Effect of Slag Particle Diameter on the Re-melting of Ferrochrome Slag by means of Steelmaking Liquid Slag

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Abstract: Stainless steelmaking slags are, currently, one of the most common non-utilized slags in steelmaking. Hence, in an integrated stainless steelmaking process with a ferrochrome submerged arc furnace, this means not only losing iron to the slag but also valuable chrome. Hence, recovery of iron and chrome have a business incentive and an important function for green industry initiative by reducing the requirement of virgin material. However, one of the challenges of slag recycling can be the energy-intensive nature of such a practice. Therefore, an energy efficient approach in material recovery could enhance the incentive of recycling of slag instead of the current practice of land field storage; one such approach is mixing the solid ferrochrome slag into liquid slag from the steelmaking production line. To that end, a static model of a suspended slag particle inside a melt has been developed to investigate the effect of particle size on evolution of temperature within the solid particles. The simulation showed that changes in the diameter of particle can have a significant effect on energy diffusion from the melt into the slag particle. As an example, the simulation suggests that the temperature magnitude at the centre of a 2mm-in-diameter particle reaches 1200 °C after 1s simulation time while, with 5mm particles the temperature magnitude is less than 200 °C. This behaviour is amplified further when the diameter of particle increases further showing a delaying behaviour of particle's diameter on energy diffusion and, consequently, remelting of solid particles.

Keywords: Slag, Ferrochrome, remelting, modelling, solid particle.

1. INTRODUCTION

As the European Green Deal has become a baseline to make the European Union (EU) climate neutral in 2050, the role of industries and more specifically iron- and steel-producers have become increasingly critical (European Commission. Directorate General for Research and Innovation. 2021). This is due to the fact that this industry is not only energy intensive but also produces a significant amount of by-product mainly in the form of slag which is larger than 1.1 tons of slag for each ton of ferrochrome (Kauppi 2007).

The ferrochrome slag contains not only SiO2, Al2O3, MgO or CaO but also some sizable percentage of chrome and iron (Karhu et al. 2020). However, a portion of the slag produced by steelmakers will be stored in slag yard (open space storage facility for unused by-product) while some is used for road construction or by concrete producers (Gao et al. 2023).

Considering the amount of slag produced for every ton of ferrochrome and the percentage of chrome and iron available in the slag (8 and 4, respectively) (Karhu et al. 2020) it is not difficult to calculate the loss of valuable material to the slag. Obviously, improving the share of unused slag material would results in reduction of the virgin material requirement. This reduction in the raw material, then, would have a direct impact on reducing the carbon footprint by reducing the need for raw material mining.

As an example, Karhu et. al. (Karhu et al. 2020) have shown the positive impact of the ferrochrome slag when used as an aggregate to produce refractories. It is shown that the refractory bricks produced using such a slag not only have an improved strength but also show better thermal insulation.

With these considerations, the current study tries a new approach where the solid ferrochrome slag aggregate will be mixed and remelted using AOD-slag. This mixed melt, later on, can be used as a feed material to recover the chrome and iron deposit of solid slag material. To that end, a CFD model of single solid slag particle within a liquid slag is modelled to investigate the effect of particle density on heat diffusion within the particle and, consequently, remelting process of solid ferrochrome slag.

2. MODEL SPECIFICATION

2.1 Modelling Approach

As mentioned, the project tries to melt the solid ferrochrome slag by pouring liquid AOD slag over a packed solid slag bed in a slag pot. However, the initial research question could be formulated as how the heat is transferred through a single pellet inside a melt and if the liquid temperature in the immediate vicinity of the pellet could drop to the solidus temperature.

With this objective in mind, the current model investigates the temperature evolution of single solid particle suspended in a liquid bath. Moreover, since the liquid assumed to be at rest, it is possible to further simplify the system by considering the liquid slag as a solid phase. This, of course, disregards the natural convection may occur around the pellet which in comparison to the liquid bath size could be of a minimal effect.

The thermal properties used for the solid ferrochrome slag particle are derived from the work of (Karhu et al. 2020) as reported below:

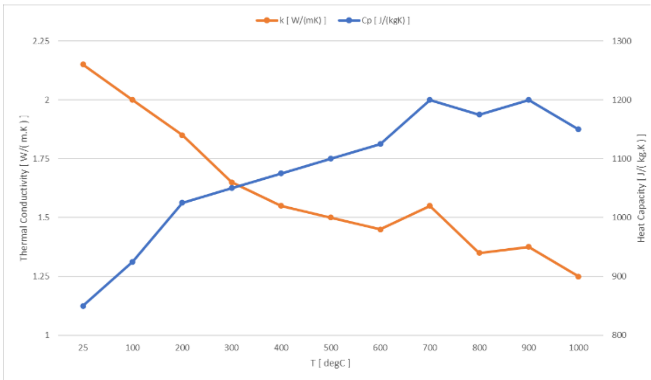

Fig. 1. Thermal properties of ferro chrome solid slag: Castable 1 modified from (Karhu et al. 2020).

2.2 Geometry and Boundary Conditions

As explained, the model looked into practice of suspended solid slag particle inside a liquid melt which is shown in Fig. 2. The domain is formed of a cubic box of 0.5 x 0.5 x 0.5 m^3 which is open to the atmosphere from the top while the sides and bottom faces were assumed to be adiabatic walls. This is to assume a solid particle inside a crucible in a controlled environment.

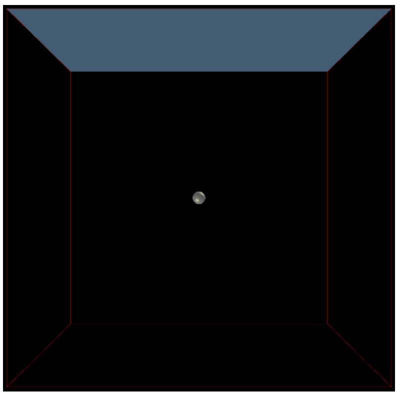

Fig. 2. Domain of calculation with suspended solid slag particle.

3. RESULTS

As mentioned, the objective of this work is to investigate the changes in the temperature profile of the solid slag particle where it is suspended in a liquid slag. Hence, to be able to paint a clear picture, it seems logical to not only look into changes in the magnitude of temperature within the solid particle but also evolution of temperature magnitude of the liquid bath surrounding the particle. This is due to the fact that if the liquid in contact with the solid particle freezes, this phenomenon could hamper the transfer of energy into the solid material.

Naturally, the solid slag particles are produced as a result of crushing solid material hence, the particles do not have a uniform diameter and it can significantly vary from a small round particle to a solid lumpy material. Therefore, it is important to investigate the changes in the solid particle temperature profile due to changes in the particle size.

3.1 Temperature Profile at and around the Solid Particle

Figure 3 shows the evolution of temperature in time at different distance from the centre of the pellet. As can be seen, the x-axis range varies from zero to 5 mm while the particle diameter is equal to 2 mm. Hence, the figure shows the changes in the temperature magnitude of the liquid slag in contact with the pellet till 4 mm away from the surface. Moreover, the vertical dashed line in the figure shows the interface of solid particle to the liquid slag.

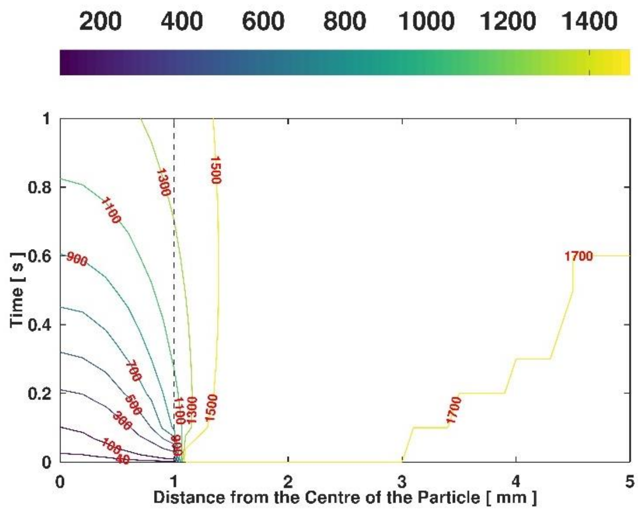

Fig. 3. Contour plot of temperature evolution from the centre of pellet till 4 mm in the liquid bath.

For the pellet, as the figure shows, the temperature at the centre reaches 1200 °C where the liquid temperature in the vicinity of the pellet is around 1400 °C. These values are around 800 and 1200 °C respectively, 0.5 s into the simulation. This suggest that the energy diffuses faster within the particle in the first 0.5 s of the simulation in comparison to the next.

Furthermore, Figure 5 shows the evolution of temperature within the pellet and inside the liquid phase with respect to time for 1 s, similar to Fig. 3. It can be seen that the temperature magnitude of pellet centre, when the diameter increases to 5 mm, drops to 200 °C, more than 80% drop in the magnitude.

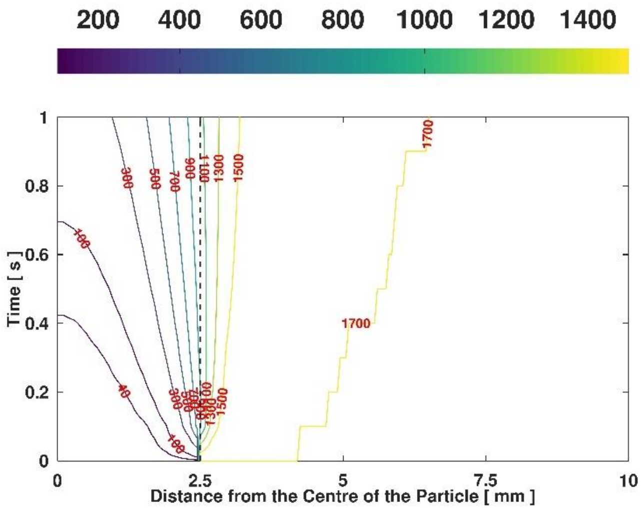

Fig. 4. Contour plot of temperature evolution from the centre of pellet till 7.5 mm in the liquid bath.

Considering the significant change in the magnitude of temperature, it seemed reasonable to try to run the simulation for longer time interval to investigate the effect of particle size on the evolution of temperature.

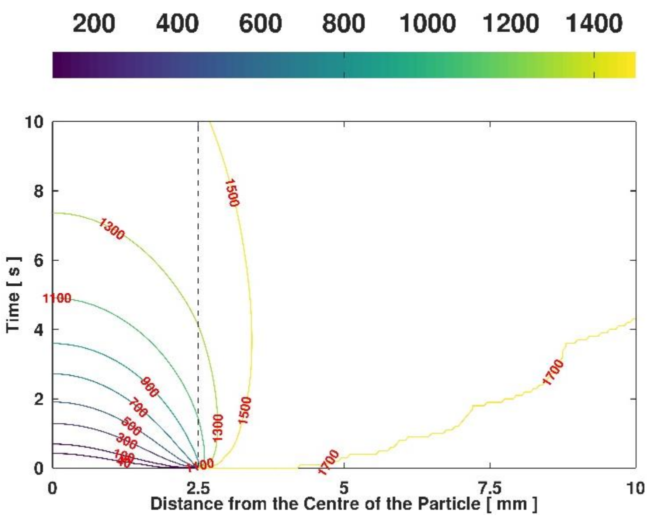

Fig. 5. Contour plot of temperature evolution from the centre of pellet till 7.5 mm in the liquid bath for 10 s.

Figure 5 shows the changes in the temperature magnitude within the pellet and inside the liquid phase for the extended time interval of 10 s. As can be seen, by increasing the diameter of particle to 5 mm, it will take 6 s till the centre of the pellet registers the 1200 °C mark.

Considering such a significant change in the temperature evolution in and around the solid slag pellet, the next logical step was to investigate the temperature profile if the particle size increases.

Figure 6 shows the evolution of the temperature within the pellet and inside the liquid phase with respect to time. It can be seen that the temperature magnitude of pellet centre, when the diameter increases to 10 mm and after 10 s simulation time, is below 700 °C.

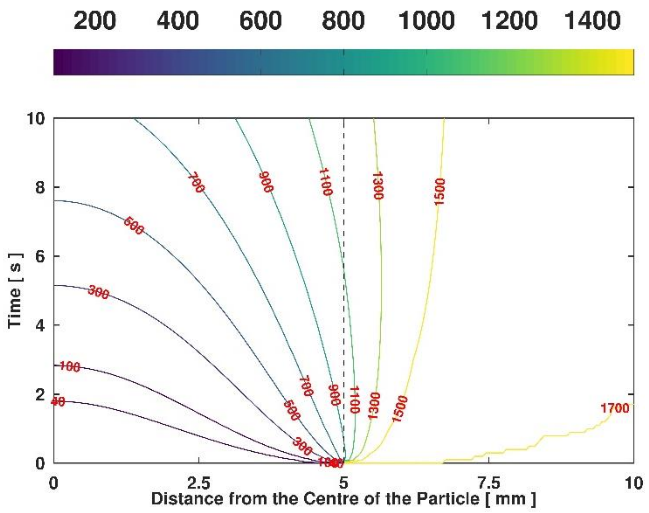

Fig. 6. Contour plot of temperature evolution from the centre of pellet till 5 mm in the liquid bath for 10 s.

The figure also shows that the liquid temperature at the beginning of the simulation is around 1000 °C and after 10 s simulation time it reaches 1200 °C.

Figures 7 and 8 show the evolution of the temperature within the pellet and inside the liquid phase with respect to time for solid particles of 20 and 40 mm, respectively.

It can be seen that the temperature magnitude of pellet centre, when the diameter increases to 20 mm and after 10 s simulation time, has not even reached 100 °C. Moreover, it can be seen that the liquid phase temperature in contact with the particle is almost 1000 °C during the entire simulation time.

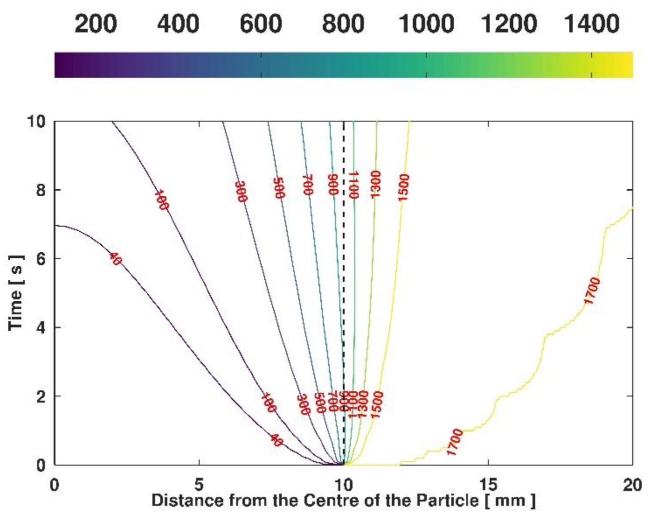

Fig. 7 Contour plot of temperature evolution from the centre of pellet till 10 mm in the liquid bath.

Similarly, it can be seen that, even after 10 s and more than 50% away from the centre of pellet, the magnitude of temperature has not even reached 40 °C and at the near surface region, the magnitude of temperature is hardly 900 °C. The figure also shows that the liquid phase temperature in the vicinity of solid particle registers a constant magnitude of 900 °C.

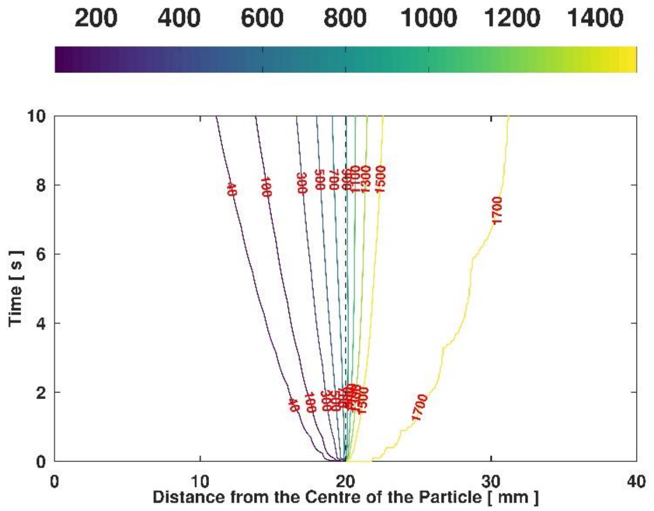

Fig. 8. Contour plot of temperature evolution from the centre of pellet till 20 mm in the liquid bath

3.2 Temperature Magnitude

Table 1 shows the changes in the minimum temperature of the liquid slag at the vicinity of the slag particle. This, in another word, the lowest magnitude of temperature the liquid slag in contact with the slag particle registers.

Table 1 Minimum Liquid Film Temperature around the Particle

Diameter	time	T_t^{Film}	T_{Final}^{Film}
2	0.13	1013	1377
5	0.20	930	1486
10	0.25	881	1197
20	0.78	884	1006
40	3.07	885	914

The importance of such a parameter is that if the liquid slag solidifies around the slag particle, then such a solid shell could hamper the transfer of energy from the melt to the cold particle. This is, of course, due to the fact that the solid slag has a very poor thermal properties and could act as an insolation layer around the solid particle.

In the table, the first column shows the particle diameter, while the second column shows when the liquid file in contact with the solid particle register the lowest magnitude. Then, the third column shows such a magnitude i.e., the lowest magnitude the liquid file registers, and the final column shows the magnitude of the same variable at the end of the simulation.

As can be seen, when the particle diameter increases, the lowest temperature magnitude drops while it occurs later in time. However, when the particle diameter increases from 10 to 20 to 40 mm, the simulation suggests that the minimum magnitude would not drop but occurs significantly further in time (3.07 s compare to 0.78 s to 0.25 s)

The final column, on the other hand, shows the lowest magnitude of temperature at the end of simulation is significantly lower for particle of 40 mm diameter compare to the particle of 20 mm.

4. DISCUSSION

As it was seen, the temperature magnitude of solid particle with 2 mm diameter at the centre of pellet reached 1200 °C after only one second with average temperature magnitude larger than 1300 °C with liquid phase temperature magnitude around 1400 °C. Therefore, it can be concluded that the solid ferrochrome slag will be melted in such a condition. However, Figure 4 seems to suggest a drastic drop in the temperature magnitude when the diameter of particle is set to 5 mm.

Figure 9 shows the temperature within the slag particle for two diameters of 2 and 5 mm. It can be seen that the minimum temperature magnitudes within the solid slag are 1200 and less than 200 °C for particles with diameters 2 ad 5 mm, respectively.

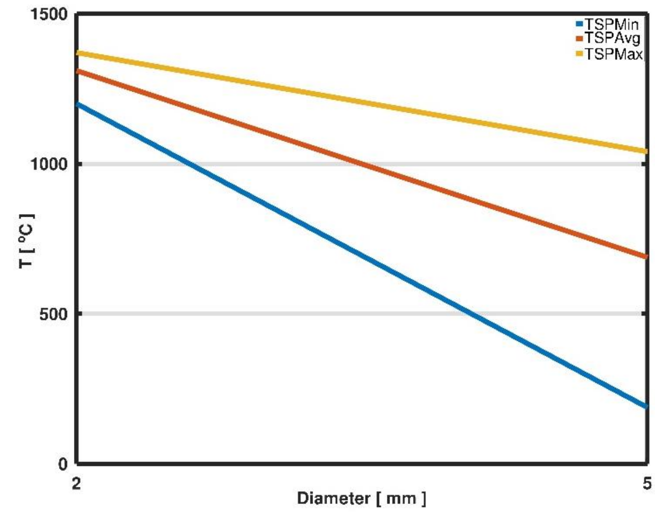

Fig. 9. Minimum, average and maximum temperature magnitude of solid slag pellet at 1 s for diameters 2 and 5 mm.

As mentioned before, the drastic change in the magnitude of temperature suggested the simulation should be run for longer time interval where the particle diameter is larger than or equal 5 mm. Figure 10 shows the final magnitude of temperature for particles diameters 5, 10, 20 and 40 mm within the solid slag and the liquid phase after 10 s simulation time.

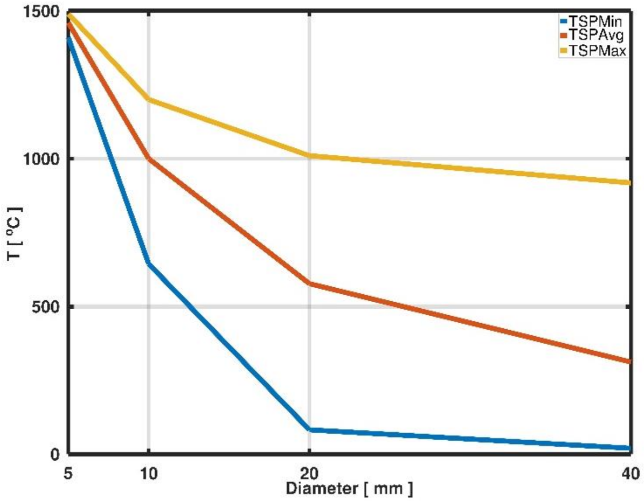

Fig. 10 Minimum, average and maximum temperature magnitude of solid pellet at 10 s for diameters 5, 10, 20 and 40 mm.

It can be seen that the minimum temperature magnitude within the particle drop from 1400 °C to 20 °C for particles diameters of 5 to 40 mm (blue curve in Fig. 10). This, of course, suggests that the temperature magnitude at the centre of particles is not affected by the liquid phase energy even after 10 s simulation time when the particle diameter is equal 40 mm. The figure also shows that the gap between the average temperature magnitude to the maximum increases with the increment of solid particle diameter. This behaviour suggests that a larger portion of the solid particle at larger diameter is yet to be affected by the liquid phase energy.

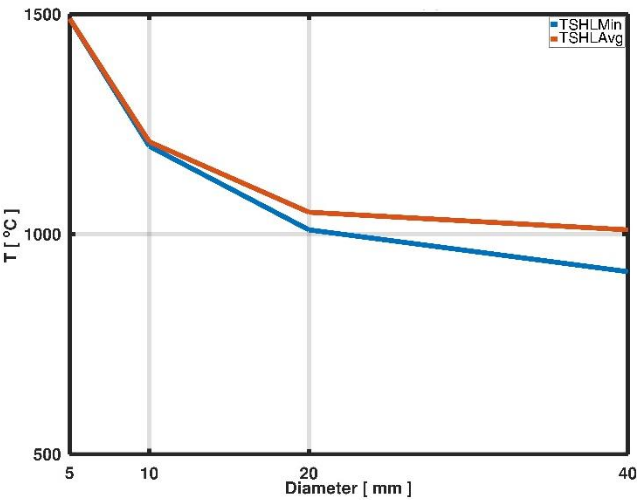

Figure 11 Minimum and average temperature magnitude of liquid phase at 10 s for diameters 5, 10, 20 and 40 mm.

Moreover, Figure 10 shows that for the two cases of 20 and 40 mm diameters, the temperature magnitude of liquid phase in the vicinity of the solid particle is around 1000 [°C]. Therefore, the probability of liquid slag to solidify at the surface of the particle to form a shell increase which, in turn, has the potential to hinder the energy diffusion from the liquid phase into the solid particle.

The cause of such behaviour could be explained through thermal properties of the solid slag. As mentioned, the solid ferrochrome slag properties were reported by Karhu et.al. (Karhu et al. 2020) and Figure 1 shows the thermal conductivity and heat capacity of such a material.

As can be seen, the figure suggests an increase in the temperature magnitude of such a material will lead to decrement of thermal conductivity and increment of specific heat, simultaneously. This, of course, imply that the solid ferrochrome slag hampers the diffusion of energy at the higher magnitude of temperature while it can absorb and store larger amount of energy. These two actions together could be a likely explanation as to why an increase in the size of the particle, even only by a factor of 2.5 from 2 mm to 5, causes such a slowdown in the transfer of energy from the environment towards the centre of solid particle.

5. CONCLUSIONS

The current study investigates the exchange of energy between the solid ferrochrome slag and the liquid AOD slag. This objective is to study the re-melting of the solid ferrochrome slag using the liquid slag collected at the AOD station. To that end, the thermal properties of the materials in use play a significant role.

As shows, the simulation suggests that after 1 s simulation time, the temperature magnitude at the centre of solid slag particle reaches 1200 °C. However, an increase in the diameter to 5 mm (by 2.5 factor) causes the temperature magnitude at the centre drops significantly to the value of less than 200 °C for a 1 s simulation.

Same behaviour can be observed with respect to increases in the diameter of solid slag particle where for a particle of 40 mm diameter, the magnitude of temperature at the centre of the particle is barely higher than initial temperature of 20 °C.

At the same time, it can be observed that the temperature magnitude of the liquid phase in the vicinity of solid particle drop to 1000 °C for a particle of diameter 40 mm. This, of course, suggest that there is a higher probability for the liquid AOD slag to solidify around the solid particle to form a shell which then hampers the transfer of energy from the environment into the solid ferrochrome slag to a larger degree.

REFERENCES

European Commission. Directorate General for Research and Innovation. (2021). *European Green Deal: Research & Innovation Call.* LU: Publications Office. https://data.europa.eu/doi/10.2777/33415 (June 3, 2024).

Gao, Wenhao, Wentao Zhou, Xianjun Lyu, Xiao Liu, Huili Su, Chuanming Li, and Hui Wang. (2023). Comprehensive Utilization of Steel Slag: A Review. *Powder Technology* 422: 118449. doi:10.1016/ j.powtec.2023.118449.

Karhu, Marjaana, Bob Talling, Patrycja Piotrowska, Alba Matas Adams, Abirami Sengottuvelan, Elina

Huttunen-Saarivirta, Aldo R. Boccaccini, and Pertti Lintunen. (2020). Ferrochrome Slag Feasibility as a Raw Material in Refractories: Evaluation of Thermo-Physical and High Temperature Mechanical Properties. *Waste and Biomass Valorization* 11(12): 7147–57. doi:10.1007/s12649-020-01092-4.

Kauppi, M. (2007). Production, Characteristics and use of Ferrochromium Slags. https://api.semanticscholar.org/CorpusID:48465274.