IMPROVING REFRACTORY DESIGN THROUGH OPTIMIZATION TECHNIQUES AND NUMERICAL SIMULATION *

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Abstract

Refractory materials play an important role in the steelmaking industry, whether in the quality of the produced steel or in the plant's productivity. Some components present higher influence in those aspects than others, therefore, more resources should be spent in their design in order to guarantee a greater performance during operation. In the present work, two different components are designed to better fulfill the customer needs: a ladle shroud and a slide gate plate. If well designed, these refractory products can assure less maintenance time and superior steel quality. Therefore, the goal here is to avoid the refractory failure and achieve longer campaigns by decreasing thermal-mechanical stress levels and, consequently, enhancing plant's productivity. The designs were conducted using numerical simulations and optimization tools. First, the relevant geometry features of the refractory parts were selected and varied within a certain range. Then, the operational conditions were applied so different scenarios could be simulated. Finally, an optimization algorithm was used to define the best set of geometry values according to a response surface created out of the numerical simulation outputs. It is possible to see that the projects have shown considerable thermal-structural improvements when compared with the base case

Keywords: Optimization, Numerical Simulations, Slide Gate Plate, Ladle Shroud.

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1 INTRODUCTION

As defined by [1], the Continuous Casting process consists of a steel flow running from the Steel Ladle to the Tundish and further to a Mold in which the steel starts to solidify into plates that might receive additional treatments depending on the quality that the steel mill wants for its final product. The steel flow is controlled by different refractory components installed throughout the Continuous Casting process. Two of these components are the objects of study in this article: the Ladle Shroud and the Slide Gate Plate. This last product is part of a more complex assembly called Slide Gate Mechanism, a flow control system capable of cease the upstream steel flow coming from the Ladle, if needed. Figure 1 shows the flow control components installed in the Continuous Casting equipments.

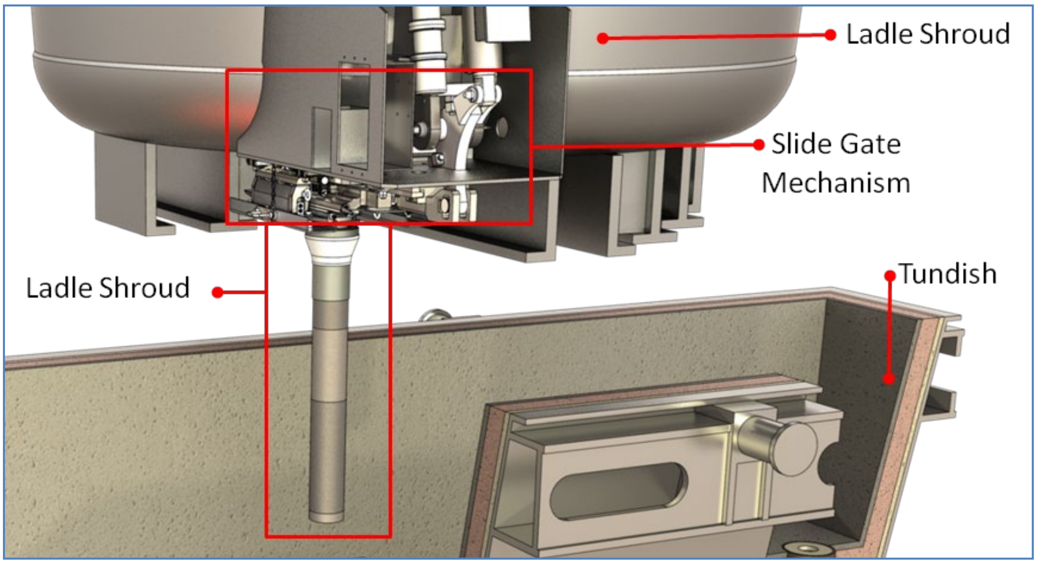

Figure 1: Flow control components in the Continuous Casting Process.

Figure 2 shows sketch view of the Slide Gate Mechanism that allows one to see the Slide Gate Plates.

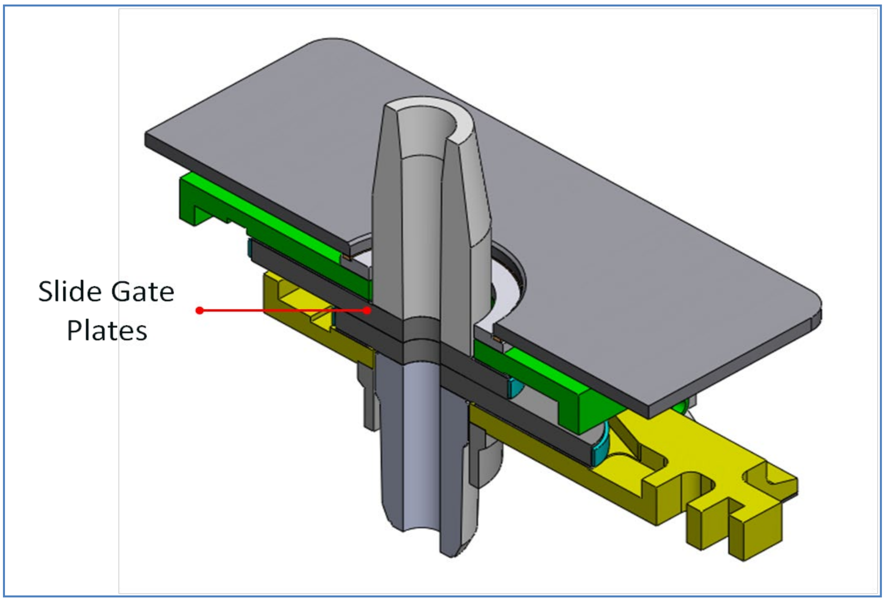

Figure 1: Slide Gate Plates in the Mechanism detail.

This refractory components are expose to liquid steel in high temperature levels, up to 1600 □C. This operational conditions creates great temperature gradients that, together with mechanical restrictions, generate thermal-mechanical stresses through the parts. The goal of this work is to reduce these stress levels by optimizing the Slide Gate Plate and the Ladle Shroud geometries using numerical simulation.

2 DEVELOPMENT

2.1 Model Description

The methodology used to study the stress profile in the refractories can be divided in four parts: the material model, the numerical model and boundary conditions, the optimization process and the final results. After these discussions one is able to understand how to benefits of the numerical tool for any optimization development.

2.1.1 The Material Model

Many authors, such as Teixeira [2] and Poirier [3], describe different models that can be used to describe the thermal-mechanical behavior of refractory materials. As this analysis consists of comparing different geometries to find the best solution that fits a costumer necessity, a linear-elastic model was adopted for the present qualitative comparison. The material properties, as thermal conductivity, thermal expansion, Young's Module and Poisson ratio were taken out from both RHI Magnesita material library and reference books such as [4].

2.1.2 The Numerical Model and Boundary Conditions

The numerical model is a quasi-static approach, which means the results taken out from the simulations are valid for an equilibrium state, time-dependent phenomena are not taken into account.

As the Ladle Shroud presents axisymmetric geometry and boundary conditions, it was possible to reduce the size of its model in order to save computational efforts, saving time as well. Figure 3 and 4 shows the simulation domain and the boundary conditions for this component. For the thermal simulation a thermal load was applied in the region that enters in contact with the molten steel and heat loss are model by convection and radiation conditions. In this part is important to remember that the metallic capsule and holder presents different radiation coefficients and must be set separately.

The Slide Gate Plates also present a symmetry, in fact the whole mechanism is symmetric in respect to the center plane. Another simulation resource to save computational sweat is to apply boundary conditions instead of modeling elements far from the area of interest. Figures 5 and 6, analogue to Figures 3 and 4, presents the boundary conditions for the Slide Gate Plate simulations. These boundary conditions were applied with the help of [5].

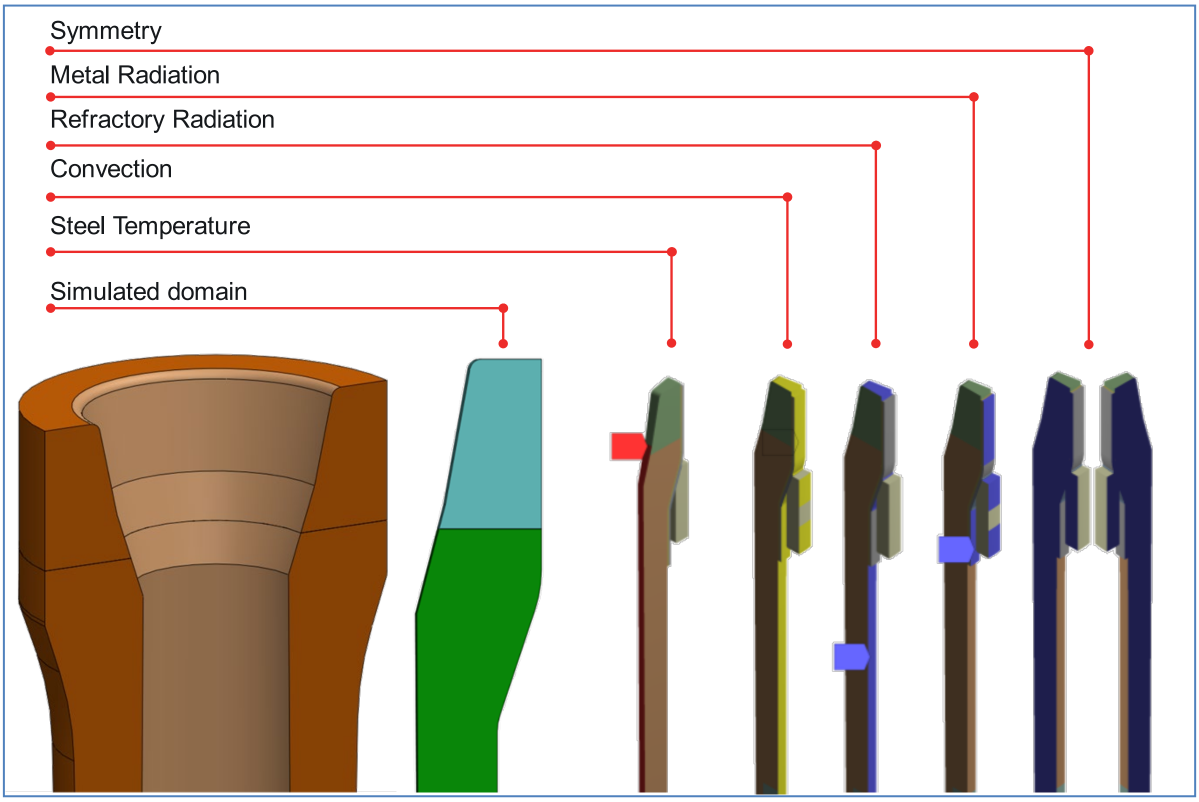

Figure 2: Ladle Shroud's simulated domain and Thermal boundary conditions

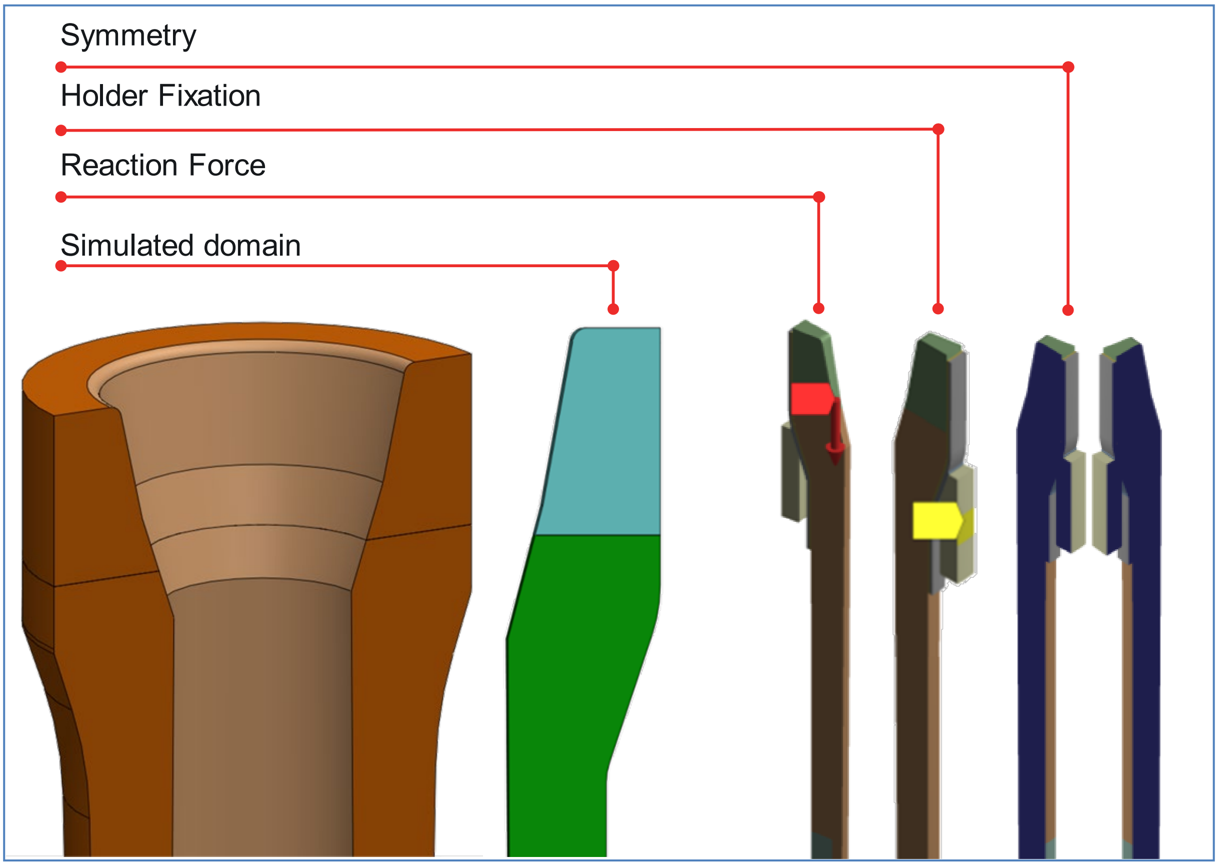

Figure 3: Ladle Shroud's simulated domain and Structural boundary conditions

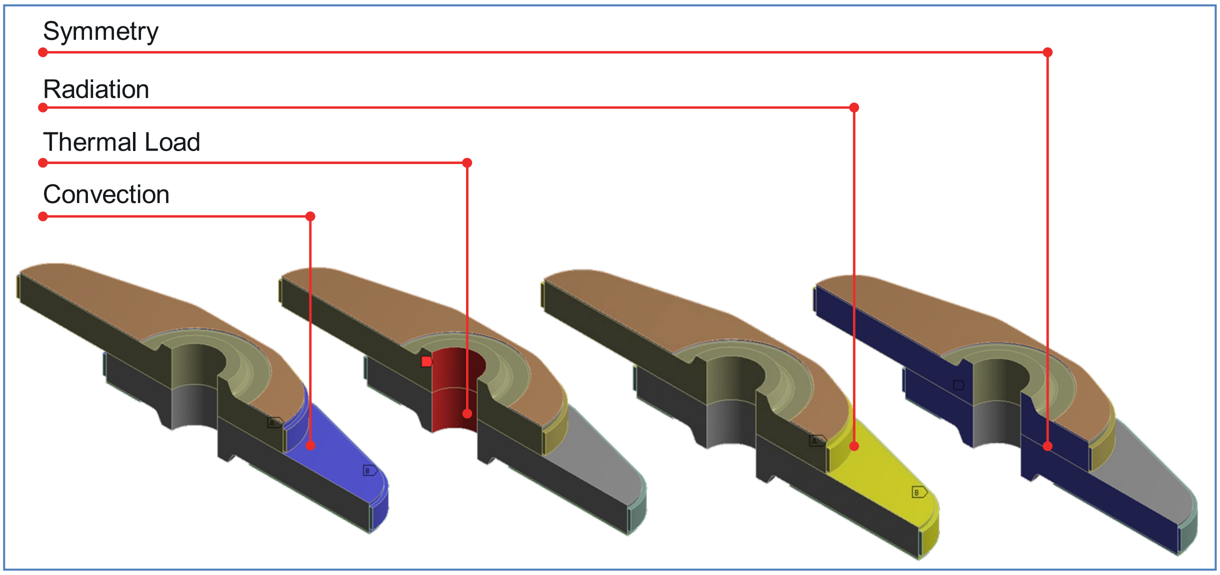

Figure 4: Slide Gate Plate Thermal boundary conditions

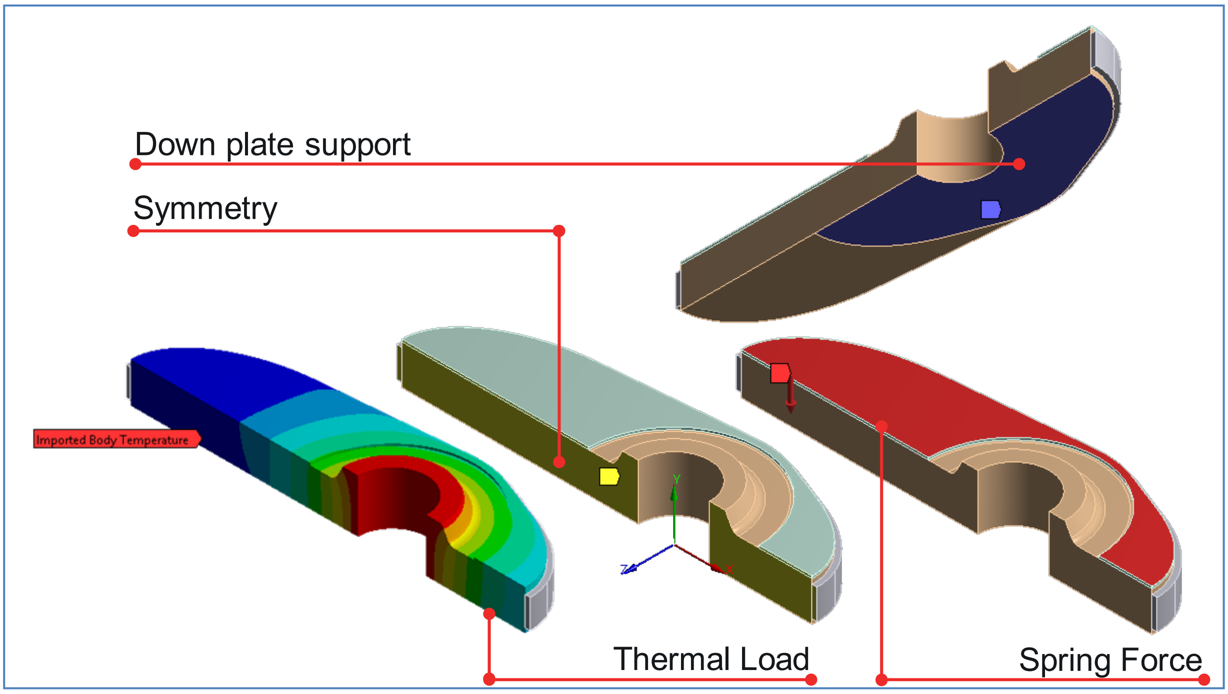

Figure 5: Slide Gate Structural boundary conditions

2.1.3 Optimization Process

In order to optimize a geometry the analyst needs to define which parameters to vary with the intention of decreasing or increasing its target variable. In this case, the objective is to decrease the stress levels caused by the thermal gradient of the equipment during operation. Experience is crucial to define these parameters so the user can have an idea of where the higher stress levels can be found and which kind of variation and ranges to apply so it is possible to see any improvement response. As the refractory it is not a ductile material, and therefore, doesn't respond well to the von Mises equivalent stress model, the principal maximum stress minimization is the goal of the optimization algorithm.

Next, Table 1, together with Figure 7, shows which geometric features of the Ladle Shroud were chosen for parameterization and the ranges that those features were varied.

Table 1. Varied geometric features and their values for the Ladle Shroud analysis.

Geometry feature	Lower limit	Upper limit
Neck radius	20 mm	50 mm
External diameter	155 mm	163 mm
Ceramic cover thickness	1 mm	3 mm

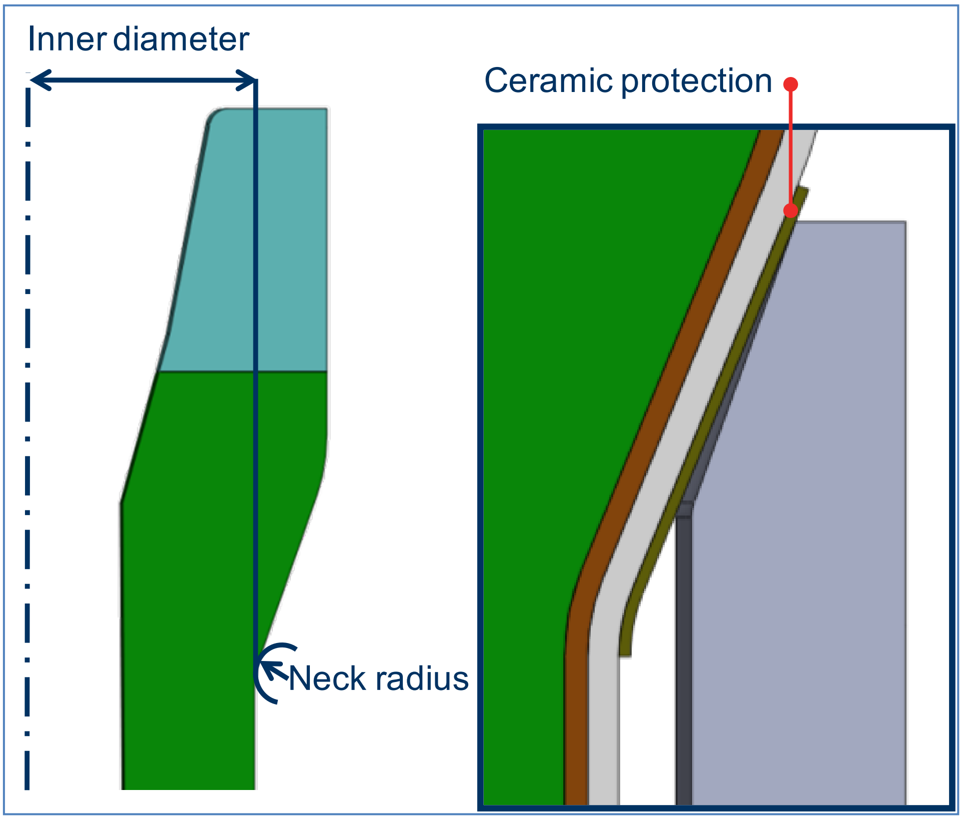

Figure 6: Varied geometry parameters for the Ladle Shroud.

The manufacturing know-how of Slide Gates Plates involves the construction of two ellipses as the base of the component topology. The variation of these ellipses radius is known to influence the temperature profile, stress profile and stress concentrations through the plates. The plates thickness weren't vary because this affects other aspects of the Slide Gate assembly, thus the analysis was restrained to radii variation. Table 2 and Figure 8 explain better the parameters variation cited earlier.

Table 2. Varied geometric features and their values for the Slide Gate Plate analisys.

Geometry feature	Lower limit	Upper limit
P1	200 mm	230 mm
P2	200 mm	600 mm
P3	200 mm	600 mm
P4	190 mm	230 mm

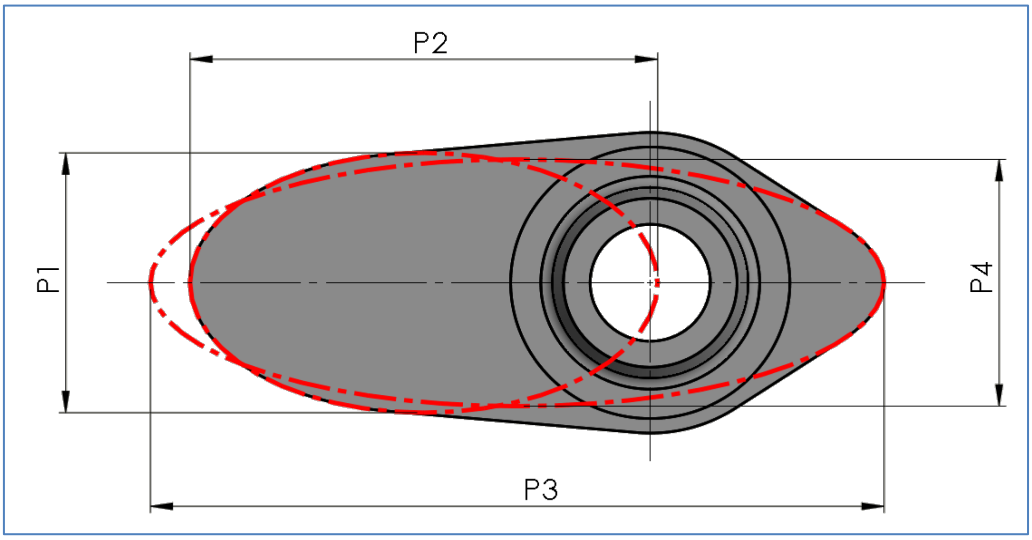

Figure 7: Varied geometry parameters for the Slide Gate Plate.

2.1.4 Results

After the parameters and the objectives are set, a Design of Experiments (DOE) matrix is generated combining different values of the geometric features range with the intention of creating a response surface with the interest variables, in this case the principal maximum stress. The initial response surface is nothing but a plot of the relations between the geometric features and the target variable. Once the surface is created, an optimization algorithm is run and tries to check for the global maximum, or minimum depending on the objectives set by the user, with a certain level of precision. Figure 9 and 10 shows some examples of 3D response surface relating more than 1 parameter and the variable of interest, the maximum principal stress in this case.

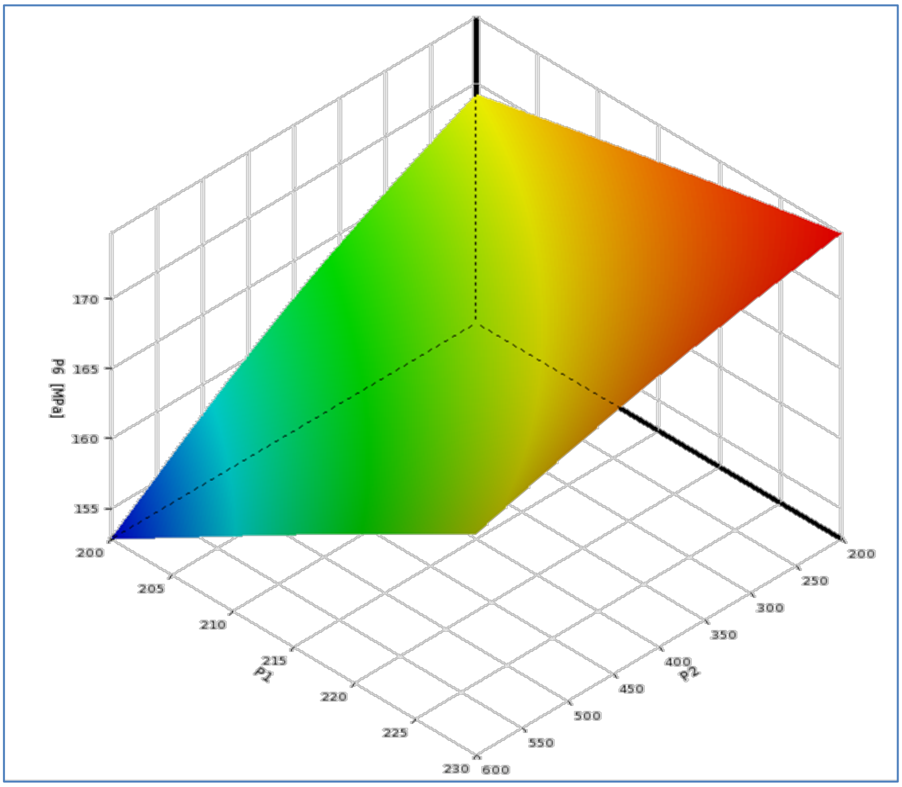

Figure 8: Response surface relating P1, P2 (horizontal axis) and Maximum Principal Stress (vertical axis).

One can note that both parameter, P1 and P2 affects the output parameter in the different manners, the reduction of P1 decrease the level of maximum principal stress found in the plate domain, while the reduction of P2 turns those output values up. The surface color corresponds to the stress levels for each point.

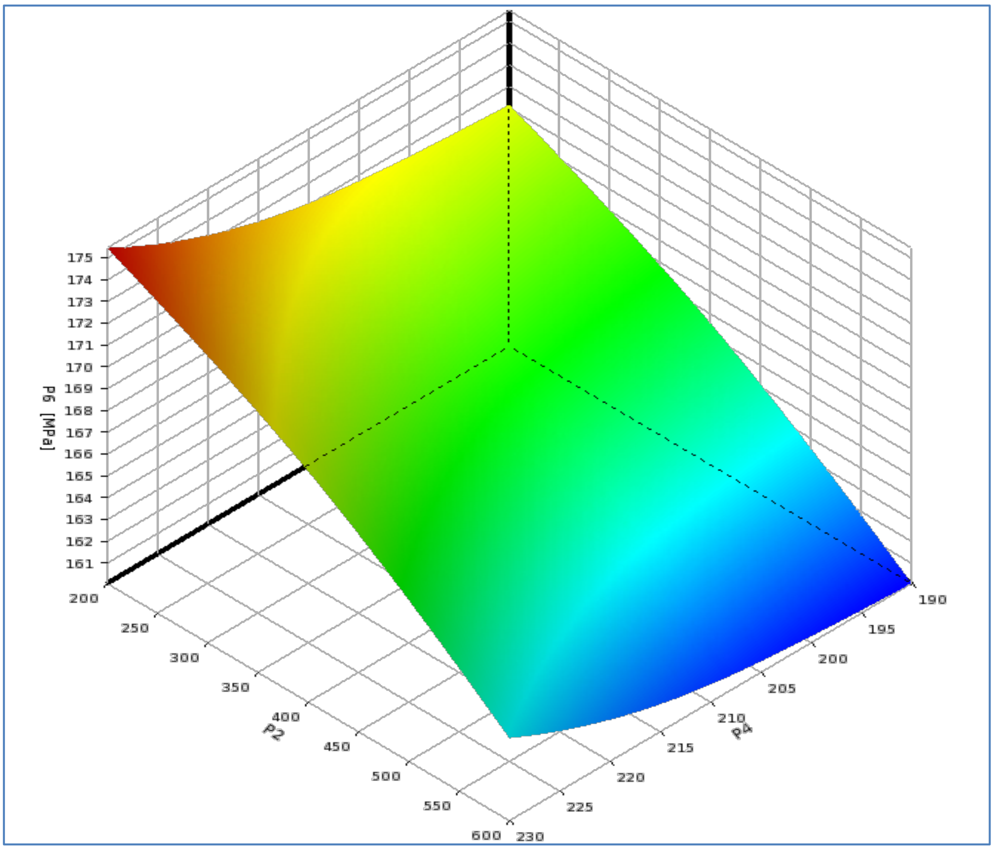

Figure 9: Response surface relating P2, P4 (horizontal axis) and Maximum Principal Stress (vertical axis).

The Figure 9 is similar to Figure 8 but with the P2 and P4 parameters. This image is able to show that the increment of P4 value is prejudicial to the refractory as it increases the stress levels. However the difference between the P4 and P1 is the proportion in which they influence the output parameter. One might note that increasing both parameters, P4 and P1, the stress profile is also increased, however, to conclude which variation reflects in bigger increments of the interest variable requires a sensitivity analysis of each parameter. Figure 10 presents this results.

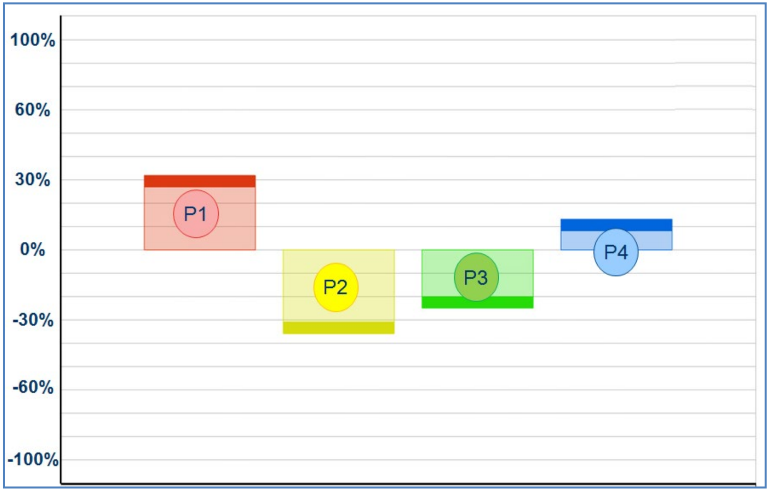

Figure 10: Sensitivity analysis

As shown in Figure 10, the parameters P2 and P3 have negative values of influence on the output parameter, -36% and -24% respectively, which means that as their value grow, the stress level tend to decrease. In that chain of thought, one can conclude that all parameters have a certain level of influence on the final stress profile, with the output parameter being more influenced by P2, then P1, P3 and finally P4.

All these analysis can also be done for the Ladle Shroud case, but for the sake of the article this writer decided to skip to the final results to avoid being repetitive. After all the scenarios of the DOE are run, the optimization algorithm takes place and the global minimum value of the variable of interest is found. Then, the algorithm proposes a set of values for the parameters and simulates it to validate the response. More information about the optimization algorithm and the optimization method can be found in [6].

Figures 11 and 12 compare the final geometry of both analysis to their base designs.

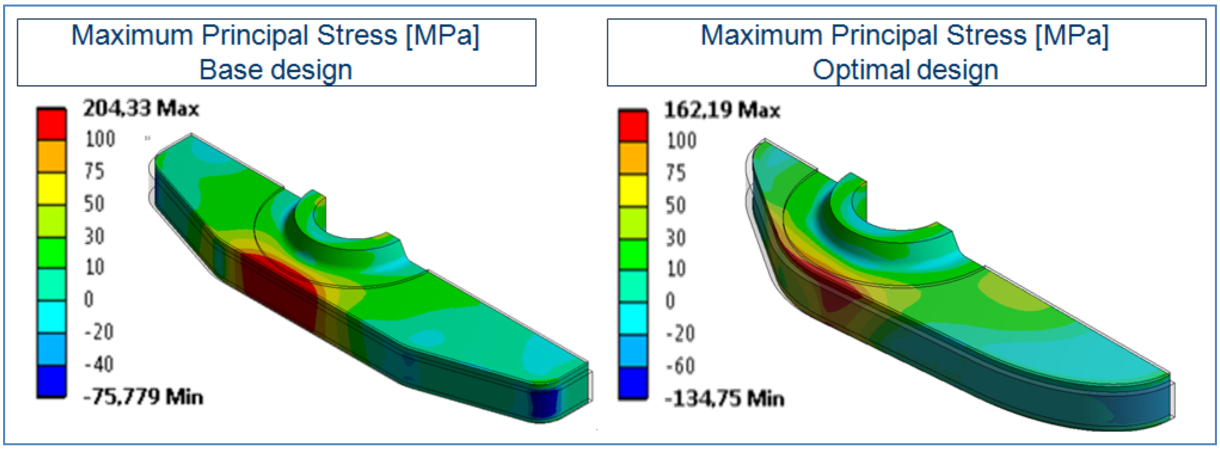

Figure 11: Slide Gate Plates designs comparison.

It is important to remind the reader that the stress values on this analysis are qualitative, refractory materials normally don't support traction stresses of such values. Nevertheless, the comparison is valid and is possible to see that the optimized design presents stress levels up to 20% lower than the base design.

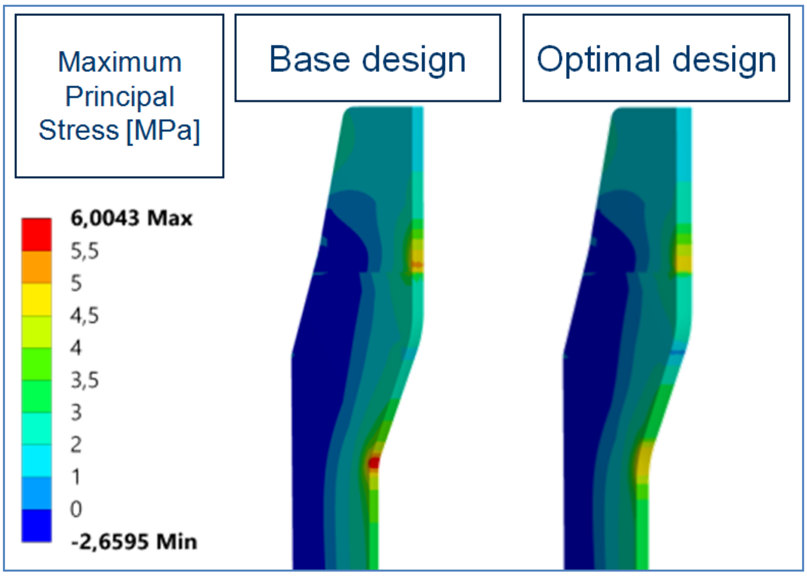

Figure 12: Ladle Shroud designs comparison.

With the proposed parameter values, the new Ladle Shroud design could reached lower stress levels in different areas of the geometry. One is able to see a stress value reduction in the neck radius and along the "head" of the shroud. The parameter modifications also reduced the maximum principal stress in 20% in some regions of the component.

3 CONCLUSION

- Refractory components are susceptible to thermal-mechanical stresses caused by temperature gradients and structural restrictions that can lead to failure of the material.
- These stresses can be reduced by modifying relevant topology features in the designs of products.
- A intelligent manner of reducing the stress levels present in the refractory components. during operation. is by applying the numerical optimization methodology described in this paper.

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