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STEEL AND REFRACTORY CHEMICAL INTERACTIONS AND MECHANICAL BEHAVIOR OF PLATES FOR SLIDING GATE DURING STEEL CONTINUOUS CASTING

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ABSTRACT

The main objective to increase CC productivity as well as steel quality by using optimized refractory from ladle-tundish-to-mold lead to techniques that allow the prediction of steel and refractory chemical interactions as well as mechanical behavior of refractory component. Specific models (CFD) have also been developed to better take into account the physical parameters at the steel/refractory interface and to optimize steel flow control. They are completed by dedicated thermal stress analysis in order to improve thermal shock resistance. The mechanical Finite Element Analysis evaluations take into account specific mechanical behavior of refractory components as well as high temperature evolution of their properties.

KEYWORDS: continuous casting, refractory materials, chemical and mechanical behavior

1. Introduction

To improve the performances of steel flow control, new approaches have been developed in order to better understand the high temperature behavior of refractory components.

One of the main objectives was to precisely evaluate steel refractory interaction to determine corrosion mechanisms. This has been achieved by coupling specific experimentation and thermodynamic evaluation. A second objective has been to determine high temperature mechanical behavior of refractory components, which are composite products. The implementation of specific properties in Finite Element Analysis codes allows improved design of components and evaluation of material characteristic influences.

Finally the development of dedicated fluido-dynamic codes allows the prediction of physical and chemical phenomena occurring during steel continuous casting.[1]

2. Optimization of the sliding gate refractory plates

The plates are the core of a ladle slide gate, and the investigations concentrated initially on establishing the optimum plate design.

Existing plate design weaknesses:

The historical rectangular-rounded plate shape has been applied in many variants such as asymmetric or symmetric versus the bore position, canned or banded, with or without spigots. Their dimensions were generally oversized. Their wear pattern showed some weaknesses such as the formation of cracks in critical zones and particularly in the throttling and tracking areas.

Fig.1. *Rectangular-rounded plate with cracks*

Modern analysis method:

Empirical research had already resulted in the development of more sophisticated plate shapes but the team decided to investigate using modern analysis methods such as Finite Element Analysis (FEA), mathematic modelling, other laboratory constraint measurements and field trials to identify an optimized pattern. [4]

The material model considered the Young’s modulus, the yield stress (plastic), the thermal conductivity, the heat capacity and the thermal expansion. The thermal boundary conditions were established based on field temperature measurements.

The mechanical boundary conditions were imposed by the mechanism design.

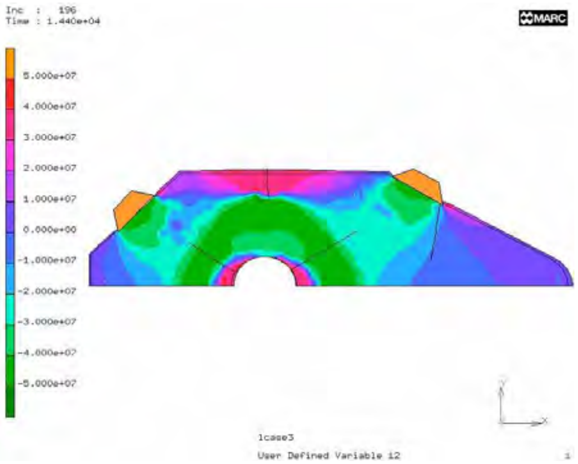

Fig.2. *Finite element analysis of an optimized plate*

Crack definition:

The observation of used plates allowed us to define three crack modes such as: outside cracks, longitudinal cracks and transversal cracks.

The outside cracks are related to the free expansion whilst the longitudinal cracks are related to the “clamping angle”, the plate length/width ratio and the bore size. The transversal cracks are linked to the plate support load.

Sensitivity analysis carried out using elastic and elasto-plastic material models.

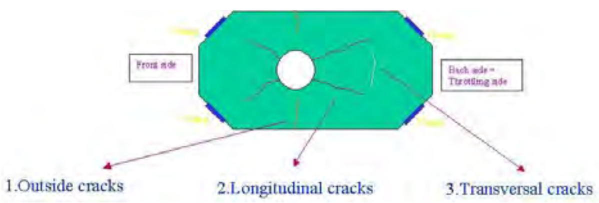

Fig.3. *Crack definition*

Theoretical conclusions:

The conclusions of this analysis can be gathered as follows:

-Critical influence of material plasticity

-Front and back-side stress pattern quite independent

-Clear influence of clamping angle on the stress pattern

-Minor influence of bore size on the stress pattern

-Clamping closest to the bore

-Limit the force applied on the plate through the clamp

“The crack cannot be avoided but the pattern can be influenced by the plate shape and clamping design” is the basis of the plate concept. Therefore, the cracks have been orientated to non-critical zones by the application of optimized clamping angle and clamping force.

Theoretical plate shape:

The so called “Coffin shape” plates are roughly fitting some of those conditions. This is the “basic design”, however, this is not enough to comply with all production and operation requirements.

It is crucial to note that due to the optimised shape, smaller plates are performing better life with equivalent bore size. It strongly improves the recycling rate when using the plate on both faces (FLIP process). This significantly reduces the operation cost of the plates and the system.

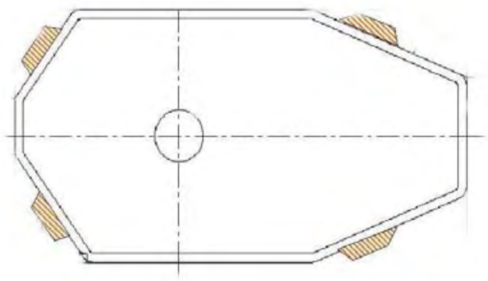

Fig.4. *“Coffin shape” plate*

Tuning this shape required more sophisticated considerations that generated a practical “optimized shape” that can be manufactured and efficiently applied in the mechanism.

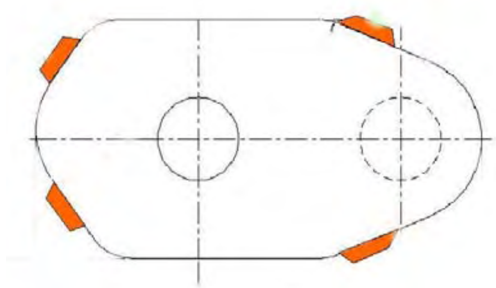

Fig.5. *“Optimized” plate shape*

A mathematical relationship has been identified between the different parameters.

The actual plate wear pattern recorded during many tests and industrial application confirmed the validity of the design.

3. Chemical behavior of refractory component during steel casting

The classical experimental evaluation of steel corrosion is not enough to determine refractory components. Standard experimentation is conducted with limited amount of steel, while in reality steel is continuously renewed at the refractory interface.

The second limitation faced with today is that refractory interface is, in reality, controlled by variables like steel dissolved elements and steel inclusions. For instance, the volume of inclusion during continuous casting is comparable to the volume of refractory components used so they have a strong influence on steel/refractory reactivity. So the only possible approach to corrosion is to determine experimentally mass transfer from refractory to steel and to extrapolate for continuous casting conditions.

3.1 Steel and refractory interaction model

To define the nature of chemical reactions, specific experiments have been conducted. For the first type of experiment, pure iron is melted in an induction furnace with tailored alloy additions.

A rotating refractory sample is placed in the melt and steel chemical composition changes are determined by steel sampling during the experiment. A second set of experiments consists of degassing evaluation on refractory samples using a mass spectrometer at increasing temperatures.[2]

For the different types of refractory composition used in steel casting the following major reactions have been determined and quantified:

- Charbon dissolution $C \rightarrow \underline{C}$ (1a)

- Silica reduction $SiO_2 + C \rightarrow SiO(g) + CO(g)$ (1b)

- Magnesia reduction $MgO+C \rightarrow Mg(g) + CO(g)$ (1c)

- Zirconium reduction $ZrO_2 + 3C \rightarrow ZrC + 2CO(g)$ (1d)

- Oxydes dissolution $M_xO_y \rightarrow x\underline{M} + y\underline{O}$ (1e)

The different reaction kinetics have been determined depending on steel grade, refractory composition, microstructure and physical parameters at the refractory interface (i.e. pressure and temperature). For example the model for carbon dissolution is shown in Figure 6.

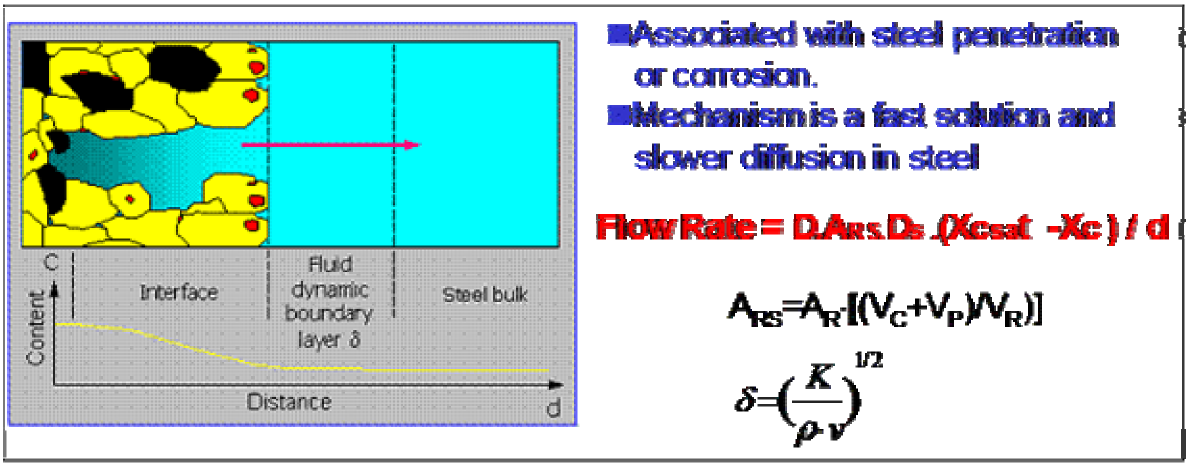

***Fig. 6.**. Carbon dissolution: carbon flow rate as a function of reactive surface (A_{RS}), carbon content (X) and steel flow.*

The global result is a mathematical program, which calculates the flow rate of species passing from the refractory interface to the steel.

4. Mechanical behavior of steel casting refractory components

The mechanical behavior of refractory components is by far more complex than generally admitted.

This is mainly caused by the composite nature of the component and the large temperature range in use.

Refractory materials behave like composite structures with specific features coming from the phase transformations occurring at high temperatures.

The standard mechanical evaluations like 3 point bending or sonic measurement of elasticity induce important approximations in thermal shock evaluation. Unfortunately the consequences are inappropriate choices for product design.

4.1 Example of mechanical properties

Cold mechanical properties of standard alumina graphite composites have been evaluated in tension and compression mode. The results presented in Figure 7 and detailed in Figure 8, are typical for graphite containing materials used in continuous casting.

The important difference between tension and compression are classical for ceramic material but the relative important plasticity observed is characteristic of a bi-phasic composite. One major consequence is that strength determined by 3 point bending is overestimated when compared to tension that is the main failure mode.[5]

The sonic determination of elasticity is only valid for limited strain while the real pseudo-elasticity is much lower. This leads to overestimated stress levels caused by a thermal gradient. Finally the permanent strain occurring during thermal loading needs to be taken into account for thermal cycling.

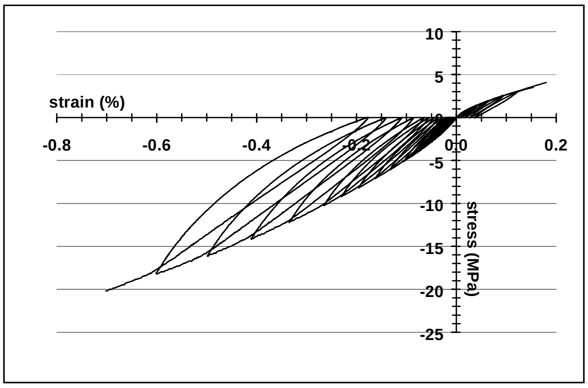

Fig.7. *Stress strain behavior of alumina graphite in tension and compression.*

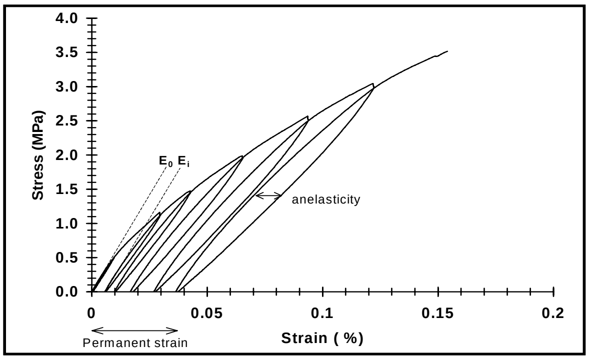

Fig.8. *Tension behavior of alumina graphite.*

4.2 Thermo-mechanical stress models

Standard Finite Element Analysis (FEA) codes don’t take into account specific refractory properties. In order to overcome this problem, dedicated Finite Element Analysis models take into account refractory material specificity.[3]

The commercially available basic code (Abaqus) is implemented with subroutines, which incrementally give a more precise model of refractory thermal loading. The subroutines take into account phenomena such as inelasticity, creep deformation, and/or phase change. Model results are compared with sensitivity analysis and validation experimentation in order to ensure the validity of the results.

4.3 Material and design development

The thermal cycling of continuous casting refractory materials generates very different stress levels during operating time. The different stress evolution between transient heating and stationary working conditions needs to be carefully analyzed with appropriate product property determination. The effects on refractory material and design are highly dependent on operating conditions. In other words, a refractory product can not be ranked in terms of global thermal shock resistance but for only one given thermal shock situation in a given application.

Thermal stress situations have to be carefully analyzed in order to determine the major cause of failure: material properties or design. The optimization of refractory component consistency, as a function of steel casting efficiency, is depending on the model accuracy. An example of nozzle design for a thin slab caster is shown in Figure 9. The view represents a quarter of the total pieces cut by the 2 symmetric planes.

The maximum stress is localized on the narrow face of the nozzle where the thermal shock cracking is usually observed. The analysis of the stress during the transient start up of the cast show that the maximum stress is developed minutes after steel casting starts and that the stress developed during preheating is much lower. As a consequence the increase of thickness of the insulation layer (Thermacoat) has reduced significantly the stress level and reduce the cracking tendency.

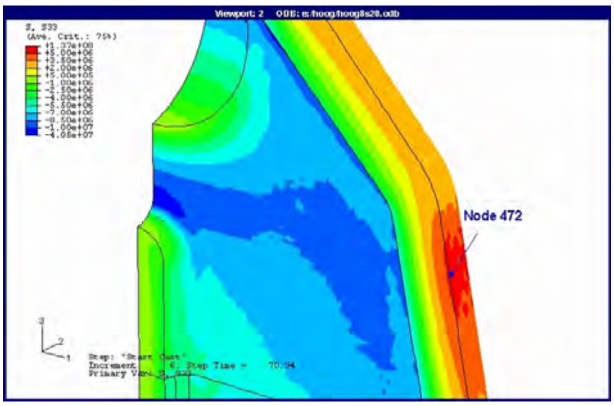

Fig. 9. *Stress evaluation of thin slab nozzle.*

4. Conclusion

Increasing demands for steel quality and continuous casting productivity require new approaches in terms of refractory component development. Advanced refractory design is achieved by coupling dedicated thermochemical and thermomechanical models with fluido-dynamic simulations. When appropriate material behavior at operating temperatures is experimentally demonstrated and validated, model results provide innovative solutions for refractory component optimization. These new approaches, combined with empirical field experience, are necessary to improve current and future steel continuous casting processes. The new scientific investigation methods applied to the sliding gate refractory and mechanism designs, cross checked with actual operating results allowed us to better understand the phenomena of crack formation and crack control leading to the implementation of optimized refractory patterns and flow control systems.

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