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STUDY OF SHELL ZONE FORMATION IN LITHOGRAPHIC AND ANODIZING QUALITY ALUMINUM ALLOYS: EXPERIMENTAL AND NUMERICAL APPROACH

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SUMMARY

Shell thickness is an important quality factor for lithographic and anodizing quality aluminum alloys. Increasing pressure is placed on casting plants to produce a thinner shell zone for these alloys. This study, based on plant trials and mathematical modelling highlights the most significant parameters influencing shell zone formation. Results obtained show the importance of metal temperature and distribution and mould metal level on shell zone formation. As an answer to specific plant problems, this study led to the development of improved metal distribution systems for DC casting of litho and anodizing quality alloys.

INTRODUCTION AND COMMERCIAL INTERESTS

Banding and structural streaks are visual defects that can be found in anodized rolled sheet ingots and are associated with a macrostructure of as-cast aluminum sheet ingot which is called shell zone. The shell zone is a characteristic of the DC casting process. It is a coarsened structure at the surface of the ingot resulting from the low cooling rates at the mould wall. Manufacturers of anodized sheet products eliminate banding and some structural streaks by scalping of the ingots prior to the homogenizing and rolling steps in their process. In order to minimize the metal losses incurred during scalping while maintaining a high surface quality of the sheet, the customer specifies a certain maximum shell depth.

To obtain a shell zone that meets the customer's specifications, all parameters that influence shell thickness require optimization. The advantages to be gained are a more consistent quality product and a reduction in overall processing costs at the manufacturer's rolling mill.

This paper describes the work that was done to further understand the formation of shell zone in anodizing and lithographic quality sheet ingot. To reduce the shell thickness, in addition to the traditional approach of reducing the effective mould length using technologies such as Hot Top, Level Pour, EMC etc. [1], parameters that influence the primary cooling or the advanced secondary cooling were also to be considered. The originality of this work stems from the fact that all parameters studied had to be easily implementable with the existing equipment of the casting plant as a first step. This is why a change in the mould technology was not considered. The objective of this study was to find out if it was possible to achieve shallow shell zones with minor modifications and optimization of the casting process. The absence of floating crystals and feathery grains was also considered as a criterion of success.

EXPERIMENTAL METHOD AND ANALYSIS

This study includes an experimental and a numerical survey of the shell zone formation as well as an introduction to possible solutions elaborated from numerical simulation. In order to have good control over the parameters studied and to have a clear understanding of the shell zone formation, the physical part of the study was conducted in a full-size experimental casting center. The following sections highlight the most important parameters of shell formation as they were defined from experimental trials and numerical simulation.

This study was divided into three different steps:

1) Characterization of the shell thickness in a casting plant.
2) Identification of important parameters from experimental and numerical trials.
3) Elaboration of casting practices and devices reducing shell zone and other macrostructural defects like floating crystals and feathery grains.

1. MONITORING OF CASTING CONDITIONS

As a first step, the identification of the problem was studied during a monitoring trial performed at a casting plant. In order to have a clear picture of what was happening in the ingot and the subsequent macrostructure generated, temperatures measurements were taken in the sump and ingot slices were cut. The two standard plant metal feeding setups used for casting the LQ and AQ alloys were monitored. The standard setup #1 consists of a large metal distributor (900 x 360 mm) which creates a reservoir of hot metal in the center portion of the ingot. The distributor #2 consists of a small distributor (330 x 100 mm) which creates two streams of hot metal which move towards the short sides of the mould. Both metal distributors are made out of glass cloth. The casting conditions and the equipment are described in Table I. It was shown from these trials that the average shell thicknesses obtained were within the specification limits of the client. However, the variability of the shell thickness around the perimeter of the ingot contributed to localized off-specs. The average shell thicknesses along the rolling faces, for the standard distributors #1 and #2, were 5,5 and 6 mm up to a maximum of 9 mm in some regions. Figure 1 illustrates the variation of the shell zone around the ingot as a function of temperature distribution for the standard distributor #1. It is also to be noted that this metal distributor often caused the presence of floating crystals in the corners of the ingot due to insufficiently high temperature. As can be seen from this figure, the corners are 20 °C cooler than the center of the rolling face.

Table I: Casting Conditions and Equipment from Monitoring Trials

Casting Conditions (AA-1050 Alloy)	**Equipment**
Casting speed = 55 mm/min Grain refiner = 0,03 % max. Ti Trough temperature = 725 °C Lubricant = Canola oil Water flow rate = 2,6L/min/cm	Wagstaff 127 mm (5 inch) moulds of 508 x 1330 mm: - Smooth surface, - Water impingement angle = 25 ° Distributor #1 (glass cloth opening: 52 %) Distributor #2 (glass cloth opening: 45 %)

Furthermore, the shell thickness was increased by the use of the distributor #2. This distributor, that fed hot metal towards the short side of the ingot, reduced the occurrence of floating crystals. However, it also reduced the feeding of hot metal to the rolling faces which resulted in an increase of the shell thickness. On the other hand, an increase in casting temperature could not be used to solve the floating crystal problem due to the appearance of feathery grains in the hot portion of the ingot, in addition to the required undesirable high temperature in the furnace. As a consequence, neither of these metal distributors were reliable for producing ingots within customer specifications.

From these observations, it was clear that a compromise had to be made between metal temperature and distribution in order to control shell zone, floating crystals and feathery grains. In order to find the optimum combination and other possible parameters that could help control these problems, casting and numerical trials were performed. As stated above, the parameters relevent to the primary and advanced secondary cooling such as water impingement angle and flow rates, moulds surface (striated vs smooth), the type of lubricant, the metal level in the mould and the metal temperature and distribution were studied. In section 4 the conclusions drawn from these trials are presented.

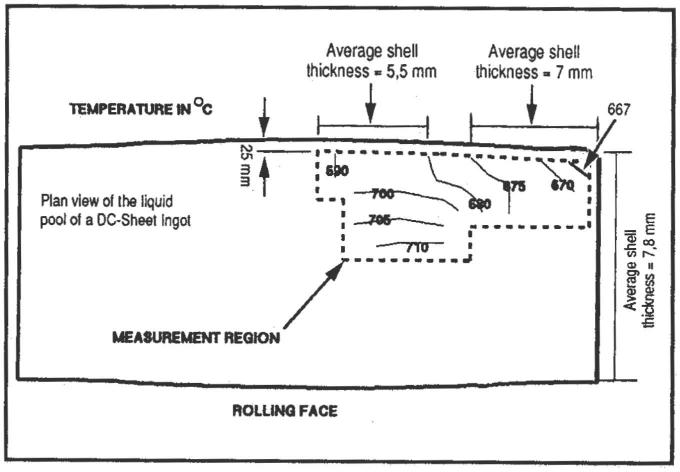

Figure 1: Variation of Shell Thickness as a Function of Temperature

2. DESCRIPTION OF CASTING EXPERIMENTS

The trials that were width-sensitive such as metal temperature and distribution were done using Wagstaff SuperTruSlot 660 x 1650 mm moulds. The other non-width-sensitive trials were done using moulds ranging from 1650 to 1791 mm in width and from 600 to 660 mm in thickness. Over 20 full-size ingots were cast using various conditions during these trials. The ingots were then sampled and analyzed for shell thickness and other macrostructures (floating crystals and feathery grains). These ingots were all cast at 55 mm/min with Wagstaff 127 mm (5 inch) moulds. The ranges studied for each parameter are described in Table II. The range of the parameters studied during the casting trials were restricted by the available equipment and safety requirements. Each parameter was varied sequentially. Nevertheless, in some cases, some difficulties were encountered in the control of the pouring temperature which turned out to be an important parameter for shell formation. However, a monitoring device with data logging capacity using sets of thermocouples was used to record all metal temperature variations. Temperature measurements in a quarter of an ingot were made using constant immersion of the thermocouple tip. This immersion was achieved by floating a refractory support at various locations across the ingot width and thickness. One ingot quadrant was scanned by 30 measurements and each measurement was taken on average for 10 seconds at a frequency of 10 Hz. Mappings of isotherms were subsequently generated by computer (see Figure 1). An automated metal level control system was also used during each cast.

Metallographic analyses were performed on the entire cross section slices of the ingots. Shell thicknesses were measured every 100 mm along the perimeter of the ingot and the results were averaged to facilitate data analysis.

3. DESCRIPTION OF NUMERICAL SIMULATIONS

Numerical simulations using an appropriate mathematical models offer an interesting and efficient alternative to the analysis of a complex process. With the rapid increase in computer performance and the availability of numerous computational fluid dynamic software programs, mathematical modelling is now widely used in the aluminum industry.

The use of a mathematical model allowed the widening of the range of the parameter to be studied. It also allowed separating the effect of each parameter on the process by focussing on one parameter at a time. Mathematical modelling was also helpful in this study in reducing the number of experimental trials at the beginning of the design process.

For these reasons, mathematical modelling has been used in this study to assist and complete the experimental trials. The numerical simulations were performed with PSICASO[1] [2, 3] software, which is a three-dimensional mathematical model of the DC casting operation, developed by Alcan International Limited. PSICASO calculates parameters such as temperature (solid and liquid), molten metal velocity in the sump, solidus and liquidus front for a wide range of operating conditions such as casting speed, ingot size, alloy type, water flow rate and mould metal level.

The present versions of PSICASO do not calculate shell thickness from the metallurgical structure of the ingot. Since the shell formation is related to the cooling rate, a cooling rate of 2 °C/s has been chosen as the upper boundary where the shell stops its formation. This 2 °C/s was determined using the relation between cell size and cooling rates. This relation was obtained experimentally for the AA-1050 alloy. Similar work is found in the literature [4]. A cell size of 50 μm was determined from metallographic observations as being the typical cell size in the "sub-shell" structure which corresponds to the 2 °C/s cooling rate on the experimental curve. This method to calculate the shell thickness using the numerical simulation results in relative values. The results obtained are adequate in this work since this study focusses on the sensitivity of shell thickness to various casting parameters rather than on comparison between numerical and experimental results.

Table II: Parameters Studied

PARAMETERS	FROM CASTING EXPERIMENTS		FROM NUMERICAL SIMULATIONS	
	Parameter Value	**Average Shell Thickness (mm)**	**Parameter Value**	**Average Shell Thickness (mm)**
Metal temperature in meniscus region (°C)	663	8,6	663	7,8
	665	8,5	666	7,2
	----	----	667	6,9
	----	----	670	6,7
	674	6,9	----	----
	675	6,0	----	----
Mould metal level* (mm)	----	----	75	13,1
	63	7,1	63	8,8
	60	6,5	58	6,9
	51	4,5	50	5,0
Mould surface	Smooth	7,1	N/A	N/A
	Striated	7,3		
Lubricant	Castor Oil	6,8	N/A	N/A
	Canola Oil	6,9		
Water flow rate (L/min/cm)	----	----	1,9	8,8
	2,3	6,9	2,2	8,8
	----	----	2,4	8,8
	2,6	7,1	2,6	8,7
			2,8	8,4
Water impingement angle (°)	----	----	15	11,8
	18 (725 °C)	6,3	20	11,2
	23 (710 °C)	7,1	25	8,7
	----	----	35	7,5

* Mould metal level is considered from the bottom of the mould

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[1] Process Simulation In Casting And Solidification.

4. ANALYSIS FROM EXPERIMENTAL AND NUMERICAL TRIALS

4.1 Metal Temperature and Distribution

The temperature in the meniscus region is a function of the superheat in the liquid and must influence shell zone formation. A high temperature in the meniscus zone will lower the solidifying front and consequently the period during which the shell is formed. An increase in pouring temperature and a uniform distribution around the perimeter of the ingot will then give a smaller and more uniform shell at the surface of the ingot. This was confirmed from shell thicknesses obtained from the casting trials and numerical simulation. The relation between shell thickness and temperature in the meniscus region is shown in Figure 2. A uniform and increased metal temperature in the meniscus region narrows the variability (standard deviation) of the shell thickness around the ingot. Temperatures over 670 °C are recommended.

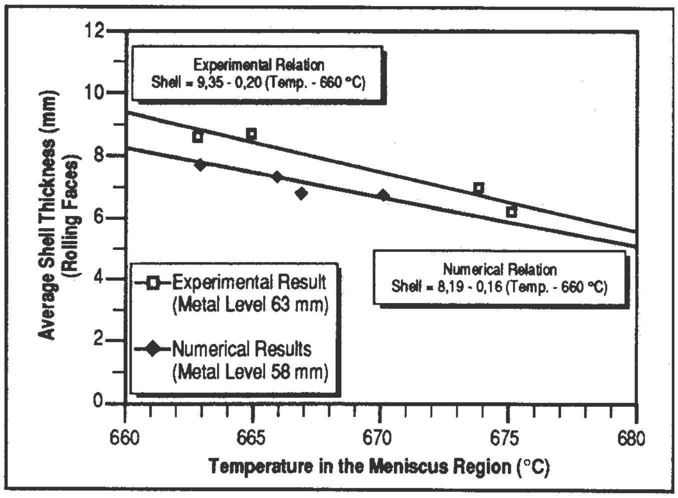
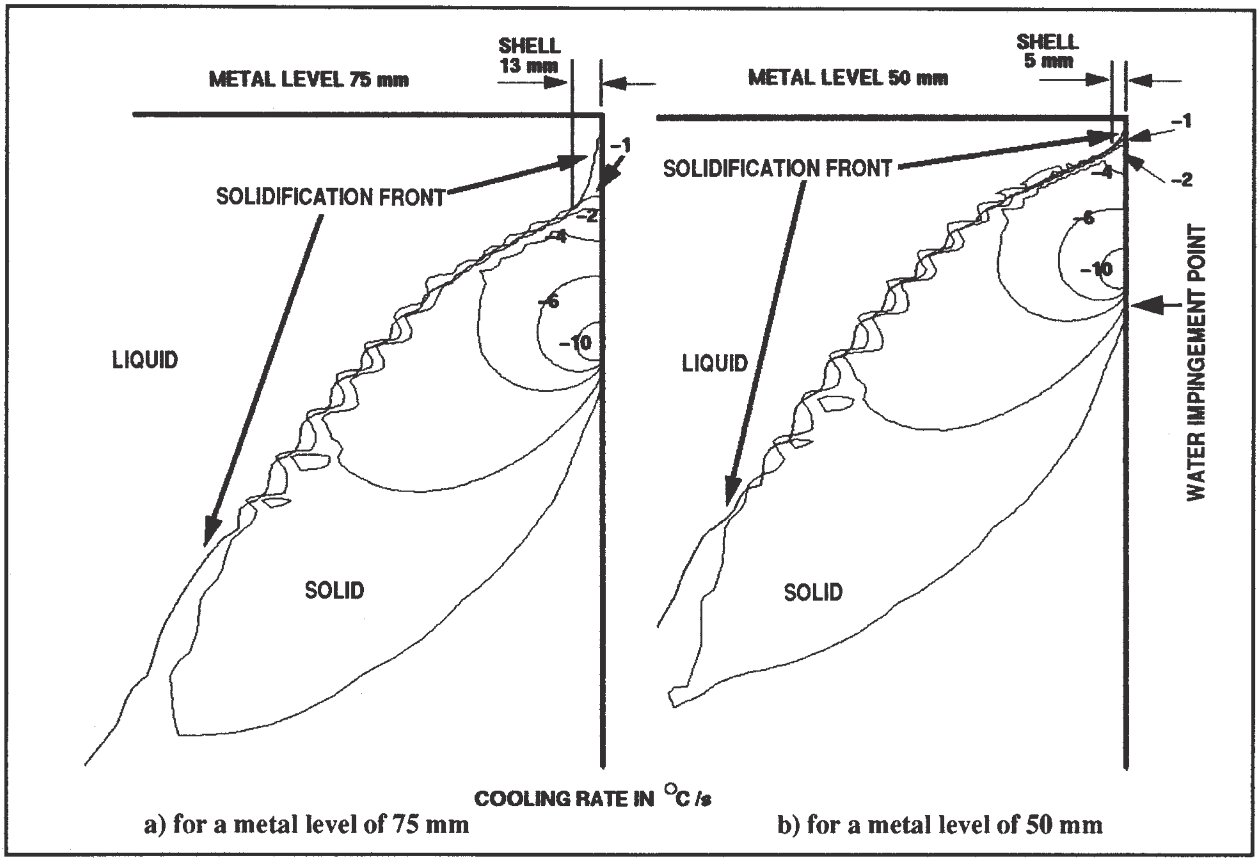


Figure 2: Effect of Temperature on Shell Thickness, Alloy AA1050

4.2 Mould Metal Level

A reduction of mould metal level corresponds to a reduction of the effective mould length which has already been proven to be an important parameter of the shell zone formation [5, 6]. A lower metal level in the mould reduces the length over which the shell develops before it hits the advanced secondary cooling and then stops its formation. The reduction of shell thickness with metal level is shown in Figure 3 for metal levels of 75 mm and 50 mm. This figure shows the lines of constant cooling rate calculated by the mathematical model. It can be seen that for the metal level at 75 mm, the cooling rate of 2 °C/s is located lower in the ingot and will result in a thicker shell. The relations between the shell thickness and the mould metal level for this alloy, obtained from the numerical and experimental tests are shown in Figure 4. A metal level below 58 mm will allow suitable reduction of the average shell thickness.



a) for a metal level of 75 mm **b) for a metal level of 50 mm**

Figure 3: Cooling Rate at the Rolling Face of a 660 mm x 1650 mm, Pure Aluminum Ingot Cast at 55 mm/min

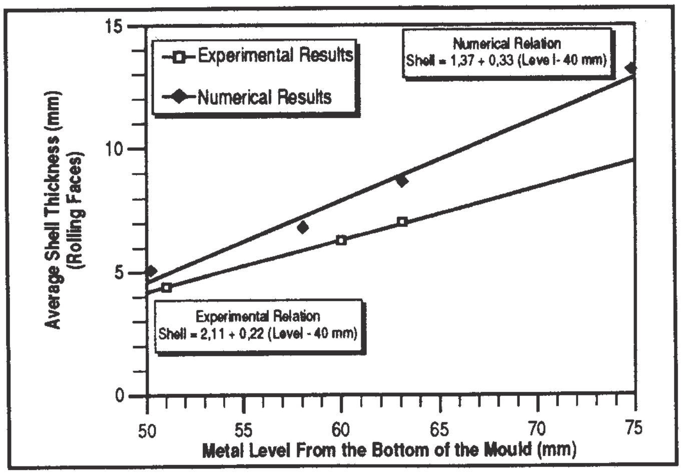


Figure 4: Effect of Metal Level in the Mould on Shell Thickness, Alloy AA1050

4.3 Surface Finish and Lubricant

The use of a striated surface, instead of a smooth surface, to cast these alloys reduced the primary cooling by reducing the surface of contact. However, no reduction of the shell thickness was obtained during these trials (see Table II). Different rates of heat extraction probably exist for these two types of mould. However, the difference is not enough to modify the shell formation process. It was also thought that the type of lubricant used could modify the heat extraction from the primary cooling and then have an impact on the formation of the shell. However, the shell thickness was not significantly affected by the lubricant type (see Table II).

4.4 Water Impingement Angle

An increase in the water impingement angle results in a reduction of the distance below the mould at which the water impacts the ingots. This results in a reduction of the effective mould length. This corresponds to a rise of the advanced cooling effect which enhances the formation of thinner shell zones. However, due to the metal temperature variations, the tests performed to verify the impact of the water impingement angle showed (Table II) no significant difference in the shell thicknesses obtained for the range of angles studied (18 to 24°). However, interesting results were obtained from the numerical simulations.

The impingement angle for the numerical simulations ranged from 15 °to 35 °. According to the numerical results shown in Table II the impingement angle is an important parameter governing shell thickness. The sensitivity of shell thickness to the water impingement angle is equivalent to the effect of the metal level on shell thickness. The similarity can be explained by the fact that lowering the metal level or increasing the impingement angle have the same geometrical effect, which is to decrease the distance between primary and secondary cooling areas, which reduces shell thickness. Angles of 35° and higher would be needed to reduce the average shell thickness suitably.

4.5 Water Flow Rate

The water flow rate was increased from 2,3 to 2,6 L/min/cm in order to increase the intensity of the secondary cooling and consequently reduce the formation of the shell zone. Over the range of water flow rates studied, it was not possible to increase the advanced cooling in the mould sufficiently to generate an effect on shell zone formation (Table II). In the experimental trials, the range of flow rates studied was limited by safety considerations. In the numerical simulations safety considerations were not relevant and the range of water flow rate was 1,9 L/min/cm to 2,8 L/min/cm. Numerical results showed a small decrease in shell thickness at 2,6 L/min/cm and 2,8 L/min/cm. This indicates that extremely high flow rates would be needed to decrease significantly the shell thickness; this is not practical in a production environment even with the development of new casting practices (casting speed, metal pouring temperature, etc.).

WHAT CAN BE DONE TO REDUCE SHELL ZONE ?

The traditional approach to reduce shell thickness is to reduce effective mould length by using other mould technologies like Hot Top, Level Pour and EMC. Without changing mould techno-logy, the results of this work indicate the only way to achieve a significant reduction and control over shell thickness and other macrostructures being produced, is to apply control over the metal level, the metal temperature and metal distribution and achieve an optimal combination of these parameters. Increasing the water curtain angle, using baffles can also be considered. However, this last option would require modifications to the casting practices and equipment which at this point is not desirable.

For these reasons our approach was to concentrate our efforts on implementing metal level control and uniform metal temperature distribution. This combination of metal temperature and level control will allow simultaneous reduction of the variability and the average shell thickness of the ingot produced. Among the sensitive parameters found in the present paper, a uniform metal temperature around the ingot perimeter is probably one of the most challenging to obtain. Standard distributors used in the casthouse lead to non-uniform temperature distribution around the mould. PSICASO has been used to design a modified metal distribution system.

The temperature from numerical simulation, at the top of an ingot during the cast is shown in Figure 5a for the standard distributor #2. The modified feeding system should bring more heat to the rolling faces without reducing too much the temperature on the short side of the ingot. Various geometries have been tried in order to reach an optimum distribution of the metal in the mould. The resulting temperature distribution at the top of an ingot for the most promising design is shown in Figure 5b. This new design distributes the heat in a more homogeneous way than the standard metal distributor and leads to more uniform shell thickness. Also, with this new design, it will be easier to increase the pouring temperature to reduce shell thickness and the occurrence of floating crystals in the corners, without the risk of runouts at the short side or feathery structure in the zone of higher temperature, which can be the case with the standard distributor #2.

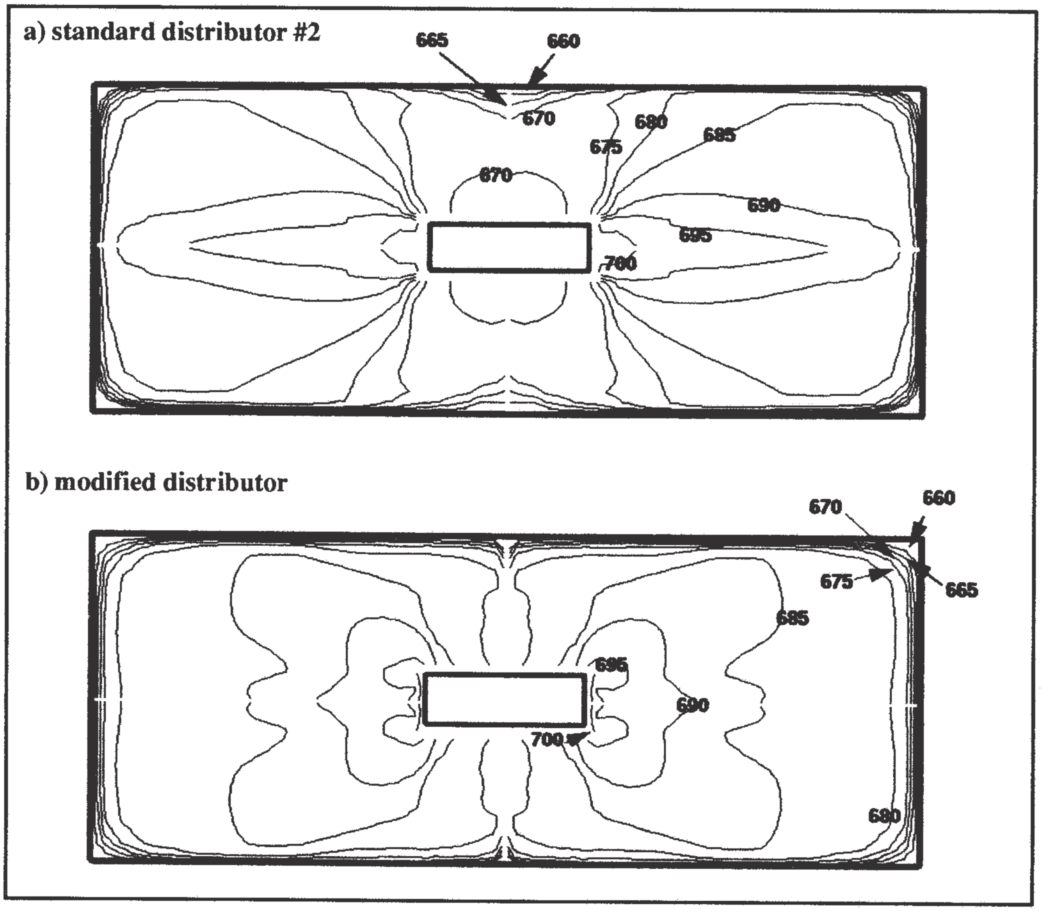


Figure 5: Temperature Distribution from Numerical Simulation, at the Top of a 660 mm x 1650 mm Mould, Pure Aluminum Ingot Cast at 55 mm/min

CONCLUSIONS

In order to produce quality ingots with consistently shallow shell zone, the important parameters to be considered are the mould metal level, the metal temperature and distribution and the water impingement angle. From the experimental and numerical results an efficient casting practice can be developed using the following conditions:

- The mould metal level should be kept below 58 mm.
- The metal temperature in the meniscus region should be higher than 670°C and uniform around the ingot.
- The water impingement angle should be higher than 35 °.

Considering the ranges covered in this work, the water flow rate, the surface finish and the lubricant do not have a significant influence on shell zone formation.

Also, it has been demonstrated with this work that the experimental and numerical approaches lead to similar tendencies for shell thickness formation as a function of the various parameters studied.

These two approaches were used in an efficient and complementary way in this work and allowed a wide range of experimentation for each parameter. The numerical approach also permitted a reduction in the number of experiments needed in the design process. Both approaches highlight the importance of metal temperature and distribution, as well as mould metal level and water impingement angle, as being the parameters that we have more to gain from in reducing the shell zone. It was also shown that these parameters have to be used in combination in order to increase ingot quality and consistency.

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