great potential to optimize the flow of steel in the tundish, and that in combination with the appropriate “tundish furniture” it can become a new part of modern tundish metallurgy with significant influence on the final quality and cleanliness of conticast steel.

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