Deliverable D 4.5
In-situ measurements on industrial steel ladle finished

Document type	**Deliverable D 4.5**
Document Version / Status	**1.11**
Primary Authors	**João Pereira, jpereira@civil.uminho.pt, UMINHO**
Distribution Level	**PU (Public)**
Project Acronym	**ATHOR**
Project Title	**Advanced THermomechanical multiscale mOdelling of Refractory linings**
Grant Agreement Number	**764987**
Project Website	www.etn-athor.eu
Project Coordinator	**Marc Huger, marc.huger@unilim.fr, UNILIM**
Document Contributors	**João Pereira, jpereira@civil.uminho.pt, UMINHO** **Pratik Gajjar, pratik.gajjar@civil.uminho.pt, UMINHO**

History of Changes

Version	Date	Author (Organization)	Change	Page
1.0	10.09.2021	Pratik Gajjar (UMINHO)	First version of the deliverable created	All
1.1	23.09.2021	João Pereira (UMINHO)	Review	All
1.2	27.09.2021	Pratik Gajjar (UMINHO)	Corrections	All
1.3	27.09.2021	João Pereira (UMINHO)	Review	All
1.4	29.09.2021	Glyn Derrick (UNILIM)	General formatting and English check	All
1.5	30.09.2021	Pratik Gajjar (UMINHO)	Corrections	All
1.6	01.10.2021	Glyn Derrick (UNILIM) Marc Huger (UNILIM)	Final check	All
1.7	04.10.2021	Pratik Gajjar (UMINHO)	Corrections	All
1.8	07.10.2021	Glyn Derrick (UNILIM)	Corrections	All
1.9	08.10.2021	Pratik Gajjar (UMINHO)	Corrections	All
1.10	13.10.2021	Glyn Derrick (UNILIM) Marc Huger (UNILIM)	Final check	All
1.11	20.10.2021	Pratik Gajjar (UMINHO)	Corrections	All

European Commission
Horizon 2020
European Union funding
for Research & Innovation

TABLE OF CONTENTS

1 Introduction

This report will review the in-situ measurements of a full-scale industrial steel ladle. These in-situ measurements will give adequate and sufficient data to calibrate and validate the developed numerical macro-models. The obtained results will be used to validate advanced numerical models at macro-scale developed within WP3, allowing proper sensitivity analysis to identify better lining layouts and optimization at industrial scale.

2 Industrial steel ladle

The steel ladle is an essential part of the steelmaking process and can directly affect the quality of steel produced, as well as the energy required to maintain the temperature of the molten steel it is in contact with. As a result of this direct contact with molten steel, the refractory materials, that line the steel ladle, experience severe working conditions in terms of thermomechanical loading and chemical exposure. The performance at elevated temperatures and the durability of these refractory materials, affects service life, which is usually in the duration of weeks, leading to the steel ladle accounting for 25 % of the global refractory consumption [1]. Therefore, it is of great environmental and economic importance to increase the current knowledge on this installation through focused experimental studies.

There are various constraints that need to be considered during the design of a steel ladle, for example steel ladles must be reliable while also being economic. The shape of the ladle must guarantee that the maximum amount of molten steel is removed from the ladle during pouring. The ladle must have an impact pad in the position where the molten steel hits the ladle during feeding. The refractories used in the impact pad should have a better mechanical performance compared to the material used in the rest of the ladle. This improved mechanical performance can be achieved by either increasing the thickness of the lining at the bottom of the ladle or by using different materials. The bricks in the slag line must provide resistance against chemical attack from the slag. Other aspects like erosion due to purging, must also be considered. Figure 1 presents a steel ladle and different lining zones.

The refractory linings of the steel ladle are composed of three layers: the working or wear lining, the safety or permanent lining and the insulating layers (Figure 2). In general, the working linings which will be in direct contact with the molten steel and safety linings are made from refractory brick units or castables. In the case of the steel ladle used at the Tata Steel plant, IJmuiden, the working lining has dry joints (no mortar), while the safety lining is constructed using mortar joints. These layers are exposed to high temperatures (in particular, the working lining) and must resist chemical wear against molten steel and slag while sustaining its mechanical performance.

There are no specific rules for the design of an industrial steel ladle, each manufacturer exploits different aspects of the steel ladle ranging from the refractory lining material to dimensions of the steel ladle. In case of the refractory materials, choices are based on the lining requirement, mechanical, thermal, and chemical performance. For the dimensions, decisions are made considering the lifting capacity of the crane and available movement area, however, in most cases the overall shape remains the same (Figure 1).

European Commission | Horizon 2020 European Union funding for Research & Innovation

In-situ measurement of thermal and mechanical fields can assist in calibration and validation of the different numerical models. When possible, these models account for viscoplasticity and damage behaviour of the bricks as well as the joint behaviour for the overall refractory lining [2],[3],[4].

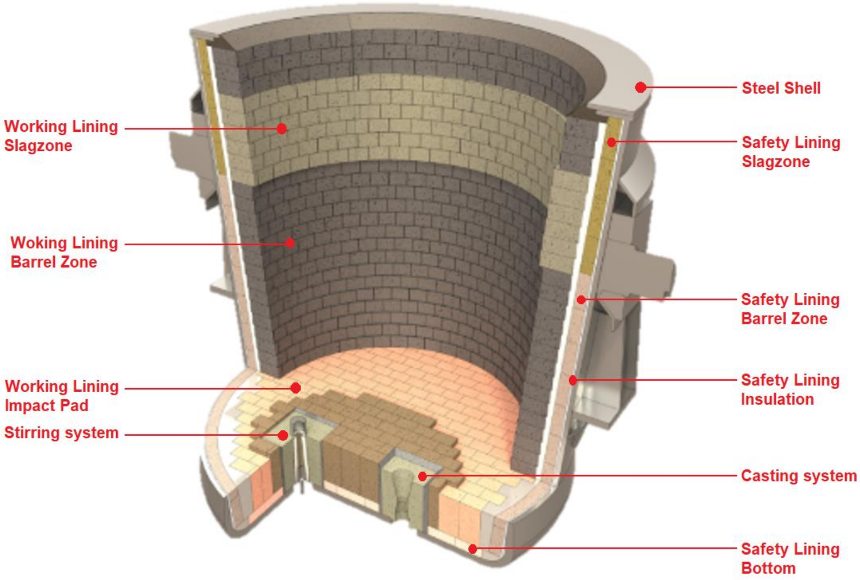

Figure 1 - Steel ladle with different lining zones.

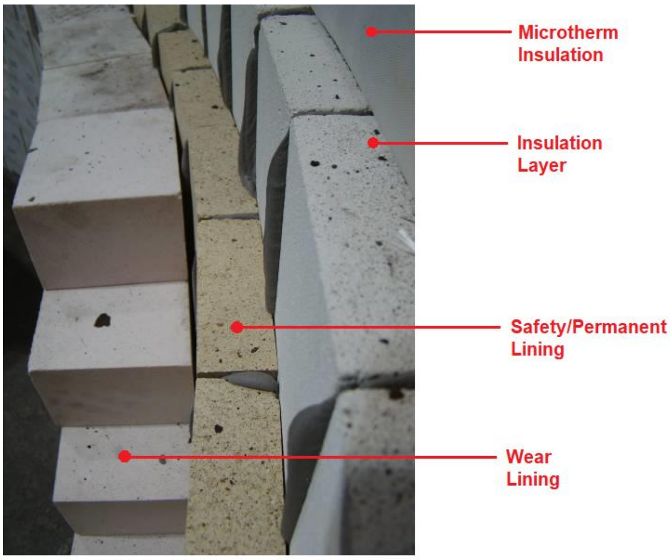

Figure 2 - Different layers of refractory linings in the steel ladle.

2.1 Geometry

As mentioned in the previous section, the geometry of steel ladles varies depending on the manufacturer. For this experimental campaign, a steel ladle from Tata Steel, IJmuiden , was considered as the model example (Figure 3). This ladle measures 4.6 m in diameter at the top and 4.3 m at the bottom, revealing a slight taper from top to bottom with an overall height of 5.0 m.

At the wall, the linings are composed of several layers including wear linings, permanent linings (safety lining and insulation lining), microporous insulation and a steel shell. The thicknesses of these layers are presented in the Figure 3. For the most part, these layers remain the same except for the wear lining, which is modified to correspond with the slag zone. The wear lining has a higher thickness and utilises a different refractory material to resist the chemical effects (corrosion) of the slag.

At the ladle bottom, the wear lining is composed of the same bricks but with a larger thickness (250 mm) in comparison to the wall (178 mm) and the safety lining is also larger (76 mm compared to 40 mm). These changes are necessary to withstand the harsh impact load of molten steel during the filling stage.

European Commission | Horizon 2020 European Union funding for Research & Innovation

This whole assembly of refractory linings are supported at the bottom and sides by a steel shell configured with vertical and lateral stiffeners, to resist the thermal expansion, and then held by crane hooks at attachments either side of the ladle.

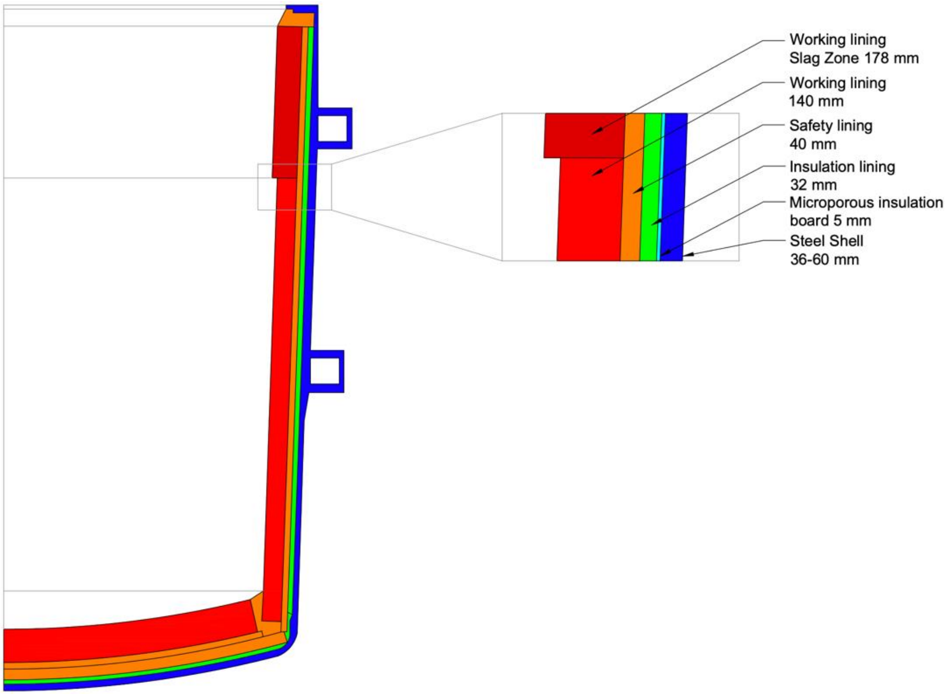

Figure 3 - Schematic of the IJmuiden steel ladle, used as the model ladle, with different parts of its refractory linings.

2.2 Material properties

Depending on the location and purpose (i.e. mechanical resistance, chemical performance and thermal insulation) of the refractory materials in the different layers of the lining, many refractory materials are available on the market. Thus different steel producers can select specific refractory materials. The refractory materials used in the IJmuiden steel ladle, in the different lining layers and locations, are presented in Table 1.

Table 1 - Materials used in the IJmuiden steel ladle linings.

Lining	Zone	Material
Working Lining	Slag zone Barrel Bottom Impact-Pad	Magnesia Carbon Bricks Fired Alumina Spinel Bricks AluMagCarbon Bricks AluMagCarbon Bricks
Safety Lining	Side wall/ Bottom	Bauxite Bricks Magnesia Carbon Bricks Insulation Board
Mortars	Sidewall/ Bottom	Fire setting mortar Air hardening mortar
Steel Shell	Steel Shell	Steel

All the materials shown in Table 1 have been studied in detail and analysed at TATA Steels' Ceramic Research Centre (CRC), in The Netherlands. Only the main thermal properties of these materials are presented in Table 2. The thermal properties are usually temperature dependent. This is indicated in the table by the values at the various measured temperatures for each material.

Table 2 - Thermal properties of the main materials. Properties: λ = thermal conductivity [W/m/K], C_p = heat capacity [J/kg/K], ρ = density [kg/m³], ε = emissivity [-].

Refractory lining	Temperature [°C]	λ [W/m/K]	C_p [J/kg/K]	ρ [kg/m³]	ε [-]
Slag lining	20 °C 200 °C 400 °C 600 °C 800 °C 1000 °C 1200 °C 1400 °C	20.72 15.40 12.83 11.19 10.22 9.62 9.26 9.27	926 1110 1216 1280 1291 1300 1299 1300	2950	0.8
Wall wear lining	20 °C 250 °C 500 °C 750 °C 1000 °C	7.88 5.63 4.19 3.56 3.34	751 898 1104 1225 1250	3174	0.9
Bottom wear lining	20 °C 200 °C 400 °C 600 °C 800 °C 1000 °C 1200 °C 1400 °C	17.75 12.77 10.9 10.02 9.59 8.88 8.72 8.87	838 1002 1134 1187 1215 1206 1203 1204	3170	0.9
Wall and bottom safety lining	20 °C 250 °C 500 °C 750 °C 1000 °C 1250 °C	1.6 1.8 1.9 2.0 2.2 2.1	535 725 845 950 1058 1149	2690	-
Bottom 2nd safety lining	20 °C 250 °C 500 °C 750 °C 1000 °C 1250 °C	1.17 1.39 1.54 1.69 1.79 1.84	643 831 1007 1098 1189 1474	2171	-
Wall and bottom insulation lining	20 °C 250 °C 500 °C 750 °C 1000 °C 1250 °C	0.41 0.41 0.43 0.46 0.47 0.52	827 1084 1189 1202 1197 1198	961	-
Microporous insulation wall and bottom	20 °C 250 °C 500 °C 750 °C 1000 °C 1100 °C	0.026 0.027 0.032 0.039 0.049 0.072	796 910 960 1015 1094 919	400	-

Here it is necessary to mention that the materials and the relevant thermal properties shown in Table 1 and Table 2 refer to the materials that were used during the experimental campaign presented in the subsequent sections. These materials are largely the same as being studied in the ATHOR project, however, the supplier of these materials might be slightly different than the current suppliers being considered under the project. Nevertheless, given the quite similar chemical composition of the materials, the thermal-property values are expected within the same range.

3 In-Situ measurements

This section presents some examples of the data that has been acquired at TATA Steel, The Netherlands. Different types of measurements were performed. This document focuses on the thermal fields and the wear of the working linings. Alongside these two measurements, additional measurements, regarding displacement fields in terms of strain measurement on the exterior of steel shell of the ladle (with DIC) are being envisaged. These last types of measurements are not available at this time.

3.1 Thermal Fields

The evaluation of the temperature fields results in the acquisition of fundamental information that is required to evaluate the thermal behaviour of the steel ladle that operates at high temperatures. The layers of the refractory lining are composed of different materials with specific properties and are subjected to different temperatures in service. Possible tools that can be employed for the thermal measurements are thermocouples and infrared cameras.

Thermocouples are widely used for the instrumentation of industrial devices. The most common is the K type, which is composed of Nickel-Chromium / Nickel-Alumel (nickel + aluminium + silicon alloy). This thermocouple is widely used because it is inexpensive, accurate, reliable and can operate in a wide range of temperatures, up to 1260 °C with an accuracy of +/- 2.2 °C. The thermocouples can be installed at the refractory layers (working, safety and insulation) and in the steel shell at different locations (Figure 4a). They can be installed in holes drilled into the refractory bricks or welded to steel parts.

The infrared camera is a useful tool that can measure the temperature distribution on the external surface of the steel ladle from a relatively far distance (Figure 4b). The infrared cameras present some advantages compared to the use of thermocouples. This equipment provides full field measurement of the temperatures, while thermocouples provide single-point measurements. Therefore, if the problem involves a significant gradient of temperatures or for large structures, many thermocouples would be necessary to evaluate the system, whereas only one IR camera would be required to provide all the necessary measurements on each surface. A drawback is the limitation on measuring temperatures inside the linings and between the layers, so in such cases, thermocouples are more suitable.

(a) (b)

Figure 4 - Examples of thermal characterisation tools: a) thermocouples and b) infrared camera.

To measure the temperature at various locations in a model industrial steel ladle, an experimental campaign was carried out at TATA Steel, The Netherlands. For this task, the steel ladle was equipped with 24 thermocouples across the different linings to measure the temperature during its service. The measurements were taken during a period of 20 days, in which the ladle made 90 cycles. This campaign was coordinated by the Ceramic Research Centre at TATA Steel.

Figure 5 presents the graphical representation of the placement of thermocouples in a typical refractory lining of the model industrial steel ladle. From the figure, it can be seen that, at a single location of a typical lining, 8 thermocouples were used. In total, there were three locations where eight thermocouples were installed across the linings. From Figure 5, the relative location and its distance from the face of the wear lining (i.e. hot-face) can be observed. Considering the presence of the molten steel and corrosion of the wear lining, no thermocouple was installed at the hot-face of the wear lining.

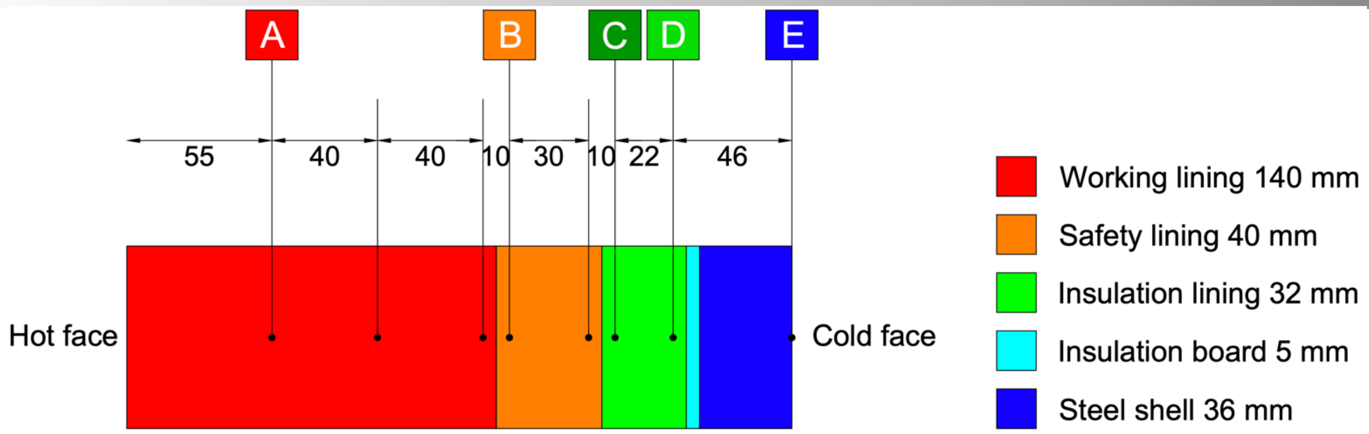

Figure 5 - Schematic of the placement of thermocouples in the refractory lining from the hot-face to the steel shell. The colour legend shows the lining type and the thicknesses. The eight embedded thermocouples are shown as black dots with their relative distances from each other indicated in mm. Data from five thermocouples, labelled A-E, are displayed in the next figure.

During a single cycle, a steel ladle goes through various steps such as, tapping, rinsing, transporting, and casting. A typical cycle takes between 244 minutes to 324 minutes. With a new ladle, there is a preheating procedure that takes approximately 21 hours. To preheat the ladle and keep the ladle warm between the cycles, gas burners are used. These burners are adjusted to increase or maintain the temperature at 1050 ºC at the hot-face.

The in-situ temperature measurements, acquired from thermocouples A - E embedded in a new steel ladle, were obtained during the preheating stage and the first 5 loading cycles, as shown in Figure 6. The measured temperatures, together with material, construction, and process data, give a good insight into the thermal boundary conditions such as the heat transfer of the liquid steel to the refractory linings of the steel ladle.

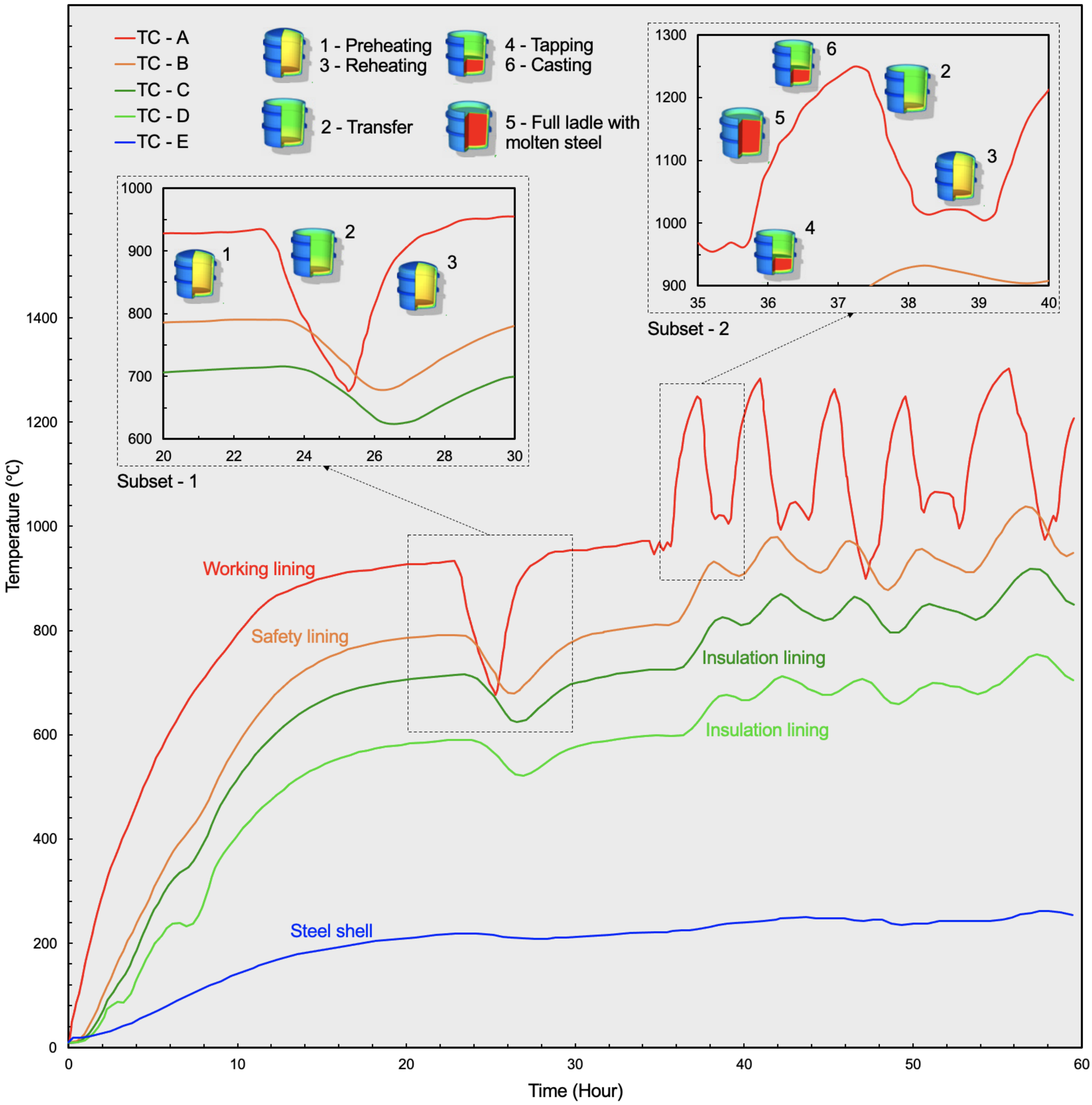

Figure 6 - Measurement results of some thermocouples in the wall of the steel ladle. The preheating stage, when the ladle is prepared for operation, and the first five loads.

A newly lined ladle first undergoes a dedicated preheating period where the temperature is increased from ambient to 1050 ºC with the help of gas burners over approximately 23 hours. This preheating period is represented by the picture of an empty steel ladle, fitted with a lid, in Figure 6 (Label 1 - Preheating). The lid denotes the placement of gas burners during this heating phase. Afterwards, the steel ladle is removed from the preheating pad and transferred to a waiting area (at approximately 25 hours) where it again undergoes heating with gas burners to keep the linings warm and ready for the thermal load. During the transfer from the preheating pad, represented by the ladle without a lid (Label 2 - Transfer), the ladle lining loses considerable amount of heat as can be observed from the sharp drop in temperature between 23-25 hours. After the ladle is placed in the waiting area and subjected to heating (Label 3 - Reheating, represented by an empty ladle with a lid), a sharp recovery is also noted. The ladle stays idle at the reheating pad for a period until it is transferred for the thermal load. This time varies depending on the plant management of the ladles. The thermal load for this ladle is applied around 36 hours. Before the ladle undergoes thermal loading, it is transported to the converter from the reheating pad. At the converter, the steel ladle is tapped (filled with molten steel). This takes about 7 minutes. During this period a sharp rise in temperature can be observed (Label 4 - Tapping). Subsequently, the ladle passes through various processes before it reaches casting machines. During this period, the ladle is full of the molten steel and the temperature continues to rise in the linings (Label 5 - Full ladle with molten steel). At the casting machine, the molten steel is gradually poured out. During the casting process, a steady rise in temperature can be observed (Label 6 - Casting). This rise, despite the pouring, is due to the location of the thermocouples which were located in the lower part of the steel ladle. Thus, for most part of the casting, the lining present with thermocouples is in contact with the molten steel. Once the casting is finished, the ladle is transported for the tipping process. During this transfer, a sharp drop in the temperature can be observed (decreasing from 1250 ºC to 1000 ºC) represented as label 2 in subset 2 of Figure 6. This drop in temperature is due to the unprotected ladle subjected to natural convections from steel shell and refractory working lining. Ultimately, the ladle is transferred to the heating pad to ensure the ladle is ready for other thermal loads (Label 3 - Reheating).

It can be observed that, between the unloading phase and the next load cycle, the temperature fluctuates due to transportation of the ladle from the tipping process to the reheating pad at the waiting area. After the first thermal load and the subsequent loads, it can be observed that the temperature at the working lining (Thermocouple A) varies by around 50 ºC (increasing in 2nd load, decreasing in 3rd and 4th load and increasing again in 5th load). This change in temperature can be explained by the fact that the temperature of the molten steel is slightly different between each loading.

The highest temperature measurements and most dramatic changes in temperature are recorded by thermocouple A. This is expected as it is located in the working lining, 55 mm from the hot-face. The temperature increase observed in the new steel ladle, from the gas burners during the preheating period, is from room temperature (20 ºC) to around 950 ºC (Figure 6). The temperature that was expected to be observed at the surface of the refractory brick was 1050 ºC. As the thermocouple A is located at the centre of the wear lining, the temperature observed at that location is lower compared to the applied temperature. The sudden drop and increase in temperature, during the transfer from the preheating pad, corresponds to loss and subsequent gain of 240 °C. The changes in temperature observed for the loading and unloading are of the magnitude of 250 ºC during the normal thermal cycles (as observed after 1st, 2nd and 4th load cycles). It can be observed that the drop in temperature is larger after the third and fifth cycles (around 350 ºC), this is due to the fact that, after those loads, the ladle was not subjected to the reheating due to plants' ladle management activities.

Thermocouple B, 145 mm from the hot-face and 90 mm from A, is located at the face of the safety lining closest to the hot-face. An approximate decrease in temperature of 120 °C is observed, in comparison with thermocouple A. The sudden changes in temperature observed for A are still observed, however, the intensity of the changes are reduced by approximately half.

Thermocouple C, located 185 mm from the hot-face and 40 mm from B, has been inserted in the insulation lining near the joint between safety and insulation lining. The data shows a similar pattern to that observed for B with a global reduction in temperature of approximately 80 °C.

Thermocouple D, located 207 mm from the hot-face and 22 mm from the C, is located at the insulation lining near the microporous insulation board. The data presents a larger global reduction in temperature (120 °C) between C and D than observed between B and C, even though the distance between them is approximately half that between B and C, as a result of the insulating material. During the preheating period, two plateaus can be observed, first at 100 °C and later at 240 °C. This thermocouple is located close to a mortar layer between the brick and insulation board. The first plateau is due to the evaporation of free water at 100 °C between 2 and 4 hours. The 2nd plateau observed around 240 ºC can be due to the removal of chemically bound water from the mortar layer.

Thermocouple E, located 46 mm from the cold-face of the ladle (36 mm of which are the steel shell), records a global drop in temperature of 400 °C. This significant drop in temperature demonstrates the effectiveness of the 5 mm of microporous insulation board present between thermocouples D and E.

Temperature measurement data provides an insight in the behaviour of different layers in the lining during the application of thermal loads. From this data, it is possible to calculate certain necessary parameters that are crucial for the numerical modelling. These parameters are heat transfer coefficients (between burner and working lining, molten steel and working lining, between different linings) and thermal conductivities (for molten steel and slag). From these parameters, it becomes easier to define the thermal boundary conditions for the different stages of steel ladle service during the numerical simulations. Moreover, a real time measurement can be beneficial to constantly inspect the temperature in the refractory linings. By doing this, it can assist in identifying the wearing rate in the working lining as the temperature will increase when the refractory brick undergoes damage due to wear.

3.2 Wear of the working lining

Deterioration of the refractory working lining of an industrial steel ladle is an important aspect of the measurements. Left unchecked, excessive damage can be caused to the bricks leading to the failure of the ladle. The failure of ladle can happen either due to an excessive temperature rise in the refractory linings (leading to heat loss in the molten steel) or it can lead to an ingress of molten steel into the linings, damaging the steel shell. A failure during a crucial production process can stop the production line, leading to significant economic consequences, hence continuous monitoring of the ladle is undertaken. Measurement of the wear can be done indirectly or directly. Indirect measurement can be performed with the help of thermal measurement in the working lining. However, these indirect measurements are only taken for a point where the thermocouples are located and are not representative for the whole working lining. To measure the overall distribution of the wear of a lining, a direct measurement with Terrestrial Laser Scanners (TLS) can be used. TLS, or 3D scanning, may be used to evaluate the geometry of the steel ladle. This equipment was originally developed for as-built modelling of architectural and engineering structures; however, they can also be used for high-resolution mapping of industrial vessels and equipment (Figure 7). Laser scanning can also be used to measure temperature. Some systems are also able to measure the reduction of the thickness of the linings, as bricks are continuously subjected to corrosive attacks by hot liquid steel and slag. The laser scanner measurements can be used to evaluate the variation of thickness of the bricks in hot conditions by sending infrared laser pulse from outside the ladle to the wall and the bottom.

Figure 7 - Example of laser scanner measures from outside position [5].

Many plants are already using these devices to scan the internal surfaces of the steel ladle after every load. Understandably, this equipment is not suitable for a constant observation but even a periodic scan after every load provides useful data that can be used to validate the numerical models.

Figure 8 presents an example of an immersed laser scan taken on a newly lined steel ladle at TATA Steel, The Netherlands. This scan shows the circumferential layout for the thickness of the working lining. From this initial scan and a set reference point on the exterior steel shell of the ladle, different thicknesses in the working lining can be identified with the help of CAD drawings. The average thickness in the lower part of the lining is 140 mm and the thickness in the upper part is 180 mm (Slag zone). These values are similar to the values described in the ladle design (Figure 3). Different zones shown in Figure 8 indicate area of high interest for the wear in the working lining. Zone S 1-4 are in the slag line of the working lining. S1 represents the upper-most part of slag line near the opening of ladle. S2-3 are in the slag line. Zone P 1-3 represents the partition, a boundary zone between the slag line with 180 mm thickness and working lining with 140 mm thickness. Zone W 1-5 are in the working lining and located in the zone near the impact pad. The impact pad in working lining is marked by zone W1. This area has higher thickness of 178 mm to withstand repetitive impact during thermal loadings. The areas near W1 are marked by W2-5. Zone L 1 and 2, represents a low impact zone in the working lining. In this area, not much wear is expected in usual service conditions.

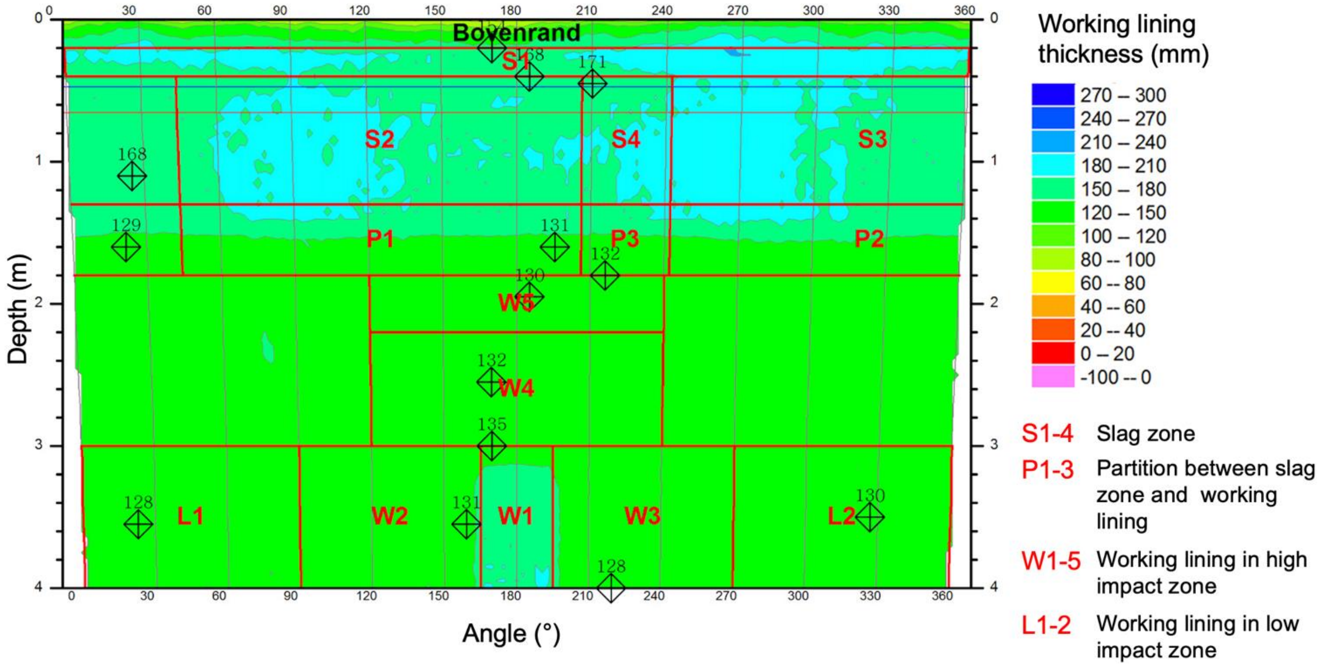

Figure 8 - Example of the working lining thickness distribution, of a newly lined steel ladle, calculated from the laser scans (taken between the inside measured point and a reference point on the inside of the safety lining). The legend shows the calculated thickness of the working lining in mm. Zones S, P, W and L indicates different zones of interest.

Figure 9 presents examples of laser scans performed at two different instances during the full life cycle of the working lining. Figure 9a indicates the distribution of the wear at half life cycle of the working lining and Figure 9b at full life cycle. A comparison between the initial scan (Figure 8) and Figure 9a shows the range of wearing. It is possible to observe wearing of 30 mm in the slag zone (marked as S2-4 and P 1-3). However, at the same instance, an increase in thickness can be observed at the upper part of the ladle (S1). This is the area where slag starts to accumulate after thermal loads.

Figure 9b presents the distribution at full life cycle after which the linings need to be replaced. From this figure, it can be observed that the working lining in the slag zone is reduced to 80 mm (from 178 mm) due to wear. Also, a reduction in the upper part can also be observed (S1) which indicates the manual removal of the accumulated slag with mechanical equipment.

From both these scans, it is possible to observed that the working lining located in the slag zone undergoes rapid wear compared to rest of the lining. This is to be expected as contact with slag creates severe corrosion that promotes rapid wear. It is interesting to note that, in this IJmuiden steel ladle, the life cycle of working lining is governed mainly by the slag zone lined with Magnesia Carbon bricks. The working lining area, that rests in contact with the molten steel, is lined with alumina spinel bricks which also undergoes wear, but the magnitude is much smaller. The areas most affected by the wear in the lower parts are shown in zone W1-3 in Figure 9a-b. The localised wear can be due to the repetitive impact generated by molten steel while being loaded.

This scan shows the level of wear that took place in the refractory lining and can help identify the areas where wear is greater than predicted. These type of laser scans can be used to validate numerical models that employ the damage due to corrosion in the wear lining of the steel ladle.

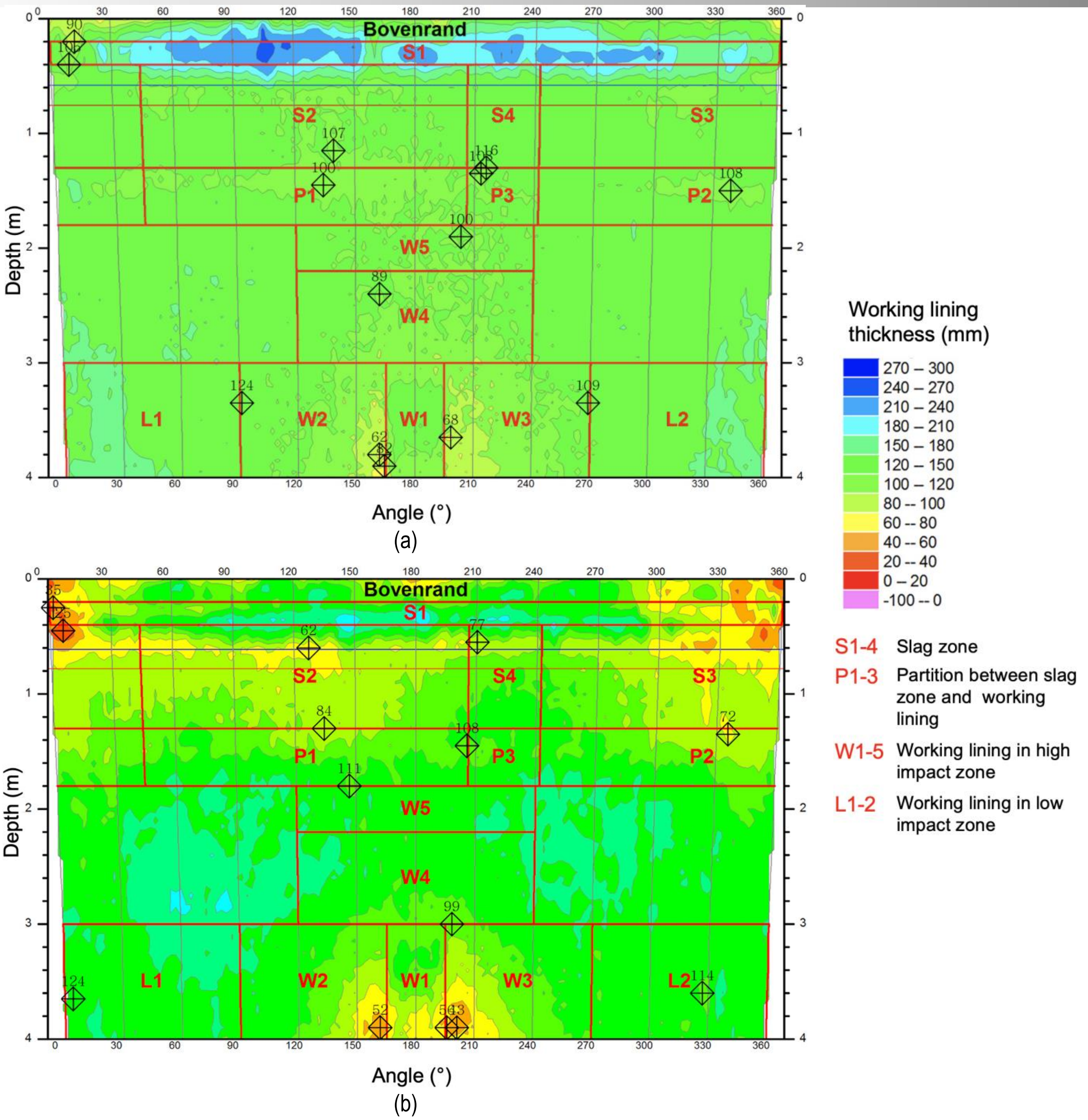

Figure 9 - Example of working lining thickness distribution on steel ladle after thermal loadings calculated from the laser scans: a) after half life cycle and b) after full life cycle.

3.3 Additional measurements

For the displacement fields (i.e. Strain/displacement measurements), marker tracking, digital image correlation, laser scanning and photogrammetry tools can be used. These techniques of strain/displacement field measurements are remote and hence it is possible to use these devices at higher temperatures where the use of strain gauges or LVDTs are not feasible.

Marker tracking is a photo-mechanical technique that tracks markers previously installed on the sample´s surface. It may be used to determine displacements and strain fields during a thermomechanical solicitation. It is a powerful technique, as it is simple, fast to use, and it requires small computational resources for the data post-processing. However, this technique is not suitable to represent discontinuities, such as cracks and ruptures.

Digital image correlation is an optical full-field measurement technique. It was created at the beginning of the 1980s and has been continuously developed since, presenting a significant increase in the accuracy. It allows the determination of an experimental full field of strains and displacements, based on the grey level conservation principle [6].

Photogrammetry is the process of generating 3D models from a series of images of the object; the resulting model can be scaled and used to measure distances between objects and to measure the deformed configuration of some structures. This technique provides reliable, low-cost measurements [7]. Figure 10 presents an example of photogrammetry applied in the case of the pilot steel ladle. With this technique, it is possible to gather cloud points with can be reconstructed into a 3D graphics. This can be useful to obtain the overall geometry of a large structure or to observe any changes in the structure over time (in terms of displacement).

Figure 10 - Example of photogrammetry (lining of Pilot steel ladle).

The constant movement of the steel ladle, safety regulations for steel ladle and restricted access to plant can limit the employment of some of the measurement techniques discussed previously. Marker tracking and DIC requires a rigid setup for camera and a constant exposure of light. Given the constant movement of ladle, a constant viewpoint from camera cannot be assured and glow coming from the molten steel during filling and pouring disturbs exposure of light. Photogrammetry, which requires 360º view from camera, cannot be used due to constant movement. For a very short duration, a ladle is held still during the laser scan of the working lining after each thermal load. In that period, the ladle is tilted to allow laser scanning, scraping of slag and leftover molten steel. Although the ladle is still, several operations are carried out in its surroundings that will restrict any placement of camera setup for measurements. After the laser scan and tipping process, the ladle is shifted to the reheating pad to keep the linings at high temperature. At that location, the ladle is held still and is in normal vertical position. During this operation as well, there are many operations being carried out in vicinity that will restrict the direct access. Moreover, there are various tipping and reheating locations in the plant which makes it difficult to ensure a steel ladle will be put on a same stand for its whole life cycle. This situation creates additional complexity of transferring measurement setups to different locations. Strain gages, that can work at high temperature, also poses difficulties during operation and a remote data acquisition system (that requires a special attachment to the steel ladle) is not possible due to plant safety regulations regarding the steel ladle. However, obtaining in-situ measurements for displacement field is vital for the validation of the developed numerical models. Considering the challenges associated with gathering measurements from an industrial steel ladle listed above, it will not be practical to obtain such constraint measurements at the working lining (except via Laser scans after every thermal cycle). Therefore, a possible implementation of DIC system is also being considered for the steel shell of the ladle. However, due to the complexities listed previously, the DIC system is being employed only during the preheating period of a newly lined ladle. This is considered achievable because during preheating period it is comparatively easier to ensure a constant exposure of light to the DIC surface and a rigid surface where steel ladle does not move due to external factors.

Figure 11 presents the proposed DIC measurement layout. For this, a representative 'observation area' on the outer side of the steel shell of the ladle will be selected. After cleaning the observation area, a suitable speckle pattern will be applied with paint. Next to the observation area, one thermocouple will be installed to measure the temperature during the period of the preheating. Due to safety regulations, this thermocouple will be attached to steel shell with magnet. During this measurement, the inside temperature will be recorded using the thermocouple present inside the steel ladle for the control of the temperature during the preheating process.

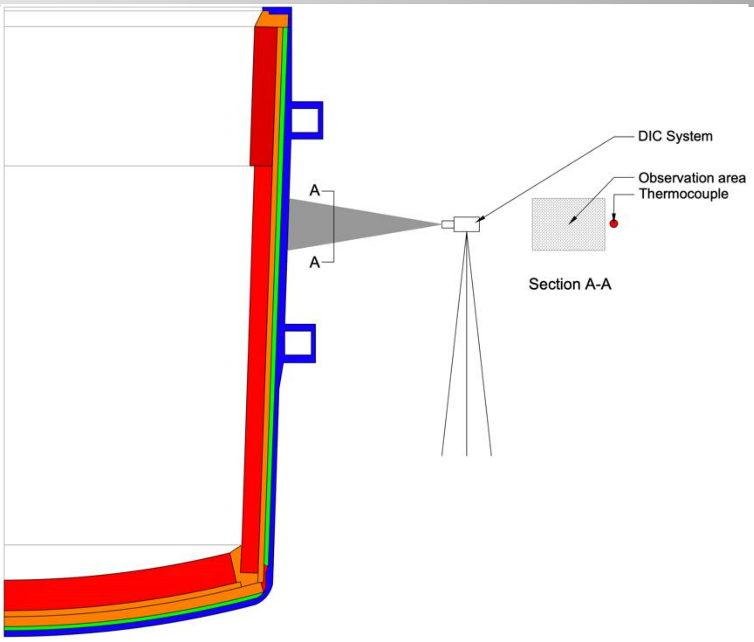

Figure 11 - Proposed DIC measurement layout.

In-situ measurements of the steel shell, obtained via DIC, along with thermal field and wear measurement data presented previously can assist with the validation of the numerical models. Although the results will be for the steel shell, with the experimental data gathered from pilot steel ladle, it will be possible to fully calibrate and validate the developed numerical models. via inverse analysis of the DIC data.

4 Conclusion

In-situ measurements of an in-service steel ladle is a very challenging task considering the constant movement, restricted access and safety regulations of the ladle. However, it is equally important to gather the data of thermal fields and displacement fields while the ladle is in service because it assists in calibration and validation of various constitutive models.

Thermal measurements obtained with thermocouples shows the thermal behaviour of the different linings during various stages of the steel ladle utilisation, such as, preheating, before, during and after the loading of the molten steel. From these measurements it can be observed that preheating with gas burners achieves a surface temperature of 1050 ºC. Observation of the temperature at the steel shell, showed that the temperature remains relatively constant, after the preheating, at 210 ºC to 250 ºC. This constant distribution of temperature shows the effectiveness of using an additional layer of the microporous insulation board. Moreover, observing the trend in the temperature changes between the load cycles, can also help identifying certain key thermal parameters, such as heat transfer coefficient and thermal conductivity.

Obtaining continuous displacement field measurements is very complex. Laser scanning offers an advantageous and innovative way of gathering the wear data periodically. The data obtained with this method still can be very useful to validate numerical models by comparing the wearing and viscoplasticity data between the numerical outcome and observed values.

A DIC campaign is being considered to be employed during the preheating period of a newly lined steel ladle as it offers continuity and less obstruction during the measurement. The data obtained through thermocouples, periodic laser scans and DIC at steel shell will be employed to validate the numerical models.

5 References

[1] A. Buhr and H. Lachmund, “Dream Ladle Lining,” in *VDEh Proceedings, 9th International Symposium Refractory Technology: Steel Ladle Lining*, 2016.

[2] A. Gasser, K. Terny-Rebeyrotte, and P. Boisse, “Modelling of joint effects on refractory lining behaviour,” *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, vol. 218, no. 1, pp. 19–28, 2004.

[3] T. M. H. Nguyen, E. Blond, A. Gasser, and T. Prietl, “Mechanical homogenisation of masonry wall without mortar,” *Eur. J. Mech.*, vol. 28, no. 3, pp. 535–544, 2009.

[4] M. Ali, T. Sayet, A. Gasser, and E. Blond, “Computational Homogenization of Elastic-Viscoplastic Refractory Masonry

with Dry Joints," *Int. J. Mech. Sci.*, vol. 196, p. 106275, 2021, doi: 10.1016/j.ijmecsci.2021.106275.

[5] R. Lamm and S. Kirchhoff, "Optimization of ladle refractory lining, gap and crack detection, lining surface temperature and sand-filling of the ladle-taphole by means of a 3D-laserprofile-measurement system that is immersed into a hot ladle to evaluate the entire condition," in *UNITECR*, 2017.

[6] G. Besnard, F. Hild, and S. Roux, "'Finite-element' displacement fields analysis from digital images: Application to Portevin-Le Châtelier bands," *Exp. Mech.*, 2006, doi: 10.1007/s11340-006-9824-8.

[7] A. Mandelli, F. Fassi, L. Perfetti, and C. Polari, "Testing different survey techniques to model architectonic narrow spaces," in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 2017, doi: 10.5194/isprs-archives-XLII-2-W5-505-2017.