FLEXIBLE USAGE LADLE SHROUD ENABLED BY ADVANCED THERMO-MECHANICAL ANALYSIS

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ABSTRACT

Ladle shrouds are subjected to a cyclic usage involving repeated thermal shocks. The inability for refractory to be cold restarted after an idle time preclude the life extension over one sequence. The paper illustrates an approach to analyse thermal shock applied to a specific customer design. The approach features Finite Element modelling accounting for the statistical nature of failure typical for refractories. The models utilise Bigoni-Piccolroaz criterion for multi-axial tensile, shear and compaction failure. The analysis of potentially instable crack is based on the ratios of the elastic and fracture energy. Necessary material properties are extracted from laboratory experiments, including Brazilian, wedge splitting set-ups and compressive tests with different hydrostatic pressure. The application of such an approach allowed developing the ladle shroud that was successfully tested at Special Steel Plant Producer in Brazil South (SSPPBS). The ladle shroud sustained record number of heats and several cold restarts. The tested ladle shroud represents the family of Duraflex products of improved operational flexibility, which assumes the utilisation over an extended number of heats during several casting sequences. Such flexibility reduces logistical efforts, waste and HSE hazards due to hot piece handling.

INTRODUCTION

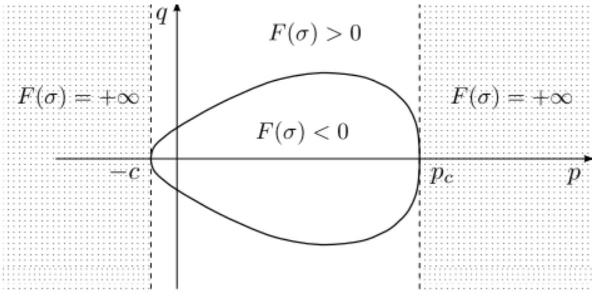
Ladle shrouds (LS) aim at protecting the molten steel stream from atmospheric contamination while it is transferred from the ladle to the tundish [1,2] and preventing associated formation of macro inclusions [3]. The shrouding has continuously evolved over time with the use of a complex alumina graphite composite structure with fine-tuned microstructure and composition to enable the repetitive usage (idle time between 2 heats is commonly <5 min) and to resist thermal shock related failures [4]. Thermochemical slag line erosion, seat wearing or long inter-sequence time (LS can't be re-used if cooled down <800 °C) are typical reasons to terminate a campaign of LS. This latter scenario is commonly encountered when the sequence length is short or when the shroud is fixed to the ladle.

In this context, engineering of LS requires combined efforts of refractory material development and modelling supported design. The present paper reports on such methodology applied to the emergence of the Duraflex product family aiming at flexible usage including cold restart capabilities. A ladle shroud designed for SSPPBS steel plant will be used as a practical case study.

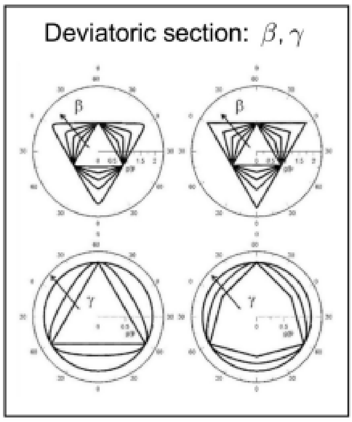
FEM MODELLING

Failure criterion

An innovative approach was developed by Vesuvius to model the mechanics of refractory devices under working conditions at high temperature for advanced industrial design. A constitutive model based on yield function proposed by Bigoni-Piccolroaz (BP) (Fig. 1) coupled with a criteria of failure (ultimate function) allows to describe the



a



b

Fig. 1 Shape of the BP yield function in (a) the p-q plan (b) deviatoric plain.

thermo-elastic-plastic behaviour of a refractory and respective probability of failure. The BP yield function is defined in terms of the stress tensor σ by:

$$F(\sigma) = \mathrm{f(p)} + \frac{\mathrm{q}}{\mathrm{g}(\Theta)} \qquad (1)$$

where f(p) represents the meridian part and g(Θ) represents the deviatoric part of the yield surface. The hydrostatic pressure and the Lode's angle are denoted by p and θ, respectively:

$$\theta = \frac{1}{3}\arccos\left(\frac{3\sqrt{3}}{2}\frac{J_3}{J_2^{3/2}}\right) \qquad (2)$$

The scalar parameter q is related to the second stress invariant:

$$q = \sqrt{3J_2} \qquad (3)$$

The median function f(p) is obtained as:

$$f(p) = \begin{cases} -M_{Pc}\sqrt{(\phi - \phi^m)[2(1-\alpha)\phi + \alpha]} \subset i; \phi \in [0,1] \\ \infty; \Phi \notin [0,1] \end{cases}$$

where

$$\phi = \left(\frac{p+c}{p_c+c}\right) \qquad (5)$$

The scalar parameters M>0, p_c>0, c≥0, m>1, 0<α<2 are related to material properties. The pressure dependency is controlled by M. The parameters c and p_c are the yield stresses for tension and compression, respectively.

The deviatoric part is:

$$\frac{1}{g(\theta)} = cos\left[\beta\frac{\pi}{6} - \frac{cos^{-1}(\gamma\, cos\, 3\theta)}{3}\right] \qquad (6)$$

the material constants are 0≤β≤2 and 0≤η<1.

The non-negative material parameters of the BP yield function define the shape of the associated yield surface. An ultimate function represents the probability of failure at 62.3% (Weibull stress) and is used as a failure criterion. The parameters of those yield functions evolve with temperature. In addition of this yield function, a temperature dependent hardening rule have been implemented to manage the damage and the softening of the refractory material.

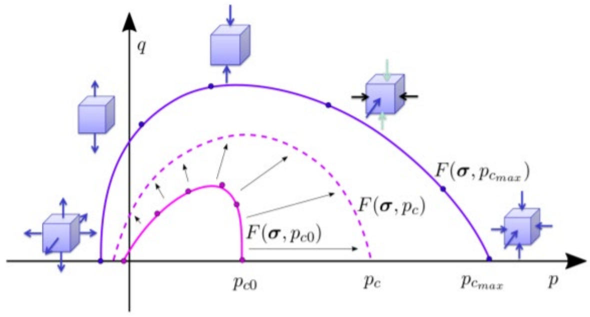


Fig. 2 Yield and ultimate function considering all stress states.

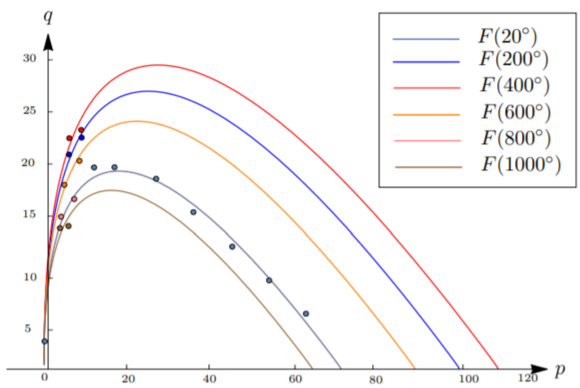


Fig. 3 Yield function depending on temperature.

Material properties

The material properties needed to define the shape of the yield function, the yield and ultimate stress are obtained in a series of room temperature (Brazilian test, uniaxial crush test, triaxial crush test, shear test, bi-tensile test) and high temperature (Brazilian and uniaxial crush tests) experiments. This identification is carrying out by polynomial regression.

Stability of crack propagation

When thermo-mechanical loads reach the critical level the initiation of the crack propagation is expected. The growth of the formed crack will be rapid if the elastic energy stored by the body at the moment of crack formation exceeds the energy to be dissipated by the forming crack. In this case the failure of the refractory structure will be unstable (brittle). If the energy balance between the elastic energy and the energy dissipated by the forming crack is in favour of the latter, no instant failure will occur. Subsequently, if no further loading takes place the growth of the formed crack is arrested.

As the energy balance is determined not only by the material properties but also by the geometry and the boundary conditions, same refractory can demonstrate both brittle and steady failure. In this respect the indexes of merit based on material properties (such as popular thermal shock criteria R) are not able to predict the nature of failure in a given structure. Computer modelling of the potentially unstable failure process is rather challenging. The standard FEM approach of smeared crack model may experience the convergence issues for the cases of elastic energy overload. The techniques of discrete failure such as DEM are not yet fully validated for the analysis of thermal shock in refractories. The other advanced approaches such as XFEM and phase-field modelling are even further from practical utilisation.

To determine the stability of the crack propagation an analytical approach to calculate energy balance in specific LS patterns is used.

HIGH FLEXIBILITY LS

SSPPBS trial

SSPPBS is a steel plant in Brazil producing over 100 grades of special steels (mostly high carbon) with a tundish life of 3.7 heats (60 MT casted in 1 hr) in average. The low tundish life is influenced by the facts that special steels are produced and by the variety of grades produced. The slag line or internal erosion is limited and seldom caused the end of LS campaign. Instead, conventional LS products were rejected for 2 main reasons: (i). argon counter-pressure loss (steel quality concern) or (ii). inter-sequence length longer than 5 min (thermal shock and HSE concern). Therefore, the typical life of a piece was limited to 2.3 heats in average, with a maximum of 6 heats. Improved flexibility combined with better argon flow stability were therefore sought by operators.

The optimization approach presented above was used to fine tune the piece design and materials to limit the thermal stress associated with a re-starting practice. A new body mix refractory was hence developed with the following features:

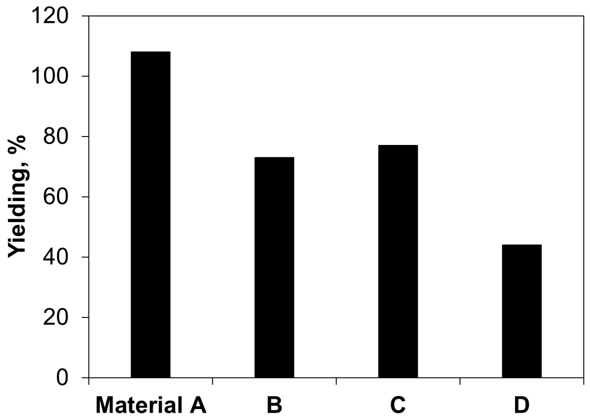


Fig. 4 Yielding probability predicted for typical cold start conditions for the specific LS geometry.

• Intrinsic thermal shock resistance that does not requires any sacrificial insulating liner (increase of the effective wall thickness);
• Limited evolution of physical and mechanical properties at molten steel temperature range to ensure the re-start ability;
• Resistance against slag line erosion which may become a limiting factor in a product capable to sustain longer sequences.

For typical conditions of cold start the newly developed materials (Fig. 4 Material D) has the lowest probability of failure and the lowest brittleness at failure. In Fig. 4 the yielding of 108%, 77%, 73% and 44% corresponds to 96%, 2%, 1% and <1% of failure probability, respectively.

Additionally, to the introduction of a better LS body material, potential seat wear and argon flow instability was addressed by using a special refractory in the part near the connection with the CNT. FEM model predicted rather low probability of failure in the newly proposed solution (Fig. 5). In Fig. 5 the failure probability of 100 % corresponds to the stress for which the probability of the failure (crack formation) obtained from Weibull analysis is 63%. One sees that the failure probability in the foot area where horseshoe style thermal shock cracking may develop is below 20 %. In absolute terms this corresponds to the less than 1% of failure probability.

For the developed LS, the field results over the first year of conversion are displayed in Figure 6. The 3 first months of usage show a progressive transition with subsequent stabilisation. The average LS life has been more than doubled (from 2.3 to 4.9 hts/pc) to ultimately last more than a sequence (from 1.6 to 0.75 LS/TD). The average life may increase further. LS usage was limited to 9 heats as a precaution, which should be reconsidered in a near future. The limiting factor encountered with this solution during extended campaigns has consequently changed to become slag line erosion related. This failure mode can be considered as less critical to either steel quality

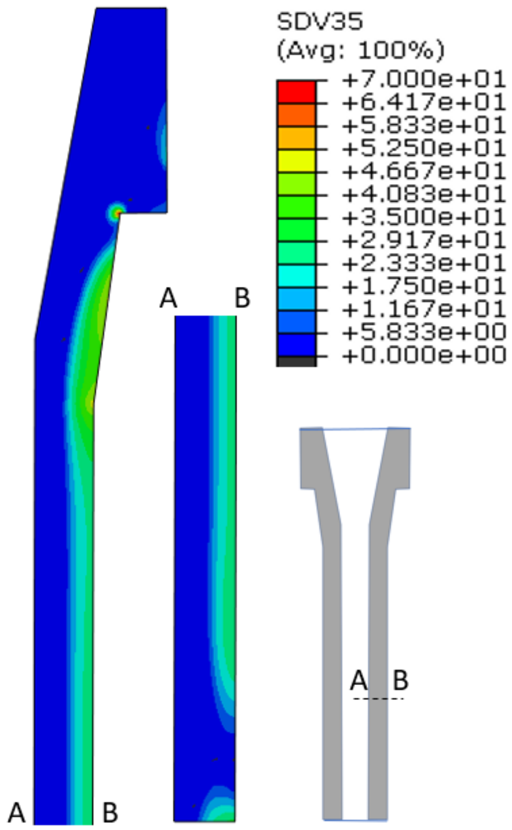


Fig. 5 Probability of failure in LS tested at SSPPBS – condition of the cold start.

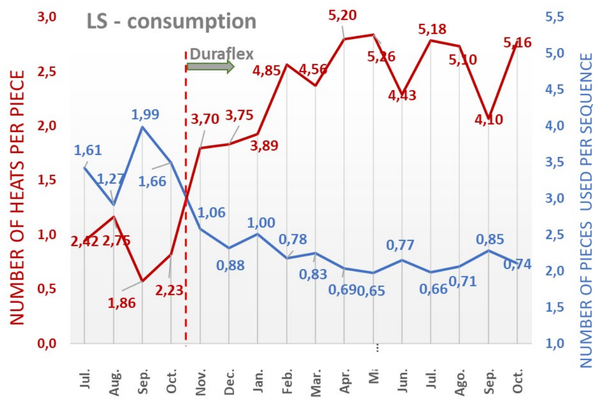


Fig. 6 Trial results at SSPPBS. The dashed line represents the conversion start.

or HSE hazards thanks to the possibility to detect the potential failure during an inspection between the heats.

Duraflex solutions

The case SSPPBS is part of a global project aiming at developing an array of LS products commercially known as Duraflex®. The main market drivers are the following:

- reduces operation risks;
- reduced HSE risks;
- improved productivity;
- waste reduction;
- lower logistics effort;
- improved overall sustainability.

A technical segmentation according to two exploitation parameters is proposed to address specific customer needs. The first parameter is based on the field practice related to the intersequence idle time duration between the heats:

- Duraflex 5, dedicated to sequences of significant length (it enables to complete the whole sequence with one LS).
- Duraflex 20 for low drain or flying tundish practice with an intersequence lower than 20 min.
- Duraflex1000 dedicated to sustaining increased number of heats and able to be re-used after an extensive idle time between two sequences (idle time up to several hours, fully cold restart is enabled).

The second parameter integrates the sensitivity to internal erosion displayed as molten steel throughput (MT/min). As the throughput (wear intensity) increases, LS designs with non-sacrificial erosion resistant liner are utilised.

SSPPBS belongs to Duraflex 1000 series, with limited internal erosion constrain. On this series, above design strategy was used for various steel plants (Fig. 7). Lifetime extension and one of more cold re-starts were achieved.

The ability of cold re-start, but also better resistance to steel and slag erosion (both through material resistance and the increase effective thickness achieved by removing the sacrificial liner) leads to longer product life in both, multiple short sequences or single long sequence applications. A single Duraflex® ladle shroud replaces 1.5 to 3 conventional pieces, reducing operating cost and environmental footprint (see Reduction factor of LS consumption, Fig. 7). In case of cold re-start the inter-sequence duration was, in some cases, of several hours.

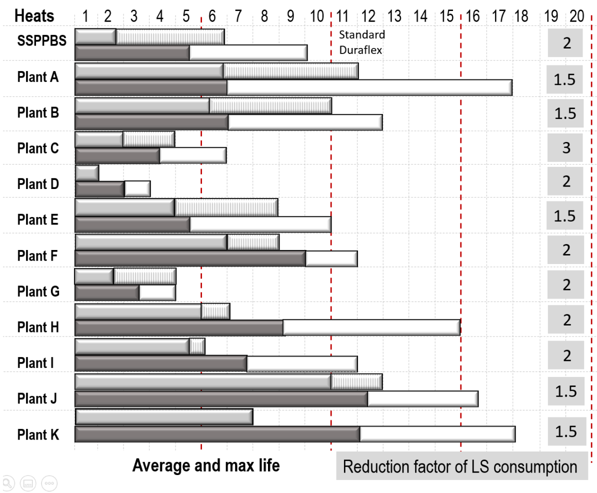


Fig. 7 Overview of Duraflex performance.

CONCLUSIONS

Through the combination of material development and FEA modeling to fine tune the LS design to the customer specific needs, innovative refractory products are developed to achieve better performance and give more flexibility to steel makers. New Duraflex LS enables increased product life and reduced consumption, which is advantageous for operating costs. The utilization of Duraflex LS also reduces HSE hazards due to reduced LS handling.

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