

# Modeling of Thermomechanical Damages of Steel Ladle Shell during Operations\*

L. Rebouillat, Y. M. Lee

Iron and steel ladles are used as transport and/or treatment vessels during the metallurgical process. Such vessels experience various thermal and mechanical loading cycles at high temperature. As shown by a combination of thermal modeling, finite element analysis and cumulative damage analysis, the formation of cracks in the vicinity of weldments of steel ladles is related to creep damage. The addition of a structural insulation board in the refractory lining dramatically improves the expected lifespan of the shell thanks to consistently lower shell temperatures. The insulation layer helps to preserve the integrity of the shell even if previously used without any insulation. The modeling of a full ladle assembly including the shell and the refractory lining also allows to confirm the thermomechanical damages observed in various areas of ladle shells.

## Introduction

Iron and steelmaking vessels used to transport and treat molten metals are often designed based on process conditions such as inner capacity, crane limits, and physical dimensions. Lot of the vessels currently in operations are older than 20 years old. During those years, the properties of the refractory materials used today for inner linings have dramatically changed with the introduction of new raw materials, compositions, and types of application. As a result, the maximum service temperature of the vessel steel grades is regularly overcome. The types of macroscopic damage observed on ladle shell in a steelmaking plant are crack propagation, bulging and scale formation. A numerical simulation can be run to estimate the influence of the different damage mechanisms induced by thermal cycling, mechanical fatigue and creep. The lifespan of the steel shell can then be estimated thanks to a cumulative damage analysis. Because of more and more severe operation conditions and more heat conductive refractory materials, shell temperature is regularly measured close to the maximum service temperature of the steel grades

used in the shell. To reduce the shell temperature, insulation materials are frequently introduced in the design of the refractory lining. ISOMAG® is a rigid insulation material. The benefits of this material on shell life expectancy is detailed.

## Main damages observed on steel ladle shell

The process cycle of the steel ladles at ArcelorMittal Burns Harbor starts at the ladle vertical re-heater. The 275 t ladle is then moved to one of the basic oxygen furnaces for tapping before a standard "treatment station/degasser (if required)/caster" process route. The heat-to-heat cycle for a ladle is about 300 min for a residence time of about 150 min. The steel shells have been in operations for more than 20 years. The body of the shell is based on a carbon-molybdenum alloy grade recommended for high temperature applications (UNS K11820). The steel grade used for the stiffener bands is a carbon grade used for pressure vessel (UNS K02100). The main damage observed in the body of the shell is some crack formation in the vicinity of weldments between the two stiffener bands (Fig. 1), and at the level of



**Fig. 1** Example of a vertical crack below the top stiffener band



**Fig. 2** Example of a horizontal crack at the bottom level

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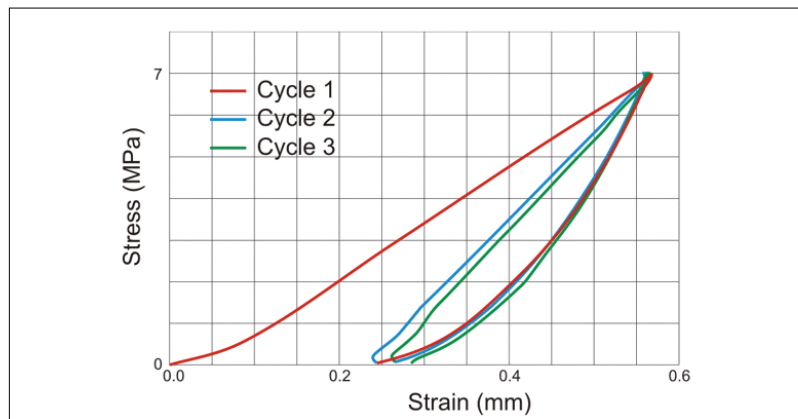
the bottom inner plate (Fig. 2). Bulging of the lower sidewall area is also common. The top retainer band is one of the items frequently changed because of high deformation. Because of the damages observed, the properties of the steel pieces used of the shell and the main retainer bands have been degraded through microstructural changes. For the modeling, the assembly is based on the initial properties of the steel grades, the objective being to estimate the evolution of the shell throughout its life and to determine the more influential factor.

### Description of the refractory lining

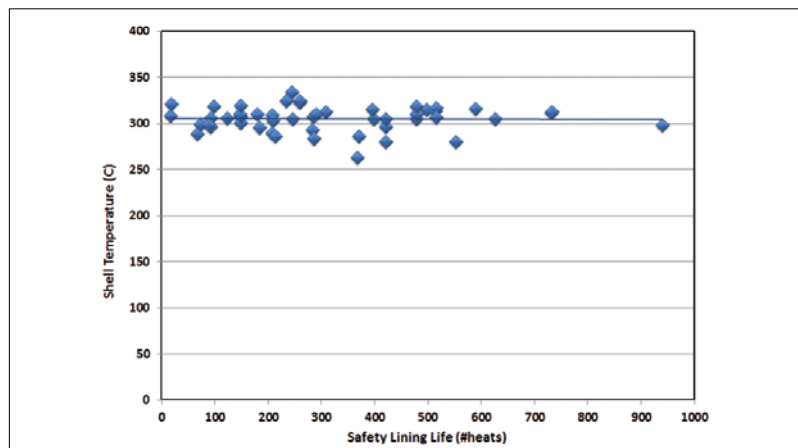
The refractory lining is a multilayer setup including a magnesia-carbon brick as working lining in the slag zone area, an alumina-magnesia-carbon brick as working lining in the barrel area, an alumina-based brick as safety lining and a dense forsteritic material as insulation material against the inner surface of the shell. The structural insulation primarily reduces the thermal loss through the ladle sidewalls. The thermomechanical behaviour of the safety lining brick and insulation material is of primary importance for the overall performance of the refractory lining.

The stability of these materials has to be guaranteed from the first preheat to the end of the last heat of the lining. Steel or slag penetration to the shell may occur through open joints if the integrity of the safety lining is lost. A well balanced stiffness/elasticity ratio and an optimum compromise between thermal conductivity and mechanical strength at high temperature is selected for the insulation material. The ISO-MAG® material actually exhibits a resilient behaviour under cyclic loads at high temperature (Fig. 3).

A constant thermal resistance of the safety lining throughout its life is definitely an advantage for process control and predictability. Shell temperature measurements confirmed the integrity of the safety lining up to the end of its life. Fig. 4 shows that the number of heats per safety lining does not have a significant effect on shell temperature (General Linear Model test,  $p = 0,91 > 0,05$ ). The stability of its thermal and mechanical properties is also a major benefit for long term damage modeling such as creep and fatigue damage.



**Fig. 3** Resilience behaviour of the insulation material after 3 cycles up to 7 MPa at 500 °C



**Fig. 4** Stability of the shell temperature throughout the life of the safety lining

### Thermomechanical modeling

The thermomechanical modeling of the ladle shell and refractory lining assembly is performed thanks to a commercial modeling software. The properties of steel grades as function of the temperature and time are quite well-known. Different models have been developed to introduce the degradation of the properties of refractory materials during service. However, recent studies on creep of refractory showed that modeling has to be further developed for heterogeneous materials before being really accurate compared to in situ observations [1, 2]. The non-linear thermomechanical behaviour of refractory is even more complex to model when considered in a brick lining structure with joints [3]. The thermal and stress patterns are then quite difficult to estimate with the commercial versions available for such modeling.

A hybrid approach is used in this study to estimate the interaction of different oper-

ation conditions on the lifespan and damage analysis of the ladle steel shell. The thermal loading is estimated including the conduction, the convection and the radiation mechanisms for the different surfaces of the ladle shell and the refractory lining when the ladle is empty and full of molten steel. The mechanical loading on the ladle shell is a mix of the loads from the moving of the ladle during the metallurgical process, and from the thermal expansion of the refractory layers.

The thermal profiles are firstly calculated and compared to thermal images of ladles in operations with the same conditions. The modeling takes into account different operation conditions such as the thickness of the working lining, the thermal state of the ladle before tap, and the residence time. An example of a calculated thermal profile and of an actual profile of a ladle in operations is shown in Fig. 5. The temperature measurements of ladle shell give an average temperature difference of about 70 °C

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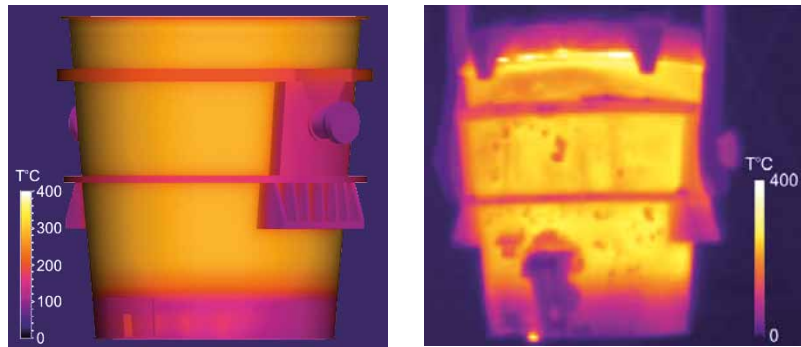
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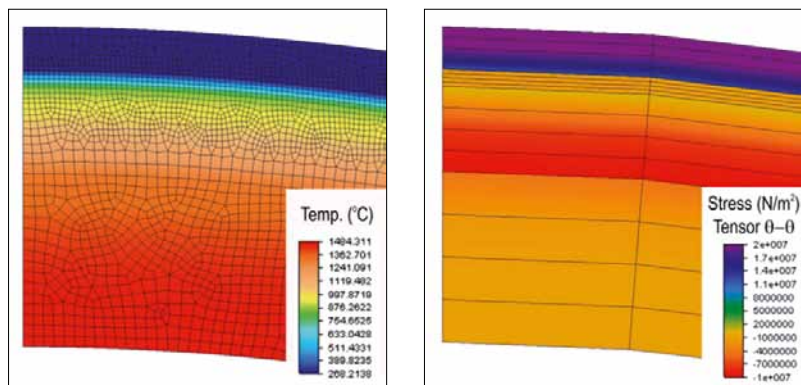
between ladle linings with and without the insulation layer [4]. The calculated profiles for insulated and non-insulated ladles are used to confirm the thermal loadings of the shells in the thermal FEA modeling module. A simple 2D-modeling is initially run to properly insert non-linear behaviour in the strain-stress relations of the refractory materials. The thermomechanical behaviour of the shell and refractory assembly is then calculated for 45 tap-to-tap cycles. An example of the thermal profile and hoop stress level calculated for the 2D-model is shown in Fig. 6. From this modeling stage, the stress estimated at the hot face of the working lining is basically at the same level with and without insulation. However, the higher thermal load of the refractory lining with the insulation board slightly increases the tensile stresses in the steel shell as already seen in similar modeling [5]. The highest hoop stress level estimated in the shell is reached after the first tap in a new lining. The stress level then decayed at every subsequent heat. The model exhibits the balance to reach between the reduction of the shell temperature and the increase of the stress induced in the shell by the expansion of the refractory lining. A too large restriction of the thermal loss through the lining might also dramatically increase the stress level at the hot face of the working lining brick, specifically in the joints of the lining structure.

**Damage analysis**

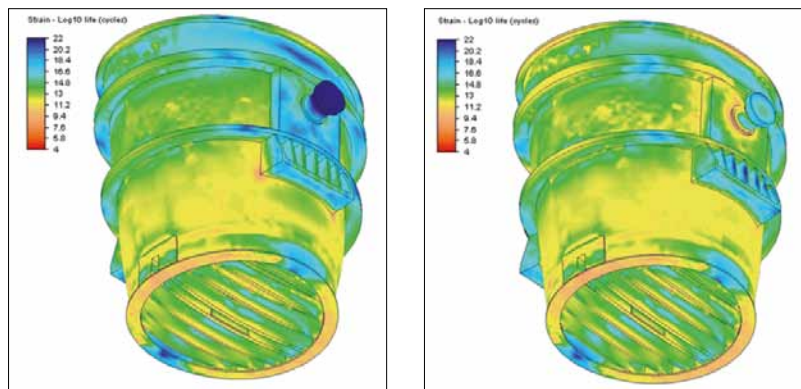
The dual effects of the temperature and stress differences on steel shell with and without insulation are estimated via a fatigue and creep damage analysis. The three primary sources of damage are oxidation, fatigue and creep [6]. The damage mechanisms are active at the same time, however one is usually dominant to explain the failure mode. Oxidation is not taken into account in the present modeling as the temperature of the shell is not in a high range. The fatigue from mechanical-only and from thermal-only loadings are estimated for the full 3D ladle model thanks to a numerical simulation module in the FEA software. At room temperature, the lowest life expectancy for both ladle positions, hooked or in standing position, is larger than 10<sup>9</sup> cycles (Fig. 7). The failure location is around the loading areas in both cases and not related to the actual location of cracks. The level of me-



**Fig. 5 Comparison of a calculated thermal profile and an actual profile of a ladle in operations with the same lining configuration**



**Fig. 6 Thermal state (l.) and hoop stress level (r.) calculated during the cooling stage of a cycle for an insulated lining**



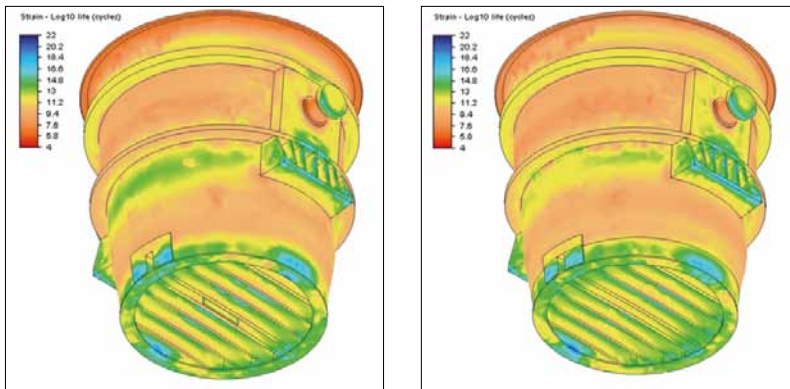
**Fig. 7 Life expectancy for a ladle shell cyclically loaded on stand and hooked positions at room temperature**

chanical damage is not expected to vary dramatically for the temperature range observed for both ladle with or without the rigid insulation material [7]. The life expectancy for the thermal-only fatigue is of the same level, around 10<sup>9</sup> heats before failure for both insulated and non-insulated ladle configurations. The use of the insulation material gives a more uniform thermal pattern (Fig. 8). The creep damage is estimated with the Larson-Miller parameter (LMP). Amongst all

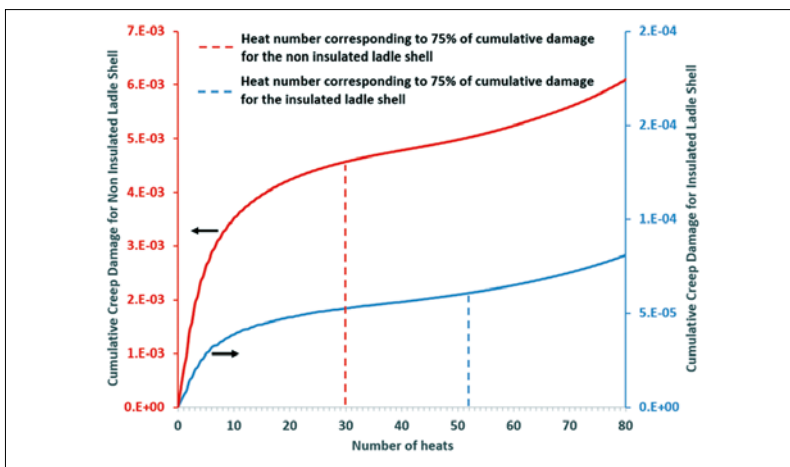
the time-temperature parameters available, the LMP is widely used in time to rupture analysis even if the life predictions are not conservative [8, 9]. The LMP combines the temperature and the time of rupture as follow:

$$LMP = T * (\log t_r + C)$$

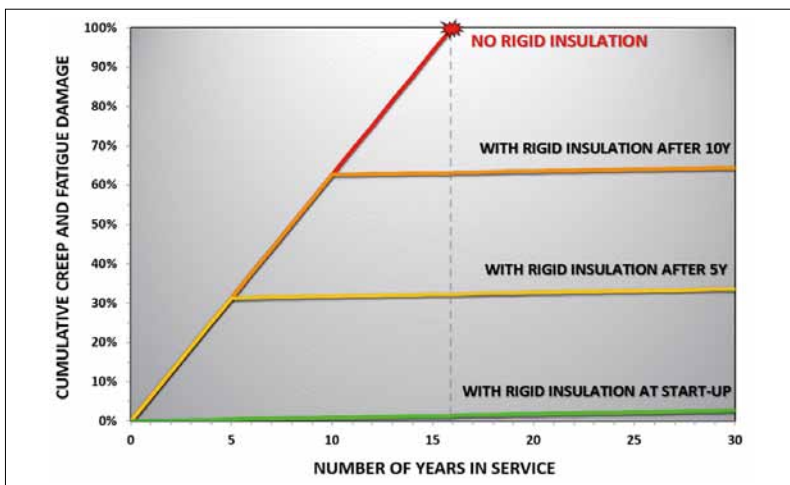
with T: the absolute temperature; t<sub>r</sub>: the time of rupture; C: material and reaction dependent constant specific to the steel grade [10].



**Fig. 8** Thermal fatigue for ladle without insulation (left) and with insulation (right)



**Fig. 9** Cumulative creep damage for one working lining campaign; the right and the left scales are for the lining with and without the insulation material respectively



**Fig. 10** Cumulative creep and fatigue damage for shells after different number of years in service before the use of insulation

C is taken equal to 19 for the grade used for the body of the ladle shell [11].

The LMP is also expressed by the following polynomial form based on stress level:

$$LMP = \alpha + \beta \log(\sigma) + \gamma \log^2(\sigma)$$

with  $\sigma$ : the stress level;  $\alpha$ ,  $\beta$ ,  $\gamma$ : regression constants.

The master curve giving time to rupture depending on stress and temperature for the steel grade of the shell body is then estimated with the following values for the con-

stants:  $\alpha = 13108$ ,  $\beta = 3647$ ,  $\gamma = -1408$ . The effect of the welded joints and heat affected zones is simplified with the introduction of a stress concentration factor. The crack stress approach for crack initiated along weld toe is used to correct the stress levels around those areas [12].

### Cumulative damage analysis

The cumulative damage analysis for pure creep is estimated by the Robinson's linear cumulative damage rule. The concept is to sum up the damages for every cycle till failure. The cumulative damage from creep with and without the structural insulation is about  $8 \cdot 10^{-5}$  and  $6 \cdot 10^{-3}$  respectively (Fig. 9). The creep damage is more than 70 times smaller for the insulated steel shell, resulting in a dramatic increase of the life expectancy. The benefits of the reduction of the shell temperature are then more significant than the effects of the stress increase observed in the early life of the working lining. Creep is the dominant damage mechanism compared to thermal and mechanical fatigue for the operation conditions experienced by those ladle shells.

The use of the structural insulation layer decreases the strain rate with creep damage more evenly distributed till the end of the lining campaign. 75 % of the creep damage is respectively accumulated within the first 30 heats and for over 50 heats for the shell without and with insulation. The insulation layer could then help to further reduce the damage in ladle shell with refractory repair at mid-campaign, specifically for the slag zone area.

The total damage for the ladle shell is estimated by the sum of the Miner's linear cumulative damage for the pure fatigue terms and the Robinson's cumulative damage as the pure creep term. The cumulative damage for ladle shell without the insulation layer gives an expected life of about 16 years. This calculated value is not far from the actual age where significant damages have been observed on shell.

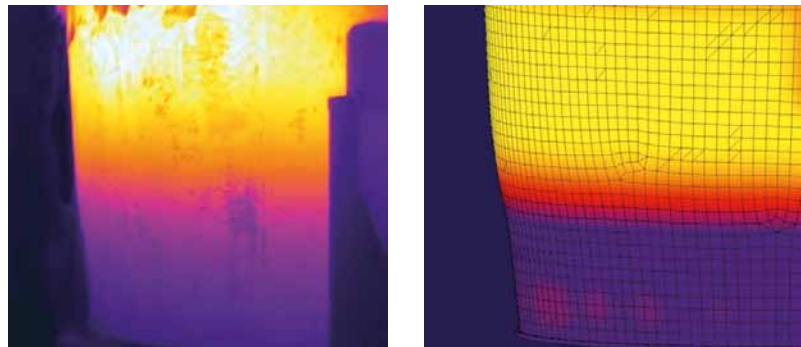
The use of the insulation layer cuts the creep damage by a magnitude of 2. The cumulative creep and fatigue damage rate is significantly lowered, hence a significant extension of the shell life expectancy compared to a non-insulated shell. However, the longer a shell is used without insulation, the more it is damaged (Fig. 10).

**Additional observation gathered from the modeling**

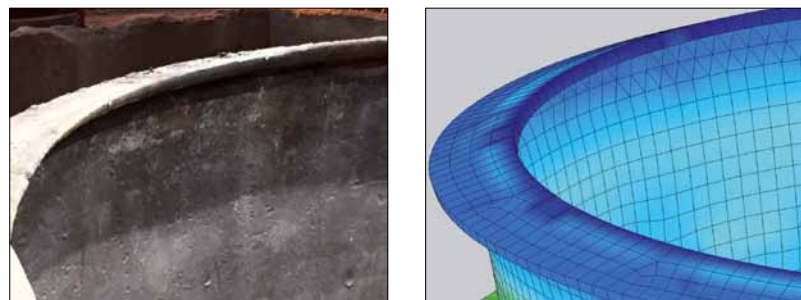
In addition to the estimation of the shell lifespan, other areas of ladle shells showing significant deformation are compared to the modeling results. The bulging observed on the bottom area of the shell sidewalls has also been observed in the model (Fig. 11). The pattern of deformation has also been compared and validated for the top retainer band (Fig. 12). The modeling of ladle shell and refractory assembly then gives some details on the expected damage for the whole ladle design during operations. This approach can be applied to improve ladle design, e.g. for the addition of local reinforcements, or to improve new designs with a better understanding of the interactions between the vessel shell and the refractory structure, e.g. interactions between anchors and castable-based safety lining.

**Conclusion**

Thermal modeling, finite element analysis and cumulative damage analysis are ap-



**Fig. 11** View of the bulging area on the lower sidewall of a ladle compared to the calculated profile without insulation



**Fig. 12** View of the top retaining band compared to the calculated profile

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plied to a whole ladle assembly, shell and refractory structure, to identify the dominant damage mode in the steel shell. Taking into account the operation conditions of the ladles, creep is the main source of damage leading to crack formation in the body of the shell. Before the addition of a structural insulation layer in the refractory lining, the shells were previously operated at temperatures close, if not higher, to the maximum service temperature recommended for the steel grade used for the body.

The life expectancy of such non-insulated shells is definitely shortened. The insulation material offers a well-balanced thermo-mechanical solution against high shell temperature without detrimental effects on the stress pattern in the refractory layers and in the shell. The cumulative damage analysis confirms the extension of the shell lifespan thanks to a steady reduction of the temperature. The addition of the insulation material is then beneficial not only for process control with a steady reduction of the temperature drop of the molten steel, but also for process improvements with improved ladle availability, lower maintenance, and higher operational safety. As the occurrence

of crack formation is related to the presence of welded joints and heat affected zones, a detailed analysis of the stress concentration factor for such areas would help to confirm whether the current model is conservative or not.

A metallography analysis of the crack morphology and the steel material around cracks would be helpful to confirm the lack of interaction between the different damage mechanisms. This modeling approach combining the vessel shell and refractory structure can be used to further analyse the other types of damage observed on ladle shell. It can then be helpful to improve ladle design.

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Please note that a meeting of the ASTM International C-8 Committee on Refractories will be held on March 28th, 2017 before this joint St. Louis Section/RCD conference. Contact Kate Chalfin at (610) 832-9717 for more information on this meeting.

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