Light Metals 2013 *Edited by: Barry Sadler*
TMS (The Minerals, Metals & Materials Society), 2013

MATHEMATICAL MODEL OF COOLING OF A STOPPED POT AND ITS VALIDATION

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Keywords: aluminum reduction pot, potshell, potshell cooling, potshell modeling

Abstract

In aluminum reduction pot technology, the potshell is used for several generations. After each shut down the potshell is cooled by free convection and radiation. This cooling takes from five to nine days depending on the surrounding temperature. Cooling by spraying water on the potlining is used in some aluminum plants; this reduces the cooling time to less than one day but this method can be harmful for the potshell and for the environment.

The aim of this study is to develop a heat transfer model of the aluminum reduction pot in a free convection and radiation environment. A commercial finite element code (FEM), ANSYS®, was used to create the 3D model and solve both the steady state and transient temperature distribution. All material properties and heat transfer coefficients were modeled as functions of temperature. The solidification of aluminum at its phase transformation temperature was included in the model to investigate the behavior of the cooling curve of the various components of the pot during this phase change. The resulting cooling curves are in good agreement with experimental data. This model will be used to design an optimum pot cooling environment.

Introduction

Ideally, an aluminum reduction pot should be kept in operation as long as possible. During pot operation, chemical and abrasive forces wear the bottom carbon lining down to the cast iron around the collector bars. By normal standards this may take 3000 days [1]. This is, however, often not the case. Earlier, long pot life was not considered a critical parameter as long as it was above 1200 days but nowadays a potlife of less than 2000 days is considered not to be acceptable. All smelters make a considerable effort to increase pot life by improving pot design with high quality lining materials, correct construction, smooth start up and good operation.

EMAL is approaching a point where a replacement cycle is forthcoming for the Phase 1 pots, and thus consideration of a delining facility is necessary to carry out the required operation and to achieve consistent production capacity. The cooling area in the delining building for Phase 1 pots is considered large for Phase 1 pots only. The main aim of this study is to reduce the cooling time of a stopped pot enough to accommodate Phase 2 potshells in the same building as well without any extension.
Lalonde et al. [2] established a method for obtaining temperatures of molten aluminum as it solidifies in a reduction pot after it has been removed from line current. The temperatures were used to develop cooling curves and models were created to predict the effect of time of anode removal, size of metal pad and distance from the cell center on the cooling rate of the untapped aluminum. However, the study did not focus on the potshell and the model considered the pot contents as a single entity.

Many other studies had paid an extensive attention to the potshell sides in operating pots; see [3-6]. One study, however, modeled pot cooling after the power interruption in order to determine the pot condition for subsequent potline restart after a few hours [7]. None of these studies established a long term cooling model for a permanently stopped pot. Even though some of the hitherto published cooling techniques can be considered for shutdown pots, the implementation of any of these may not fit the delining room design.

The main goals of the study are to build and validate a full scale 3-D FEM model to be used, first, to map the temperature distribution inside the stopped pot after pot cutout and, second, to study and design an appropriate cooling system to reduce the shutdown cell cooling time without damaging the potshell. This paper shall focus upon the first goal associated with building and validating the FEM model. The model is based on ANSYS® commercial code and set up for a DX pot. The validation was done with measurements made on a stopped DX pot at DUBAL. The DX pot technology has been described previously [8].

Experimental

Advances in FEM software such as ANSYS and availability of the very fast computers with large memory made it possible to build a full scale 3-D model of one quarter of DX pot with very detailed representation of the potlining and of the potshell steel structure. The objectives are: to build the 3-D FEM model for an operating pot design, perform onsite measurements on a stopped pot of that design, validate the model using these measurements, and use the model to map the temporal and spatial thermal contours in the pot at similar experimental environment and boundary conditions. The following two sections will explain the onsite measurements and results followed by the FEM model.

<u>Plant measurements on a stopped DX pot at DUBAL</u>
The onsite measurements were made on a stopped DX pot in Dubai Aluminium (DUBAL). The temperature measurements started just after the pot cutout and continued for almost seven days throughout different stages of the pot movement from the potroom to the delining room space. Bath temperature was measured at two locations, before and after tapping. Evolution of temperatures with time was measured in the metal on the potshell surface (on the upstream and downstream of the potshell side, and at the tap end), on the deckplate, and on the bottom of the

potshell. These measurements were taken on an hourly basis inside the potroom immediately after pot cutout until the pot was removed from the potroom. Additional points were measured on an hourly basis during the following seven days. Figure 1 shows the thermocouple locations for the above mentioned points.

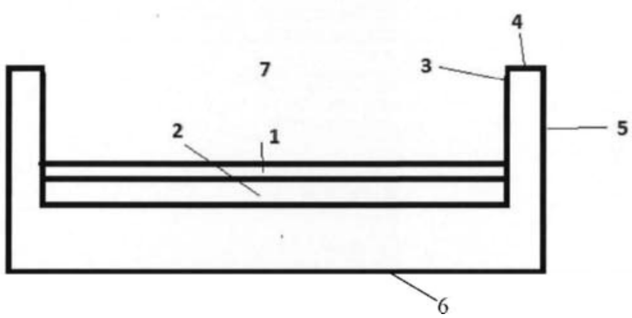

Figure 1. Thermocouple locations for onsite measurements

Thermocouples were located on three spots upstream and downstream of the potshell side and three spots on the tap end of the potshell. Three thermocouples were located on the deckplate, one on the upstream side, one on the downstream side and one on the tap end. Two thermocouples were located on the bottom of the potshell, 800 mm from the upstream and the downstream side edges. In the potroom the 800 mm locations could not be reached, so the measurements had to be taken at 100 mm from the edge instead. The following instruments were used: K-type thermocouples for the potshell surface temperature, Marshal Tip thermocouple assembly for metal and bath temperature, Fluke and Anristo thermometer. Data was acquired manually from the preinstalled thermocouples.

In the potroom the first set of measurements was completed 15 minutes before the cutout and 15 minutes after cutout and then hourly for 19 h. Outside the potroom, the first set of measurement was carried out by pot delining team starting 3 h 20 min after the pot had been transferred and the last set of measurement was completed 6 days 23 h after the cutout.

Experimental Results

Thermocouples were preinstalled in different locations of the pot to follow the temperature history of the bath, metal, and the potshell as outlined in the above section. The bath temperature was 982 °C 15 minutes before the cutout and 953 °C 1 hour after the cutout. After 1 hour, the bath temperature measurement was impossible as the bath height was only a few centimeters and was mushy, as indicated by dark red colour in Figure 2. The metal temperature measurement was stopped 19 hours after the cut out in the potroom and restarted 3 hours 20 minutes later in the pot delining area. Measurements were interrupted once again for 2 hours during the remaining bath removal on the 3rd day and for a further 1 hour while the potshell was removed from the pit on the 4th day. The metal cooling curve in Figure 3 showed high cooling rate (43.6 °C/h) right after the power cut out because of bath and metal tapping in addition to the presence of anodes before the metal started to solidify. A very slow cooling rate (7 °C/h) followed due to the metal phase change. Then the cooling rate increased again to 30.8 °C/h in the solid phase. The cooling rate increased to 45.3 °C/h while the pot was moved to the delining area. The cooling rate went down significantly in the delining room to 4.6 °C/h. The temperature reached 85 °C after 4 days and 7 hours from the time of cut out.

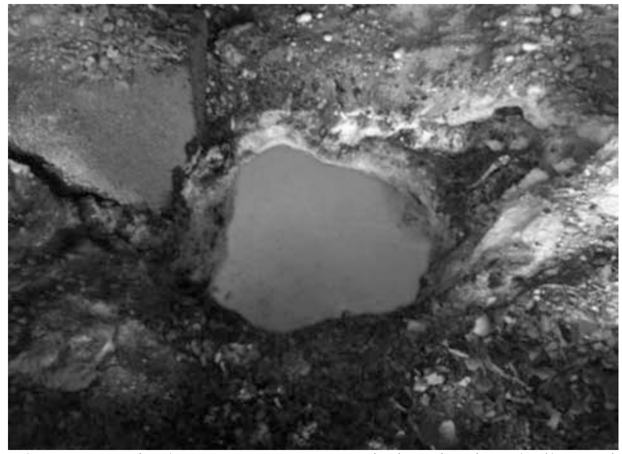

Figure 2. Bath picture at 10:00 a.m.; dark red colour indicates low temperature near solidification.

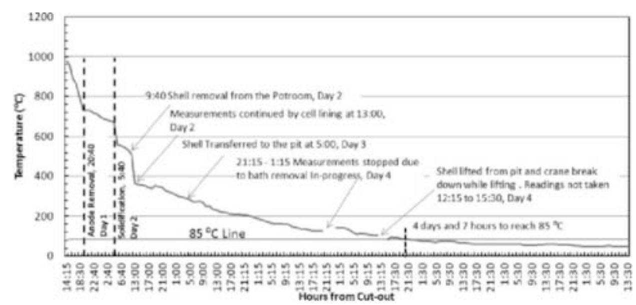

Figure 3. Metal temperature cooling curve for the DX pot

The potshell temperatures were measured upstream and downstream on the centre of the potshell sides. Three locations were measured in each side of the pot, bottom, centre, and deckplate. The centre point is located 360 mm below the deckplate, and the bottom was 800 mm from the lower edge on the bottom of the potshell. The measurements were stopped three times while the potshell was transferred to the pit, while remaining bath removal was in progress and when the potshell was lifted from the pit. The measurements on the pot sides and bottom were interrupted for 56 hours after the transfer to the pit because the thermocouples broke during the transfer.

Potshell cooling curves at different locations are shown in Figure.4. While the pot was sitting in the potroom, the first 20 hours, the cooling rate was approximately 4.4 °C/h on the deckplate and 8.5 °C/h at the centre point of the potshell, on both the upstream and downstream sides. This cooling rate was reduced to 1.4 °C/h in the deckplate and 4.9 °C/h in the centre point during the following 15 hours in the open space. Then the temperature reduced from 85 °C to 61 °C in the following 40 hours with cooling rate of 0.6 °C/h in both locations. When the pot was moved to the pit area, the potshell deckplate cooling rate became approximately 0.2 °C/h in the last 80 hours before it reached the room temperature of 40 °C. The bottom of the potshell cooling rate was 1.9 °C/h in the potroom to reach 81 °C. Outside the potroom, the bottom of the potshell temperature increased to 115 °C and then cooled again to 103 °C 18 hours later with cooling rate of 0.67 °C/h. This temperature jump in the bottom of the potshell after it left the potroom was due to the change of thermocouple location from 100 mm from the edge to 800 mm from the edge. The bottom of the potshell cooling rate matches the low rate of the other locations of the potshell, 0.2 °C/h during the last 80 hours.

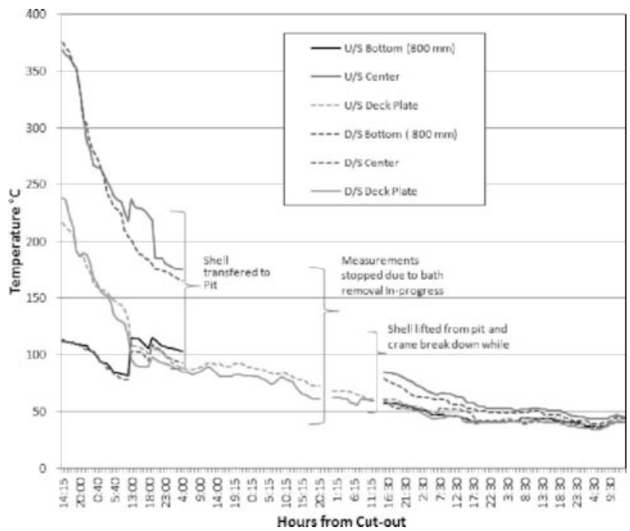

Figure 4. Potshell temperature cooling curve for the DX pot

3-D Finite Element Pot Model

The 3-D model is made for one quarter of the pot. Materials properties were obtained from the suppliers. Figure 5 shows the main features of the model geometry. All properties are implemented in the model as a function of temperature in order to eliminate the uncertainty that would be generated due to their temperature dependency. The boundary conditions are chosen to be similar to the onsite measurements - free convection and radiation. The free convection coefficients (h_c) were determined as a function of temperature using empirical correlations for the standard geometries like flat plate and ANSYS FLUENT CFD modeling for complicated geometries like the cradles. The radiation heat transfer coefficient (h_r) is added to the convection as function of the surface and surrounding temperature for each surface. After building the CAD drawing of the model using the exact pot dimensions, the pot model was meshed by sweeping through each component of the pot separately and manually connecting the faces of each component to ensure the transfer of the solution from one component to its neighbour through appropriate interface. This method is flexible for discretization as the mesh in each geometry could easily be manipulated for improved quality. Mesh consists of about 5.99 million nodes and 2.71 million cells.

A mix of tetrahedral and hexagonal elements was used for meshing. The model was then exported to the Mechanical APDL code (ANSYS® Steady Sate Thermal & Transient State Thermal) for finite element heat transfer analysis. During the setup, the boundary conditions were imposed on both models as free convection environment with 40 °C ambient air and radiation with variable surrounding temperature at the outer potshell steel surface (sides and bottom). The metal and bath thicknesses were initially 21 cm and 18 cm and then reduced to 1 cm each after the metal and bath taping.

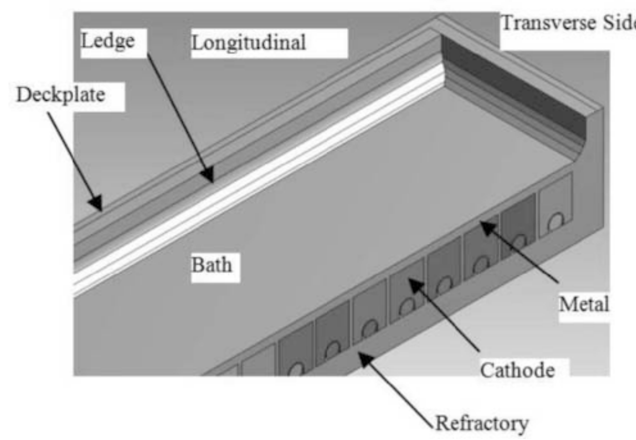

Figure 5. FEM geometry

The cooling curves for the metal and the potshell, generated from the FEM model are compared to measurements in Figures 6 - 9. The metal cooling in Figure 6 was measured in the pot centre. The calculated metal cooling curves shows good agreement with the measurements. Temperatures at all locations are nearly the same 84 hours after the pot cutout. How long does it take for the metal to reach 85 °C? There is good agreement between the model and the measurements in the answer to this question:, 4 days 6½ hours and 4 days 7 hours, respectively. After 5 days the model gives a uniform metal temperature of 70 °C.

Figure 7 shows the model and measured temperatures at the centre location of the potshell. The measured temperature increased in some instances due to the movement of the pot from one area to another which most likely changed the convection boundary conditions. This may have caused higher or lower cooling rates on the surface for a certain time while the heat conduction rate from the pot interior remained the same. The model uses free convection and radiation boundary condition that is varying with the potshell surface temperature, as shown in Figure 13 for the deckplate as an example. The deckplate results in Figure 8 show good agreement in the potroom and the pit areas; but differ significantly when the potshell was in the open space, most likely because there was some wind in that area. Figure 9 shows the bottom of the potshell temperatures. The model and measurements agree well, but as noted before, the measurement point changed from 100 mm away from the edge of the potshell when the pot was in the potroom to 800 mm away from the edge when the pot was moved outside. This explains the temperature increase at that time in both, the model and the measurements because the model output location was also moved as the measurements did.

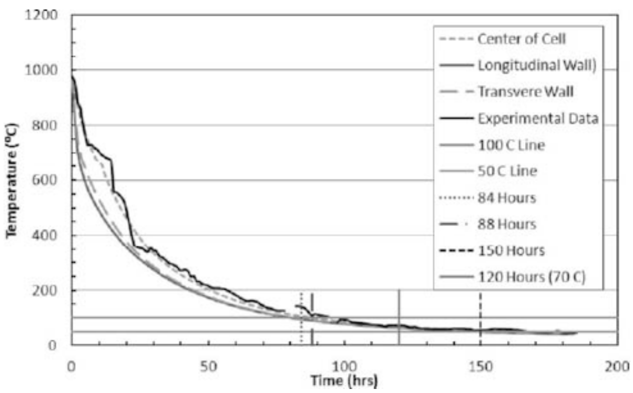

Figure 6. Model cooling curves at different locations on the metal surface, compared to the measured location at the centre.

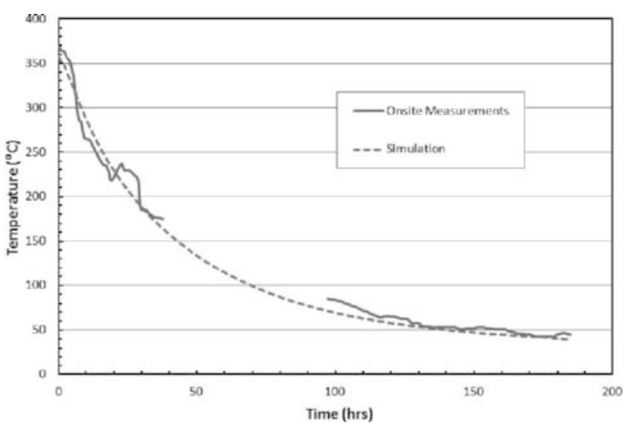

Figure 7. FEM cooling curve at the centre location

The pot temperature contours are shown in Figures 10 - 12 at different times, note the changes in the contours color scale. Figure 10 shows the temperature contour of the pot right after the power cut out. The metal and bath thickness is 1 cm each, a very thin layer on the top of the cathode blocks. After 5 days the metal surface showed a uniform temperature around 70 °C. Also it can be seen that the highest temperature is located above the bottom of the potshell; which indicates insufficient cooling in this area. It would be beneficial to increase the cooling rate from the bottom of the potshell by using a fan.

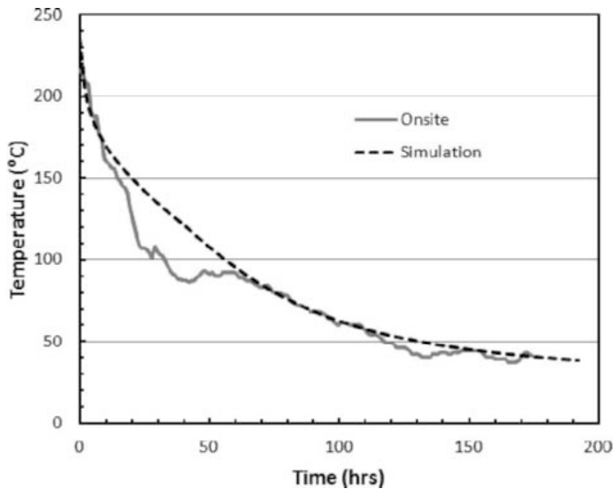

Figure 8. FEM cooling curve at the deck plate location

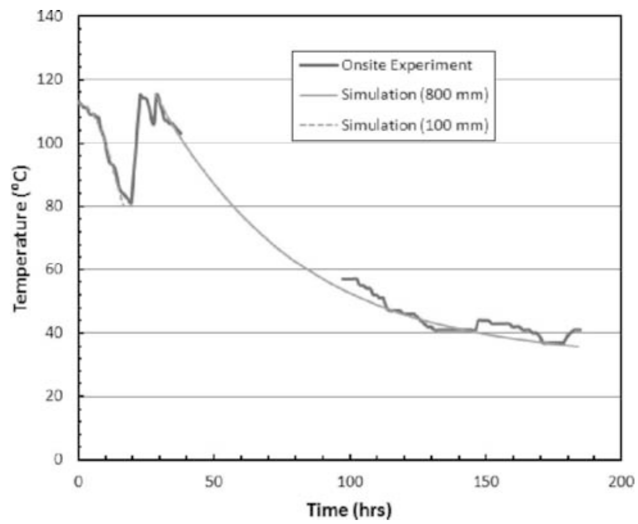

Figure 9. Model and measured cooling curve at the bottom of the potshell location.

Figure 13 shows the convection radiation and combined heat transfer coefficients as function of temperature for the deckplate. The combined coefficient is used in the model as function of temperature. Similar functions were generated and fed to the model for all other surfaces through user defined functions.

As presently the pot is left to its own natural cooling, the model is built to simulate free convection cooling using free convection heat transfer coefficients. These are not the same for all pot geometry features that are exposed to the ambient air. The features are: horizontal plate facing downwards (bottom of the potshell and bottom of the deckplate), horizontal plate facing upwards (deckplate and bath top surface), and vertical plate (side of the potshell and cradles, end of the potshell). Radiation has to be taken into account at all temperatures, but surface to surface radiation complicates the calculation of radiation heat transfer coefficients. This can be simplified by using different radiation reference temperatures as in this work.

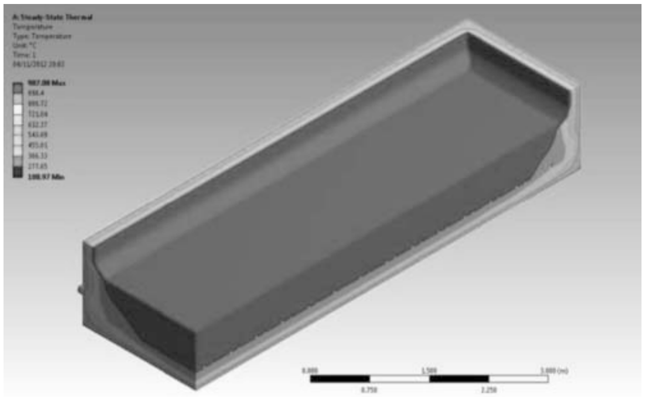

Figure 10. FEM temperature contour right after the power cutout.

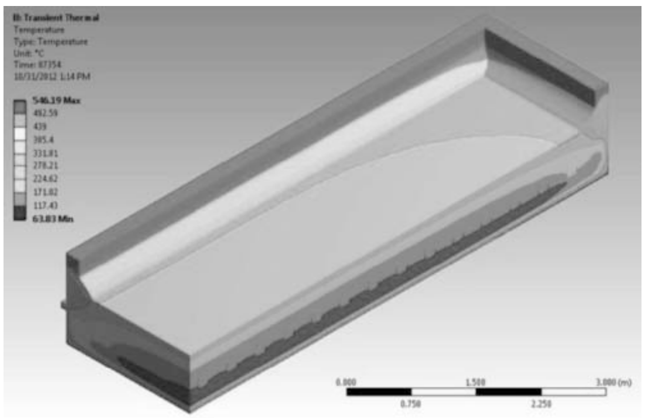

Figure 11. FEM temperature contour 1 day after the power cutout.

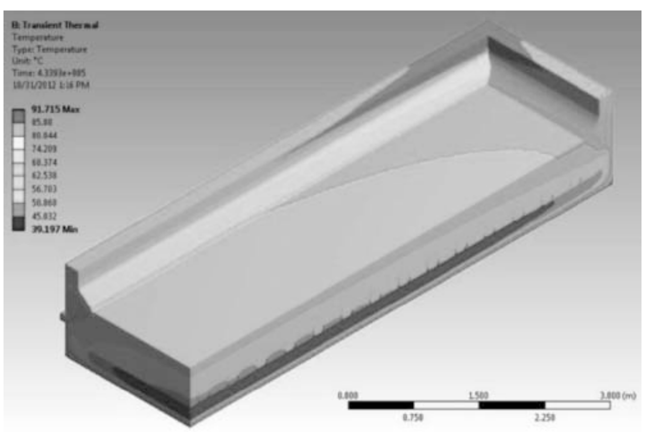

Figure 12. FEM temperature contour 5 day after the power cutout.

Conclusions

A 3-D full scale mathematical model has been developed for cooling an aluminum reduction pot and its results are validated by onsite measurements on the same pot design. The model results are in good agreement with the measurements and the model is ready for different cooling studies on the pot in order to build an efficient cooling environment for the pot.

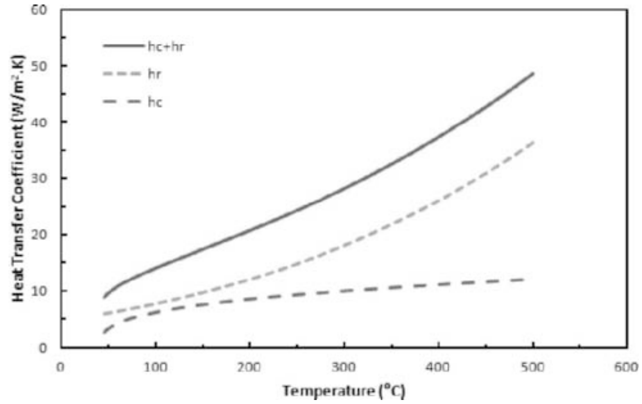

Figure 13. Convection radiation and combined heat transfer coefficients of the deckplate

Acknowledgements

We would like to acknowledge Emirates Aluminum (EMAL) as the sponsor of this research and the reduction service department at EMAL for their sincere collaboration. Also, we would like to acknowledge Dubai Aluminum (DUBAL) for collaboration in performing the onsite measurements and productive discussions.

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