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Influence of Covers on Thermomechanical Performance of Steelmaking Ladles

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ABSTRACT

Esfahan Steel Company is one of the major steel companies in Iran producing 2.2 million tons of steel annually. It is important to steel producers that steel vessels experience long campaigns. In this regard understanding the thermomechanical performance of refractories and their strength against thermal shock resistance is necessary. The present work uses thermomechanical modeling to evaluate changes in casting ladle refractory performance that result from addition of a ladle cover.

Results from this research indicate that covering the ladle during casting maintains the heat in the ladle, conserving the heat in the refractory body while only slightly increasing the level of stress. The positive influences of ladle covers appear during the idle time before and after converter tapping. Using ladle covers can improve the ladle rotation program and the performance of the steel plant.

1. INTRODUCTION

Esfahan Steel Company has three 130 ton converters to produce nearly 2.2 million tons of steel annually. A fleet of 10 ladles are used to transport the molten steel to converters, secondary metallurgy and continuous casting stations. Ladle rotation in the plant is shown schematically in **Fig. 1**. A preheated ladle is idle (typically 15 minutes) before tapping molten steel from the converter. The ladle transports the molten steel either to the caster directly or to the ladle furnace (LF) process. Approximately 50% of the heats are treated by the LF process. Continuous casting of 130 tons of steel typically requires 75 minutes. Prior to converter tapping the ladle requires 30 minutes for maintenance, 45 minutes for preheating and 15 minutes of staging before a tap starts as shown in **Fig. 1**.

Researchers have completed intensive simulation studies on ladle refractories[1-7]. Results indicate that the refractory lining and steel shell are subjected to two types of thermomechanical loading. The first occurs during heating, which includes initial preheating and converter tapping. The second occurs during cooling, which includes holds and after casting. Additionally, researchers have used modeling to study the stress distribution and damage in other refractory structures[8-19]. These results confirm that modeling is a valid tool for examining stress and temperature in static and dynamic systems.

2. PROCEDURE

A cross section of the ladle is included as **Fig. 2** with dimensions in mm. The ladle includes a dolomite working layer, a fire clay insulating layer and a steel shell. The sidewall-working layer of the ladle consists of 16 rows of brick.

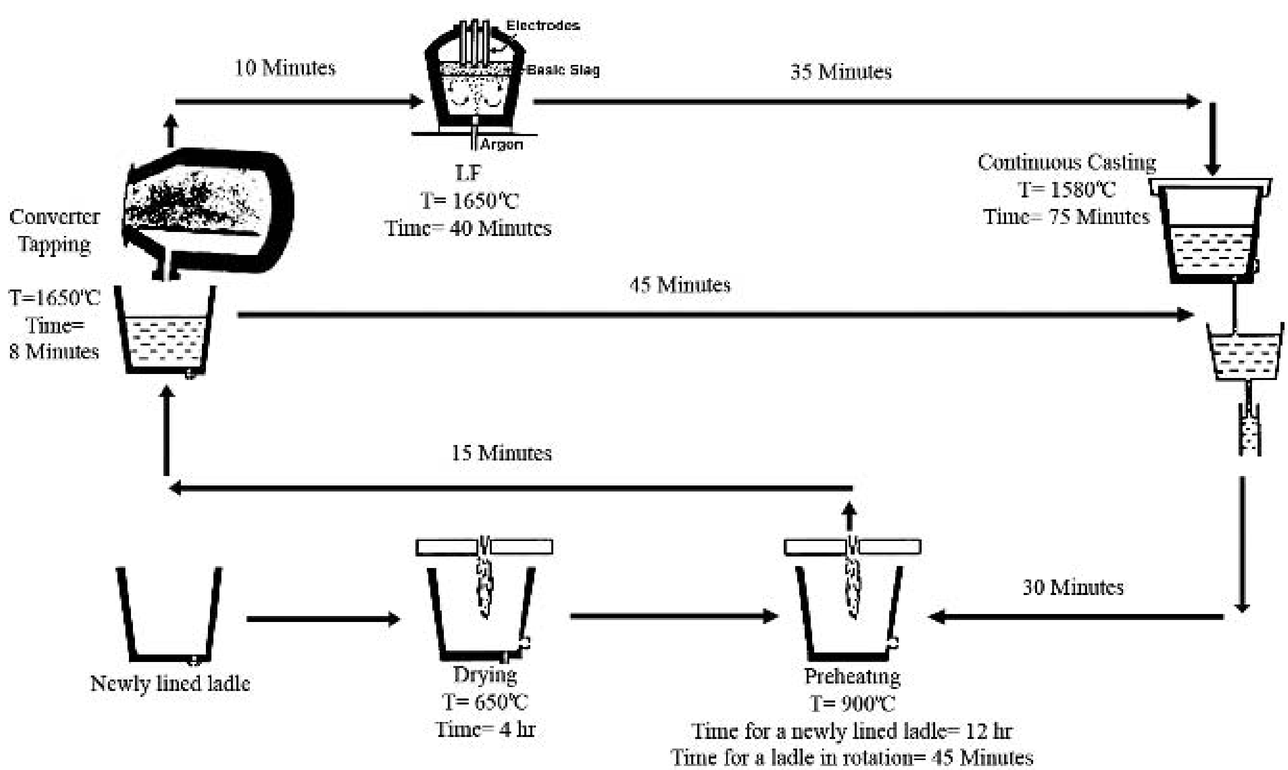

Fig. 1. Ladle rotation at Esfahan steel plant.

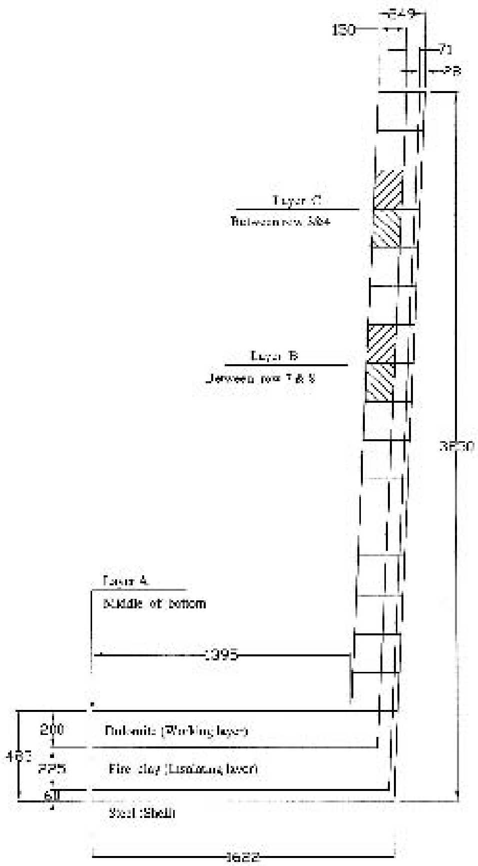

Fig. 2. Ladle cross section showing working and insulating layers.

Three regions (refer to **Fig. 2**) were selected for simulation: (A) in the bottom center, (B) below the seventh row and (C) below the third row.

Thermal shock is known to be the dominant factor controlling the refractory wear in this plant. Additionally, penetration of molten metal into refractory lining through cracks and compromised joints leads to the separation of the working and insulating layers in the ladle. Steel penetration after a full campaign of the refractory lining is obvious in the image that is included as **Fig. 3.** The dolomite working lining is coated with a thick steel layer that results from penetration of the refractory surface. In this research the effect of covering the ladle during casting on the distribution of temperature and stress are studied without considering this issue of metal penetration.

The current study applies ANSYS software version 5.4 to simulate the behavior of refractory ladle linings. Simulations of the ladle refractory lining during casting, idle time after casting and after converter tapping will be discussed. A 2-dimensional Plan13 element was used to mesh the model, as the ladle geometry is axisymmetric along its longitudinal axis. The problem was defined as a coupled analysis of thermal and stress fields; both field equations were solved simultaneously to provide a more reliable solution. The Plan13 element not only solves the coupled field analysis, but also analyzes the axisymmetric model condition.

The material properties, such as modulus of elasticity, coefficient of thermal expansion, the specific heat and the coefficient of thermal conductivity, were considered as temperature dependent parameters. Also, the thermal properties of molten steel and slag, such as the specific heat and thermal conductivity, were used in software calculations. Seconds and meters were used as the units of time and dimension, respectively.

Von-Mises stress was used for the analysis. This equivalent stress was used to indicate the depth into the ladle lining that the maximum stress field

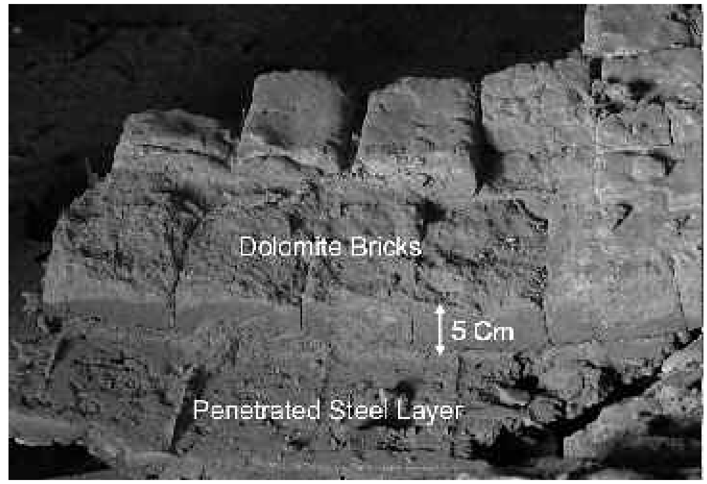

Fig. 3. Penetration of steel through cracks and compromised joints.

occurs. The equivalent stress is used to check against the yield stress of a ductile material to determine if yielding has occurred in combined stress cases. The origin of microcracking in brick can be estimated by comparing the equivalent stress to the apparent yield stress of the material. The direction of crack propagation can then be estimated by comparing the principal stress to the fracture toughness of the material.

3. RESULTS AND DISCUSSION

The aim of this research was to reduce the thermal stresses which determine the erosion rate using a cover on the ladle during continuous casting. For this purpose a cover consisting of a 1 cm steel shell and a 30 cm light insulating refractory material was designed. The thermal properties of these two layers were entered into the simulation software. The simulation results are presented in the following three sections:

3.1 During Continuous Casting

High tensile stress develops in the refractory linings upon cooling both during and after the casting process. This can lead to crack growth in the hot face of the dolomitic brick and subsequent penetration by molten steel. The distribution of temperature versus X/L in a ladle after casting is shown in **Fig. 4**. The modeling requires a dimensionless thickness for each working and insulating layer, which are produced by dividing by the respective thickness. Therefore, position X/L=0.5 is located half way through each working lining and position X/L=1.5 is located half way through each insulating lining. This X/L parameter enables comparison of the state of a layer in the wall and bottom. This profile considers the thermal situation of the refractory linings with and without ladle covers. The results indicate that the hot face of section (A) with or without a cover are warmer than sections (B) and (C) due to the presence of hot slag and considerably more insulation. The insulating layer temperature decreases to 200°C in this section. In section (B) a drop from 1320°C in the hot face to 460°C at the back of the insulating layer occurs for a ladle without a cover. Thermal gradients between the hot face and the end of fire clay bricks are higher when a cover is used during casting. It can be stated that using a cover during casting can increase the effective heat capacity of the body and control the applied stresses in other operational steps; however, the increased temperature may accelerate reactions between the refractory and slag.

The distribution of stress in the ladle refractory versus X/L is shown in **Fig. 5**. The hot face of a ladle with without a cover is subjected to a 15-28 MPa stress that is higher than the strength of the dolomite bricks and thus would cause fracture and crack propagation. In sections (B) and (C) stress increases as X/L ratio increases and position X/L=0.45-0.73 in the dolomite brick in both cases is subjected to the highest stress, 45-50 MPa. After that point stress

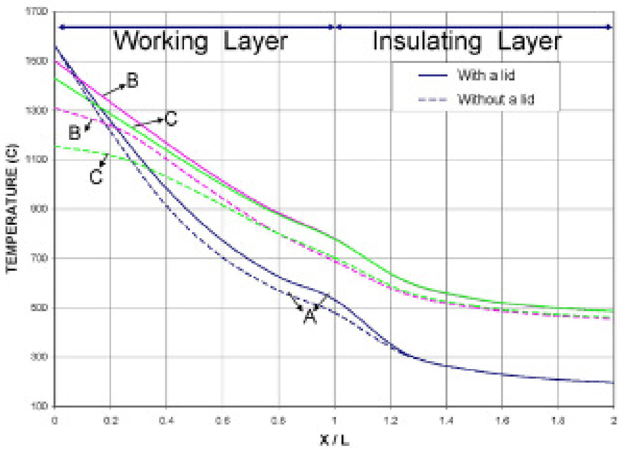

Fig. 4. Distribution of temperature versus X/L after casting.

reduces considerably and in the insulating layer the stress of each section in the specified cases become similar.

This profile indicates that the stress levels in sections (B) and (C) are slightly higher for a ladle with a cover; the reason is the higher average temperature of the refractory lining. Section (A) in the bottom is under less stress and the maximum stress in this section was as high as 32 MPa at X/L=0.77. This profile shows that the insulating lining faces less stress than the working lining. Failure is not expected in the insulating layer, given the low stress and the mechanical strength of fire clay.

3.2 Idle Time After Casting

After the casting process it takes approximately 30 minutes for a ladle preheating station to become available. This time is used for refractory maintenance. The thermomechanical behavior of refractories after the 30 minute delay for a ladle with and without a cover during casting was studied. The distribution of temperature after 30 minute for sections (A), (B) and (C) versus X/L are presented as **Fig. 6**. These data indicate that a cover on the ladle during casting leads to higher temperatures in all sections of the hot face to the end of the working lining. In both cases the temperature in the insulating layer are quite similar for each section.

For section (A), the maximum hot face temperature is 950ºC for a ladle without a cover during casting, while with a cover it is 1180ºC. The maximum hot face temperature for section (B) is 870ºC without and 1160ºC with a cover during casting and for section (C) the temperatures are 930ºC without and 1100ºC with. These results show a 150-300ºC increase in hot face temperature after 30 minutes by using a cover during casting. This should improve the performance of the ladle because this hot face temperature is higher than the typical temperature achieved during preheating. Using this approach allows the preheating process to be eliminated, reducing the required number of ladles from 10 to 8.

The results in **Fig. 6** also show the presence of a peak temperature in the different sections some distance from the hot face after the cooling process. Increasing the idle time shifts these peaks to higher X/L ratios.

The stress distribution after the 30 minute idle time is included as **Fig. 7**. Comparing this figure and the stress distribution profile after casting indicates the level of stress has increased considerably in the hot face and the first thickness of the ladle lining but has decreased in the ladle bottom. Higher stress can occur during the idle time in a ladle without a cover during casting. The maximum stress for the wall and bottom were observed at X/L=0.73-0.78 and that maximum has fallen to a level slightly less than during the casting process, but toward the back of the insulating layer the stress is higher. It is concluded that in this step, stress higher values than during the casting process and the hot face of a covered ladle during casting is subjected to less stress during idle time than a ladle without a cover.

3.3 Idle Time After Converter Tapping

As stated previously using a cover during casting eliminates the need for preheating, reducing the turnaround time to 30 minutes for maintenance and after that time the ladle still has more heat than it would have had after a standard preheating. Tapping from the converter into "hotter" ladles will change the temperature profile and stress distribution for the period after tapping and prior to casting. The temperature distribution versus X/L after converter tapping is included as **Fig. 8**. It is clear that the temperature of the hot face, both with and without a cover reached the 1650ºC molten steel temperature. In sections (B) and (C) the impact of a ladle cover becomes more pronounced as X/L increases within the working lining reaching a maximum of about 200ºC at X/L=0.25 to 0.50. In section (A) the maximum temperature difference is also about 200ºC but it occurs at an X/L=0.1-0.5.

In the insulating layer of each section the temperature distribution is very similar for both conditions. The data indicate that using a cover during casting has a significant effect on the temperature in the working layer when a converter taps the molten steel to a ladle.

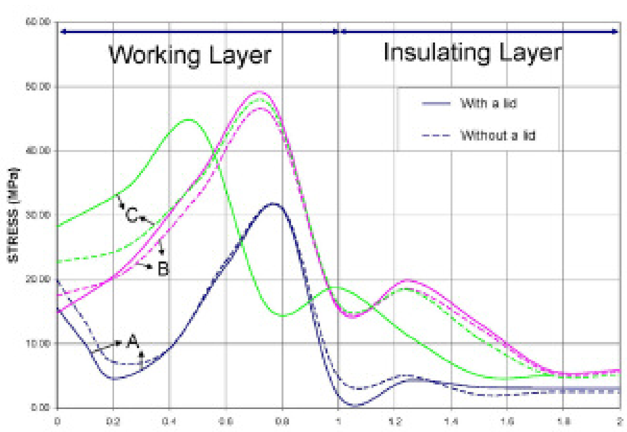

Fig. 5. Distribution of stress versus X/L after casting.

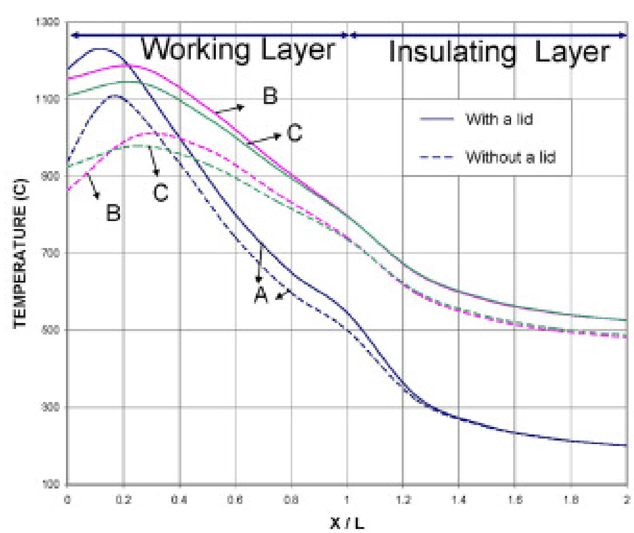

Fig. 6. Distribution of temperature versus X/L after 30 minute idle time.

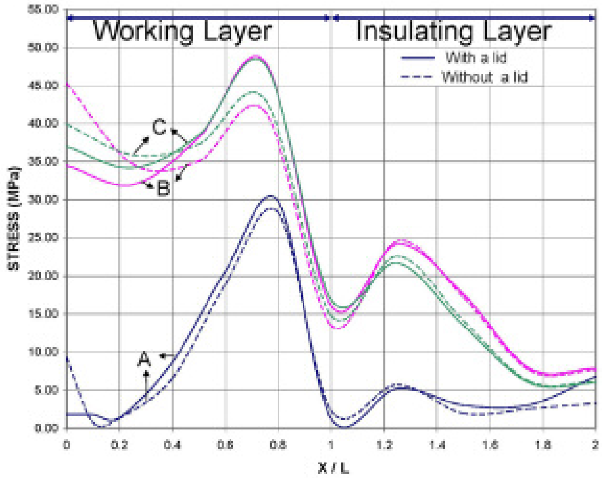

Fig. 7. Distribution of stress versus X/L after 30 minute idle time.

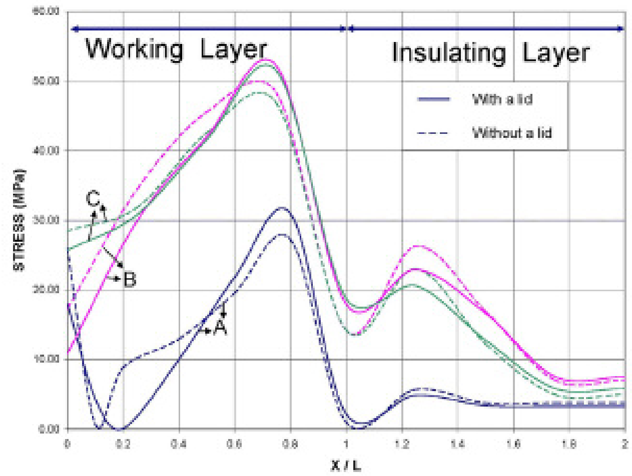

Fig. 9. Distribution of stress versus X/L after converter tapping.

Distribution of stress versus X/L after converter tapping is shown in **Fig. 9**. For the case with no cover, the data indicate that the hot face is under higher stress when using a cover while the level of stress decreases in the insulating layer. When a cover is used a reduction of stress until X/L=0.5 while slightly more stress occurs between X/L=0.5-1 because of the increased thermal gradient.

4. CONCLUSION

Using a cover during casting may slightly increase the level of stress in this process because of an increased thermal gradient in the ladle body, but it controls the stress applied during the idle time and when the converter pours the molten steel into the ladle. Because of the warmer refractory lining, the preheating process can be omitted for the ladles and a smaller ladle fleet can be used. Omitting preheating not only saves energy it is also beneficial from the stress distribution aspect and the ladle rotation program.

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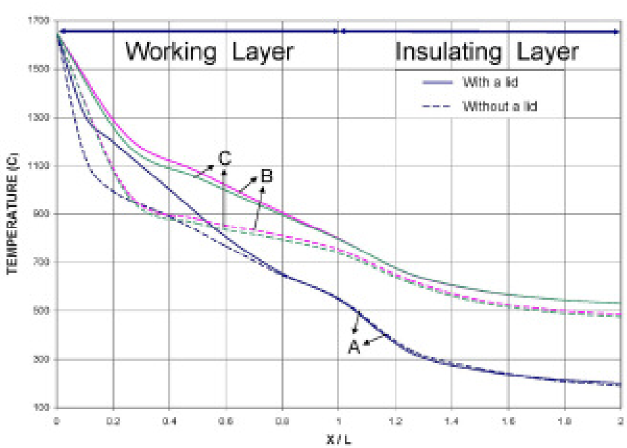

Fig. 8. Distribution of temperature versus X/L after converter tapping.

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