THE VALUE OF MODELLING FOR RAW MATERIAL DEVELOPMENT

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ABSTRACT

The development of sintered synthetic alumina based refractory aggregates requires a couple of hundred tons of material for plant trials. Therefore it is important to have a sound business case for such new aggregate development projects in order to justify the economic risk inherent in large plant trials. For the business case of developing a new lower density alumina aggregate it is essential to be able to quantify the value of such a proposition when applied in steel ladle wear lining. The steel ladle model of Tata Steel IJmuiden was used to evaluate the technical and economic impact of a model brick using a lower density aggregate. The results enabled a sound business decision to be made whether to pursue the new development project. This shows the value of modelling for new raw material development.

INTRODUCTION

Steel production is a very energy intensive process and accounts for a significant share of CO_2-emission from industrial processes. Therefore fundamental transformation projects have been started to reduce CO_2-emission significantly (especially scope 1). However, to reach carbon-neutral steel production, additional improvements are required. Therefore, incremental improvement steps in existing processes are important to further reduce energy consumption and CO_2-emission. The latter is the focus within this investigation, which addresses the development of a new alumina refractory aggregate for steel ladle refractories.

The steel quality is mainly achieved through secondary metallurgy which takes place in the steel ladle. Continuous developments of these processes require adjustments of the refractory lining of the ladle. In addition to these metallurgical requirements, focus is on the steel ladle capacity and heat losses from the steel in the ladle . These are influenced by the refractory lining.

The steel ladle capacity is often the limiting factor for increasing the productivity of a steel plant. Therefore many steel plants in Europe have reduced the thickness of the refractory lining of the ladles to provide an increased volume of steel tapped into the ladle[1]. For example, the lining thickness in the ladle side wall of Tata Steel Europe Ijmuiden is 77 mm for the permanent lining and 140 mm for the wear lining. During the ladle campaign, refractory wear increases the volume available for steel tapping until the total weight of the filled ladle reaches the maximum crane weight limit. Here, a reduction of the bulk density of the refractory lining can increase the ladle capacity when the volume is no longer the limiting factor.

Heat losses of steel in the ladle are expensive (e.g. 0.1€/K per tonne of steel[1]) and increase scope 1 CO_2-emissions in steel production. The refractory lining plays an important role as shown in Fig. 1. In addition to heat loss through the refractory lining to the steel shell, there is significant heat loss at the hot face during those times during the campaign when the ladle is empty. The more heat in the wear lining that is lost by radiation prior to tapping the next charge, the more heat that will be taken from the next steel charge. The magnitude of heat loss depends on the heat capacity (bulk density) and thermal conductivity of the wear lining. When comparisons are made between MgO/C brick which has a higher thermal conductivity than alumina-spinel castable, higher energy losses are clearly shown with the brick lining[3].

Synthetic alumina based refractories are important materials for steel ladle lining. Fired alumina-spinel bricks and spinel-containing or spinel-forming castables provide high wear resistance. This enables thinner wear lining and an increase in steel ladle capacity. The thermal conductivity is significantly lower when compared to carbon-bonded refractories. This reduces thermal losses of the steel in the ladle. Reduction of bulk density would enable further improvement here.

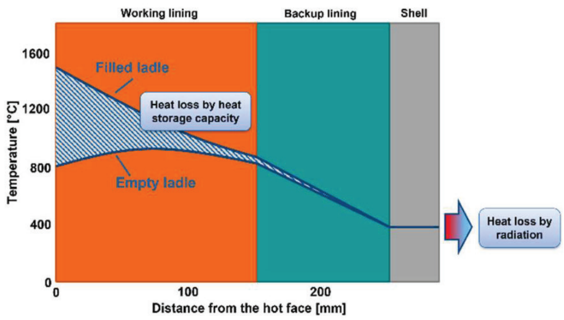

Fig. 1: Schematic drawing of the temperature change in the refractory lining of a steel ladle during operation. Drawing after Ogata et al.[2].

NEW REFRACTORY AGGREGATE IDEA

For dense refractories, the bulk density of the main raw material aggregate strongly influences the bulk density of the refractory product. Therefore the idea was to develop a new sintered alumina aggregate with lower bulk density than tabular alumina T60/T64 or white fused alumina but with comparable wear resistance for ladle wear lining. This would result in a reduced weight steel ladle wear lining leading to a higher tapping weight when the crane weight limit is reached. In addition, it would reduce the thermal conductivity and heat capacity of the wear lining resulting in lower heat losses of steel in the ladle.

Sintered synthetic alumina aggregates such as tabular alumina and magnesia-alumina spinel are produced in a ceramic manufacturing process. The raw materials are ground to a fine powder, granulated into a green body which is dried and then fired at temperatures of up to 1900°C in a shaft furnace (Fig. 2). Such a sinter plant is a large facility which requires a couple of hundred tons of material to conduct a plant trial during the development of a new sintered aggregate material. It cannot be done with just a couple of tons of material during new development projects. Therefore it is important to have a sound business case for such new aggregate development projects in order to justify the economic risk inherent in large plant trials.

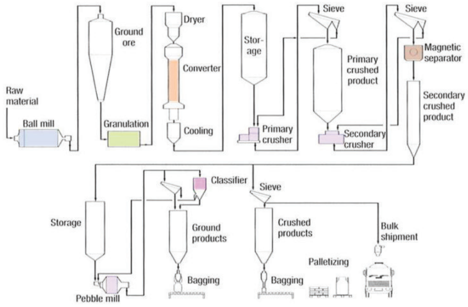

Fig. 2: Tabular alumina production process at Almatis.

The idea of a new sintered alumina aggregate was discussed in the Stage-Gate process which is used for new product developments within Almatis. The question was raised, whether the value created in the steel ladle application would be high enough for all stakeholders in the business: Almatis as raw material producer, refractory producers as customers, and steel plants as end users. In 2016, the motivation and advantages of applying a sophisticated steel ladle model at Tata Steel IJmuiden were discussed in the keynote lecture at the International Colloquium on Refractories in Aachen, Germany[4]. The model allows a quantitative assessment of the economic impact from refractory changes in the ladle lining. The general value proposition of the new aggregate idea was interesting for Tata Steel IJmuiden therefore it was evaluated in the ladle model for the plant in IJmuiden.

TATA STEEL LADLE MODEL

Since refractories form a significant part of the total spend of a steel plant, there is often a drive to lower spend by using less and/or cheaper refractories. In practice the total refractory costs might actually increase when using a cheaper material, if it leads to a lower lifetime, which it often does. Although a focus on increasing the lifetime is usually the better option, this too could have a negative outcome, when materials are too expensive or when it leads to lower ladle capacity because of increased lining thickness.

It is evident that changes to the refractory lining of a steel ladle can have a major impact on the steel production route and associated costs. Making the right decisions for both the short term ("Should we use material A or material B?") and the long term ("Should we focus on increasing ladle life, increasing ladle capacity or reducing thermal losses?") requires that all cost effects are understood, quantified and taken into account.
Tata Steel IJmuiden has recognised that to achieve an optimum lining concept for the steel ladle (=highest value in use), the following factors must be taken into account:

- Total refractory cost (materials, installation costs, heating up etc.)
- Temperature losses of liquid steel
- Ladle capacity (heat size)
- Ladle safety (risk of breakout)
- Ladle availability (risk of having no ladles available)

The first three factors can be expressed in financial terms to compare the total economic impact of different options, the latter two (ladle safety and availability) are enablers that need to have a certain minimum value, often based on the current situation (e.g. risk of breakout should not increase as a result of changes to the lining). Since the different aspects are strongly interrelated it is very difficult to make these calculations by hand, therefore a steel ladle economic model was developed to calculate the total cost effect of changes, as shown schematically in Fig. 3.

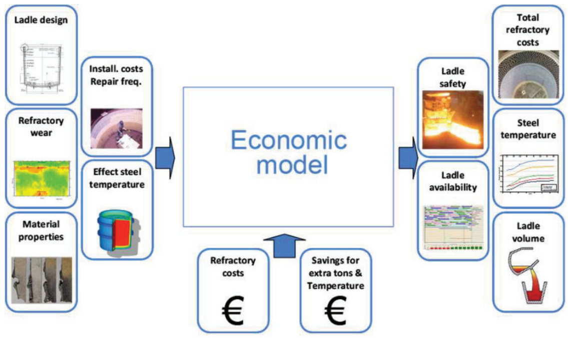

Fig. 3: Schematic overview of Value in Use (ViU) model inputs and output.

Of course any model output is only as good as its inputs. For the steel ladle model the critical inputs are:

- Ladle design: type and thickness of refractory material in the different areas of the ladle.
- Refractory wear: reduction of wear lining thickness in mm/heat for each area, based on laser scan data. This is used to predict ladle life.
- Material properties: e.g. density (to calculate ladle capacity) and thermal conductivity (to calculate thermal losses). This data is measured by Tata Steel IJmuiden to make sure that any difference in measured values reflects a real difference in material properties and is not caused by differences in measurement method or equipment.
- Installation costs: costs of installing new refractories and heating the lining before use.
- Effect on steel temperature: calculated using separate finite element model (FEM).
- Refractory costs: price for each material.
- Financial impact of changes in output and temperature: costs per heat, contribution margin for extra output, savings for 1K decrease in temperature loss.

The model does not report absolute economic values, but rather is set up to compare scenarios and calculate the cost effect of changing from one scenario to the other. Most often the current situation is compared with either a known alternative (e.g. supplier A vs. supplier B) or with a hypothetical future situation ('what-if" analysis). The model reports the calculated effect on the five factors mentioned before, e.g. the change in ladle life and ladle capacity, as well as the resulting economic effect of these changes. The reasoning behind the model and its technical workings are described in more detail in the paper associated with the aforementioned keynote lecture[4].

As an example of using the model for short-term decisions, consider the following scenario: a plant trial with an alternative material for the steel ladle slagline has been performed and a decision is required on whether this material should now be implemented as standard. The new material is based on higher grade raw material and therefore more expensive and more dense than the old material, negatively affecting ladle capacity. The plant trial has shown that wear rates are lower and, since the slagline often has the highest wear, ladle life is going up. Using FEM calculations it is shown that the higher thermal conductivity leads to an increase in temperature losses. In the past it would have been impossible to decide if it makes economic sense to apply this new material, as it was not known which cost effect is strongest (higher price, higher life, lower capacity or higher thermal losses), However since all required inputs to the ViU model are known, it is now possible to calculate the exact economic impact and make a substantiated decision. It is even possible to run the same scenarios with different boundary conditions to check if the outcome is still favourable if plant or market conditions change in future.

A similar approach can be followed when using the model for long-term strategic decisions. Some examples of questions that could be evaluated in this way:

- What is the maximum life we can achieve by reducing slagline wear?
- Does it make sense to reduce heat losses by introducing additional insulation (at the cost of ladle capacity and potentially life)?
- Should we increase ladle capacity by increasing the internal volume or by reducing the weight of the ladle (in case crane capacity is limiting)?
- What is the optimum refractory design (material qualities and lining thicknesses)?

For such questions most often not all input data is known, e.g. when evaluating a material for plant trials, the actual wear rates are not yet known and therefore ladle life cannot be accurately predicted. In this case the model is used for "what-if" calculations: what will the cost effect of changing to this material be if the wear rate is x% lower. In this case x is either an educated guess, based on other, known properties or alternatively x is varied through or a range of values to evaluate under which conditions the resulting economic impact is positive. By varying multiple properties through a range of likely values, it's even possible to use the model as an optimizer to find the best potential design.

When the output of "what-if" calculations is used to implement changes in practice it is important to verify the estimated inputs with real world data whenever possible, for example by measuring actual material properties or performing a plant trial to establish wear rates. Similarly it makes sense to reevaluate model outputs when boundary conditions (e.g. market situation) change over time, to check if the economic impact is still favourable.

In the case shown here the approach with educated guess values as inputs was followed, as the new aggregate material was not yet produced, but sufficient data was available to make reliable estimations of critical properties.

ECONOMIC ASSESSMENT OF THE IDEA

The input data for model bricks with the new aggregate were calculated based on the following assumptions:

- Alumina-Spinel fired brick with 95 wt% Al_2O_3 and 5 wt% MgO
- Bulk density of the new aggregate 3.2 g/cm³ (vs. 3.55 for T60/T64)
- New aggregate compound in brick 50 wt%, spinel with bulk density of 3.3 g/cm³ 18 wt%, other alumina compounds (bulk density 3.8 g/cm³) 32 wt%
- Apparent porosity of brick 14 vol% (just matrix porosity, disregarding open porosity of the coarse aggregate
- New brick bulk density 2.93 g/cm³ vs. standard brick density 3.1 g/cm³
- Thermal conductivity values derived by extrapolation from existing bricks with different bulk densities to calculated bulk density of the new aggregate brick
- Wear performance and lining life identical for new vs. standard brick

Tab. 1: Bulk density and thermal conductivity of fired alumina-spinel bricks – standard vs. new aggregate brick

	Standard brick	Low density brick
Bulk density [kg/m³]	3.10	2.93
Thermal conductivity [W/mK]		
25°C	4.5	2.6
250°C	3.6	2.3
500°C	3.1	2.3
750°C	2.7	2.1
1000°C	2.5	1.9

With the FEM model for the IJmuiden steel ladle, the steel temperature at the start of casting was compared between standard and low density brick. These settings were used, which represent an average steel ladle cycle:

- Ladle full time 90 minutes
- Casting time 45 minutes
- Ladle empty and preparation time 120 minutes

The difference between the two designs was 1.5 to 2K lower temperature loss for the low density brick. That could mean a cost saving of about 0.15 €/tonne of steel when referring to published figures[1].

The second aspect evaluated with the ladle model was the increase in ladle capacity with respect to steel tapping weight, when the maximum crane weight becomes the limiting factor during the ladle campaign. Different examples with regard to steel market conditions, production levels, etc. were used. Calculations were made to investigate the potential economic gains by an increased ladle capacity. As these calculations were done with actual, specific data from the IJmuiden steel plant, the exact outcome for the absolute economic impact cannot be published for proprietary reasons.

To evaluate the business case for the planned new lower density alumina aggregate, a different approach was chosen. Tata Steel IJmuiden gave a potential price range for the new lower density brick. This would represent an economic break-even situation for the steel plant when compared with the existing standard brick price range. In this way, the difference between standard and new brick price ranges represented the value created by the new development. Naturally, this total value gain would need to be shared between all business stake holders: the raw material producer, the refractory supplier, and the steel plant customer. If the value improvement is sufficient for each stakeholder, only then will it make sense to invest effort and money into the development of a new raw material, new refractories based on it, and on site testing in the steel plant.

A third benefit would be the reduction of CO_2 emissions by using lower density bricks for the steel ladle wear lining. Scope 1 emissions could be reduced through lower temperature losses of steel in the ladle and consequently lower tapping temperature from the BOF or reduced reheating in a ladle furnace. Scope 3 emissions could be reduced by overall reduced material consumption when the lower density bricks achieve the same lining life performance as standard bricks. However, these factors have not been evaluated and quantified at this stage and will be the subject for future work.

The model evaluation of the potential new lower density Alumina-Spinel fired brick based on the new lower density refractory aggregate provided a potential value gain which was high enough to justify the business case for the development of the lower density alumina aggregate. This modelling was an essential contribution for making the development decision in the Almatis Stage-Gate process.

CONCLUSION AND OUTLOOK

The evaluation of alumina-spinel fired bricks based on the new lower density ECO-TAB® aggregate in Tata Steel IJmuiden´s steel ladle model has shown the potential for improvements. Firstly, the ladle tapping weight can be increased once the volume is no longer the limiting factor but the crane weight. Secondly, the heat loss from steel in the ladle to the refractory lining can be reduced. The economic impact of these improvements is about equal for both of them. In absolute numbers, which cannot be disclosed here for proprietary reasons, the economic improvement is large enough to make an attractive business case for all stakeholders. In addition, lower material consumption through lower weight refractories provides an additional economic and environmental advantage.

Based on the positive results from the modelling the development of the lower density aggregate was agreed and carried out. The new product ECO-TAB® was launched at UNITECR 2023[5]. It has about 7% lower bulk density when compared to tabular alumina T60/T64, so that the castable or brick density is reduced by 3-4%. The thermal conductivity of alumina-spinel castables with ECO-TAB® is reduced by about 10%.

ECO-TAB® testing at Tata Steel IJmuiden has been postponed due to the decision to change from fired alumina-spinel bricks to alumina-spinel monolithic steel ladle lining. Initially full focus will be on this transition.

Meanwhile, ECO-TAB® was tested in steel ladle castables at different steel plants. The wear behaviour is comparable to castables with Tabular T60/T64.

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