VALIDATION OF MAGMASOFT SIMULATION OF THE SAND CASTING PROCESS

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ABSTRACT

There is an increasing demand in manufacturing environment for the best quality of casting products at the right time and quantity. Foundries must be able to meet the just in time (JIT) requirement in order to survive in the competitive market and to achieve customer satisfaction. Trial-and-error method to produce casting products from design to manufacturing is too costly and not effective. Various computational packages of CAD/CAE systems can be used to assist in mold design and prediction of casting quality ahead of mass production. This paper intends to validate the integrity and reliability of MAGMAsoft for the simulation of metal flow and solidification during the casting process. Sand casting is ascertained for a block of dimension 160mm x 75mm x 36mm. The validation is made against experimental data obtained from a thesis of previous research. The temperatures of control points in the sand mold and casting are used to compare the results between computational model and experiment in a qualitative manner. A very good match between them is observed. Directional solidification is achieved in the runner, however, there is a hot spot in the middle of the cast. The runner design is good because it ensures a simultaneous inflow of molten metal into the cavity through all gates. Overall, MAGMAsoft produces results that match the experimental data qualitatively and therefore the validation procedure is successful. Further work will be using MAGMAsoft for simulation of more complicated castings for sand and die casting processes.

Keywords : *solidification, aluminium-silicon alloy, thermal analysis, computer simulation, temperature contours, near net shape, hot spot, gating system, latent heat of fusion, specific heat, thermal conductivity, carbon dioxide molding.*

INTRODUCTION

MAGMAsoft is a three dimensional solidification and fluid flow package developed to perform numerical simulation of molten metal flow and solidification phenomena in various casting processes, primarily die casting (gravity, low pressure and high pressure die casting) and sand casting. It is particularly helpful for foundry applications to visualize and predict the casting results so as to provide guidelines for improving product as well as mold design in order to achieve the desired casting qualities.

Prior to applying the MAGMAsoft extensively to create sand casting and die casting models for the simulation of molten metal flow (mold filling) and solidification (crystallization in the process of cooling), it was suggested to carry out a validation plan to verify the validity and integrity of MAGMAsoft simulation results. This work intends to present a preliminary validation of MAGMAsoft capability by comparing its simulation results with previous empirical thermal results of a sand casting mold carried out by a previous researcher [1]. The cast and mold design of the experiment is transformed into a 3D model and imported into MAGMAsoft to conduct the sand casting process simulation.

Certain validation of MAGMAsoft simulation for high pressure die casting (HPDC) had been reported in literature [2]. For example, comparison of smoothed particle hydrodynamics (SPH) and MAGMAsoft simulations with experimental results for the water analogue modeling of HPDC was reported by Paul Cleary, Joseph HA, Vladimir, Alguine and Thang Nguyen [2].

Sand casting is the casting process that has the longest history. Sand casting still accounts for the largest tonnage of production of shaped castings [3]. This is due to the fact that sand casting is economical and possesses the flexibility to produce castings of any material and the weight of castings can range from tens of grams to hundreds of tons. Cast materials capable of sand casting are plain carbon, alloy and manganese steels, white and grey irons, nodular iron, nickel and copper alloys, gunmetals, phosphor and aluminium bronzes, brasses, aluminium alloys and magnesium alloys [4].

Common sand mold consists of top and bottom halves (cope and drag), and the number of cores may vary from none to a dozen depending on the complexity of casting design. Conventional sand casting is not a precision process and requires after-cast machining processes and surface finishing to produce the required dimensions and surface quality. However, advanced high technology sand casting process (improved sand quality and mold rigidity) enables this method to produce higher precision cast products with better as-cast surface finishing that reduces the cost of after-cast touch-up. This will enhance the capability of sand casting to produce *'near-net-shape'* products and improve its competitiveness. For conventional sand casting (low technology sand casting), the maximum variability in dimension for a meter long casting is ±0.13% corresponding to ±1.25 mm. The probable variability of a good sand casting technique (high technology sand casting) for a meter long casting yields ±0.04% corresponding to ±0.40 mm [5], which is comparative to investment casting.

Most sand molds and cores are made of silica sand for its availability and low cost. Other sands are also used for special applications where higher refractoriness, higher thermal conductivity or lower thermal expansion are needed [6]. The average grain size ranges from 220 to 250 microns. The earliest method of bonding sand grains to form a sand mold is by the use

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of clay and water as binder. The molds can be used in the 'green' or undried state (hence the term green sand molding) or they could be baked in a low temperature oven to dry and strengthen them to allow heavy castings to be made [6]. Non siliceous sands are also used, such as zircon sand (zirconium silicate, ZrO_2SiO_2) and chromite sand (essentially of chromium oxide, Cr_2O_3, iron oxide, FeO, and aluminium oxide, Al_2O_3) [4]. The *flowability*, sometimes called moldability, of molding sand is an important factor that determines the quality of mold and cast. Good flowability of sand will form a more uniform sand surface. Water content in the sand mixture will affect its flowability and hence is a key control specification in modern automatic foundry. An in depth study of the flowability of bentonite bonded green molding sand was reported by Y. Chang and H. Hocheng [7].

COMPUTER MODELING OF SAND MOLD

Three dimensional modeling

The cast part of the sand casting model is a rectangular box of the dimension 160mm x 75mm x 36 mm. It has three ingates connected to a stepped runner system and down sprue. The gating ratio is 1:2:1. A feeder is designed to cater for volumetric contraction (shrinkage) effect. The 2D and 3D drawings of the overall mold design is presented in Figure 1, Figure 2 and Figure 3 respectively.

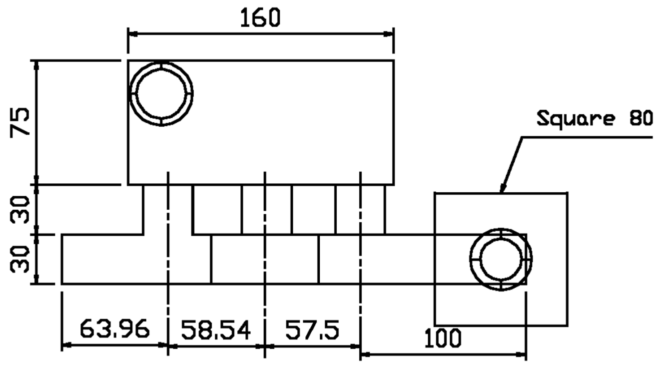

Figure 1: top view

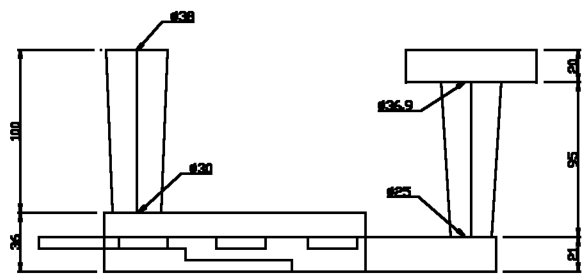

Figure 2: front view

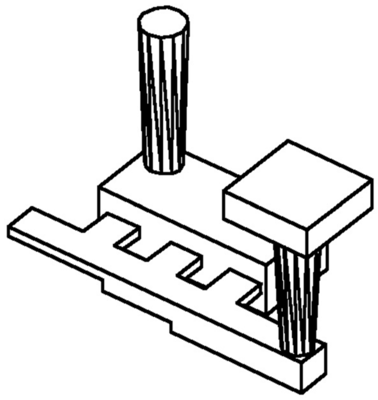

Figure 3: 3D view

The 3D model was created in Autocad mechanical desktop R14 and exported in STL file format so that it can be recognized by MAGMAsoft preprocessor. Creation of a 3D model with Autocad is faster and easier to manipulate compared with MAGMAsoft preprocessor drawing tool. Additional jobs done in MAGMAsoft preprocessor are to define the *control points* for thermocouples to record and keep track of the temperature changes in the cast and mold starting from mold filling to completion of solidification. The previous work [1] only shows the locations of thermocouples in 2D top view without the information of their z-coordinates. The author assigned the x-y coordinates of control points to be the same as previous work [1], and standardized the mold and cast control points z-coordinated at the height of ingates center line. For the pouring basin, the control points are at the top and center of their circular cross sections. The control points are shown in the 3D model of Figure 4. Points 2,3,4,5,7,10 are sand points. Point 1,8,9 are cast points (surrounded by cast material) while point 6 is an interfacial point between the casting and mold.

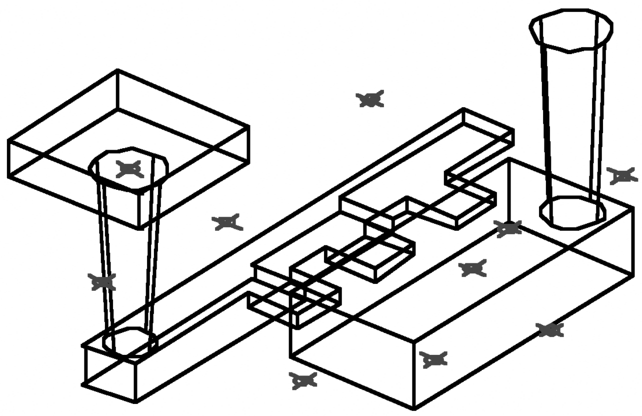

Figure 4: Control points location

The cope and drag of the sand mold were modeled in MAGMAsoft preprocessor and designated as 'topmold' and 'bottmold'. An inlet to the pouring basin must also be created in MAGMAsoft preprocessor and was named 'Inlet1'.Other entities of volume were also assigned with specific names as 'gating1', 'feeder1'. However, the casting does not need a name. The material group for volume entities in MAGMAsoft

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basically are casting, sand mold, core, feeder, gating and inlet, cooling channel, filter and chill for sand casting simulation. In this simulation, the authors did not apply core, cooling channel, filter and chill.

Setting simulation parameters

The simulation will start with geometry enmeshment. Enmeshment is done to divide the geometry into cells or control volumes. Basically the parameters of accuracy, wall thickness, element size, smoothing and ratio are defined. For this simulation, a total of 58941 elements were created for the entire model. Figure 5 shows the mesh generated for the poring basin, gating system, feeder and casting.

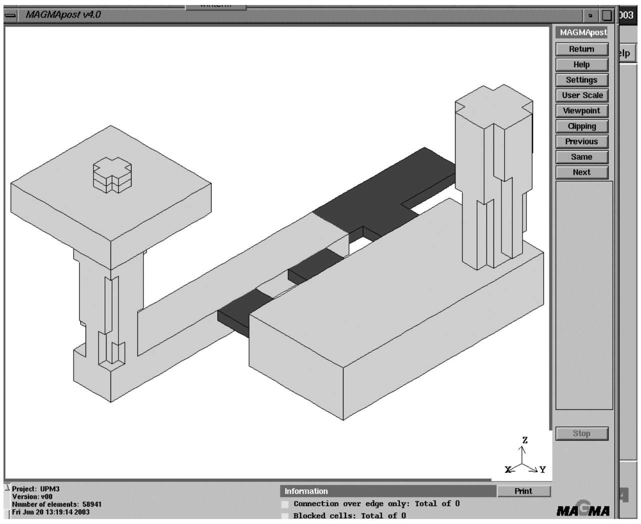
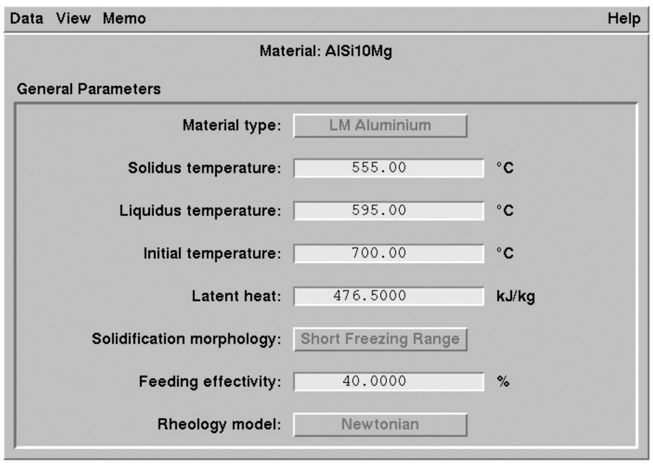


Figure 5: Enmeshment of casting

To start simulation, the authors must assign specific materials for the mold and casting, which can be acquired from MAGMAsoft database. The material database also include the initial boundary conditions for casting and mold. In this simulation, the mold material is assigned as 'green sand' and the cast is AlSi10Mg. Previous experimental work [1] utilized LM6 as the cast material. Unfortunately this material is not available in MAGMAsoft material database, therefore AlSi10Mg was selected to substitute for LM6 because it has the most similar thermal properties as LM6. Hence, the comparison of results between computer simulation and experiment is essentially *qualitative*. The following tables and figures show the critical thermal properties of AlSi10Mg, some of them vary with time and presented in graphs.

Table 1: AlSi10Mg, general properties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Material: AlSi10Mg

General Parameters

Material type:	LM Aluminium	
Solidus temperature:	555.00	°C
Liquidus temperature:	595.00	°C
Initial temperature:	700.00	°C
Latent heat:	476.5000	kJ/kg
Solidification morphology:	Short Freezing Range	
Feeding effectivity:	40.0000	%
Rheology model:	Newtonian	

Table 2: Properties of LM6 aluminum alloy

(Source: http://www.matweb.com/)

PHYSICAL PROPERTIES	VALUES	US / Other Units
Density, g/cc	2.66	2.66 g/cc
MECHANICAL PROPERTIES	*VALUES*	*US / Other Units*
Tensile Strength, Ultimate, MPa	290	42,050 psi
Tensile Strength, Yield, MPa	131	18,995 psi
Elongation %; break	3.5	3.50%
Poissons Ratio	0.33	0.33
Fatigue Strength, Mpa	130	18,850 psi
Machinability	30	30
Shear Strength, Mpa	170	24,650 psi
THERMAL PROPERTIES	*VALUES*	*US / Other Units*
CTE, linear 20°C, µm/m-°C	20.4	11 µin/in-°F
CTE, linear 250°C, µm/m-°C	22.4	12 µin/in-°F
Heat Capacity, J/g-°C	0.963	0.23 BTU/lb-°F
Heat of Fusion, J/g	389	167 BTU/lb
Thermal Conductivity, W/m-K	*155*	*1,076 BTU-in/hr-ft_-°F*
Melting Point, °C	574	1,065 °F
Solidus, °C	574	1,065 °F
Liquidus, °C	582	1,080 °F
ELECTRICAL PROPERTIES	*VALUES*	*US / Other Units*
Electrical Resistivity, Ohm-cm	0.0000044	0.0000044 Ohm-cm

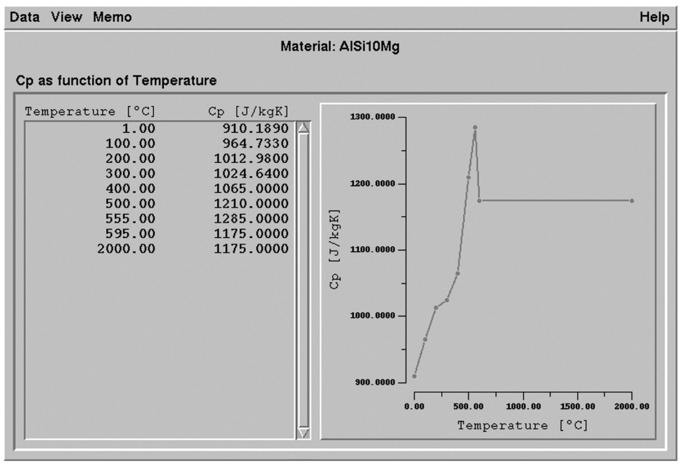

Figure 6: Specific heat (Cp) as a function of temperature for AlSi10Mg

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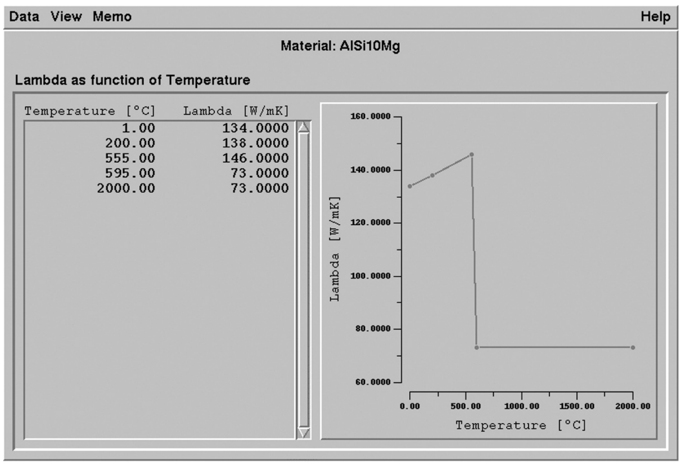


Figure 7: thermal conductivity as a function of temperature for AlSi10Mg

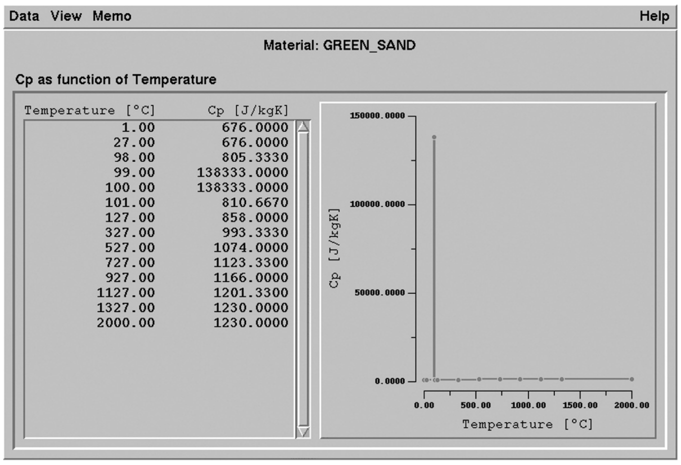


Figure 9: Specific heat (C_p) as a function of temperature for Green sand

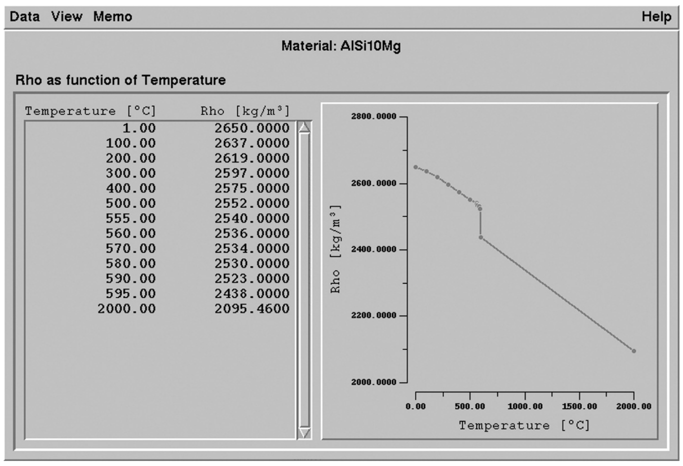


Figure 8: density as a function of temperature for AlSi10Mg

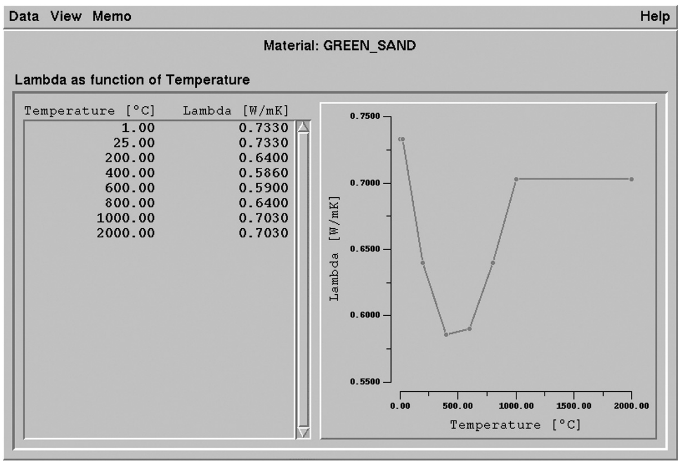
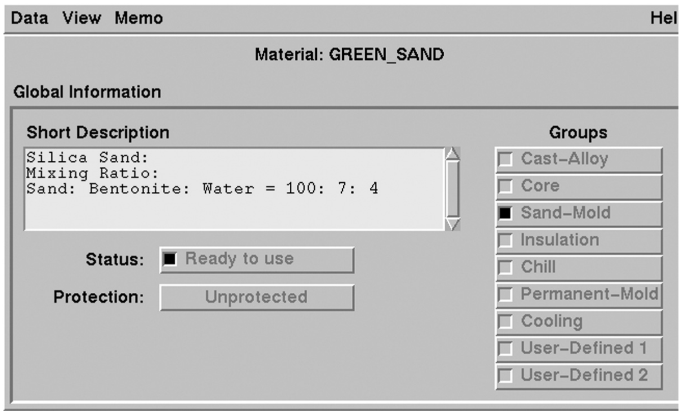


Figure 10: thermal conductivity as a function of temperature for Green sand

Table 3: Green sand constituents



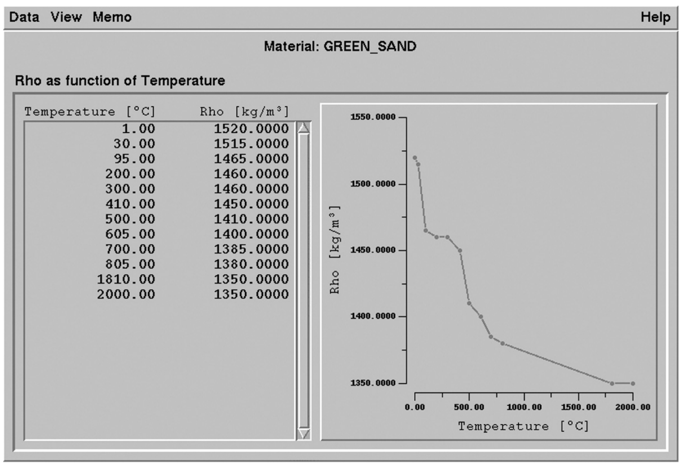


Figure 11: density as a function of temperature for Green sand

A very important parameter for the boundary conditions is the convective heat transfer co-efficient, h_c, between casting and mold. The value is set constant at 1000 $W/m^2.K$

RESULTS AND DISCUSSION

Mold filling

The MAGMAsoft simulation solved for mold filling and solidification processes at the same time. Previous experimental work [1] did not include the mold filling output, therefore the discussion about mold filling is solely based on MAGMAsoft simulation results. The mold filling process can be visualized from Figures 12 to 19. The flow front was being tracked with VOF (volume of fluid) method by MAGMAsoft. It is found that for every succession of one second, 10% of the total volume (encompasses pouring basin, sprue and runner system, gatings, casting and feeder) will be filled up. Due to the design of stepped runner system, Figure13 shows that the molten metal entered the mold through all gates at the same

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time. The melt was rising almost uniformly in the cavity of the mold untill it was completely filled up. This is a good filling because it ensures the temperature distribution in the mold will be equal everywhere just after filling so that solidification rate will be fairly consistent throughout the casting. Equal rate of solidification will entail uniform shrinkage of the casting to minimize defects such as shrinkage cavities as a result of non-uniform cooling rate. The color contour also indicates that during mold filling, cooling has actually started especially at the end of runner. It can be seen that the down sprue and feeder were filled up simultaneously since their dimensions and shapes are very similar. Though the down sprue is the entrance of molten metal, it was not filled up or completely wetted during the mold filling of cavity. To ensure there is no risk of air entrapment that can be carried into the casting and causes porosity, the authors may have to redesign the down sprue dimensions so that complete wetting of its wall occurs during initial mold filling. Generally, the mold filling is successful as a result of proper design of stepped runner system.

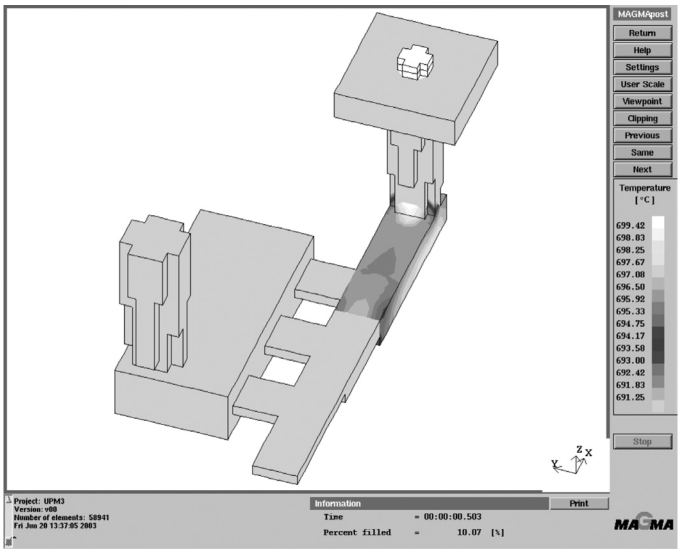

Figure 12: 0.5 second, 10% filled up

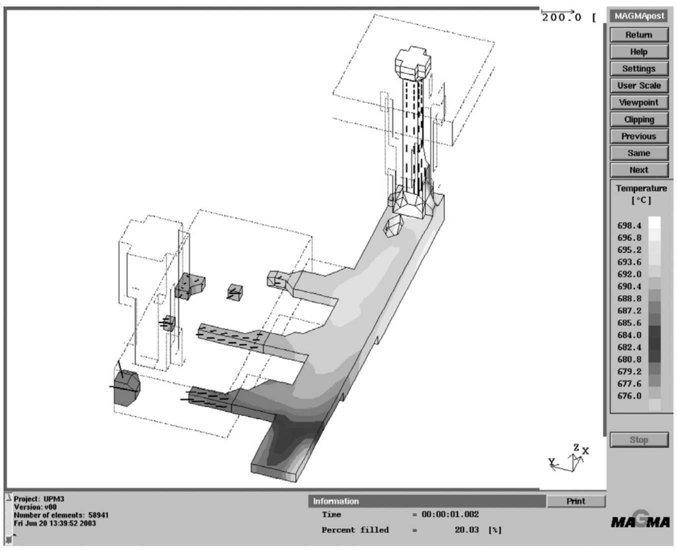

Figure 13: 1.0 second, 20% filled up

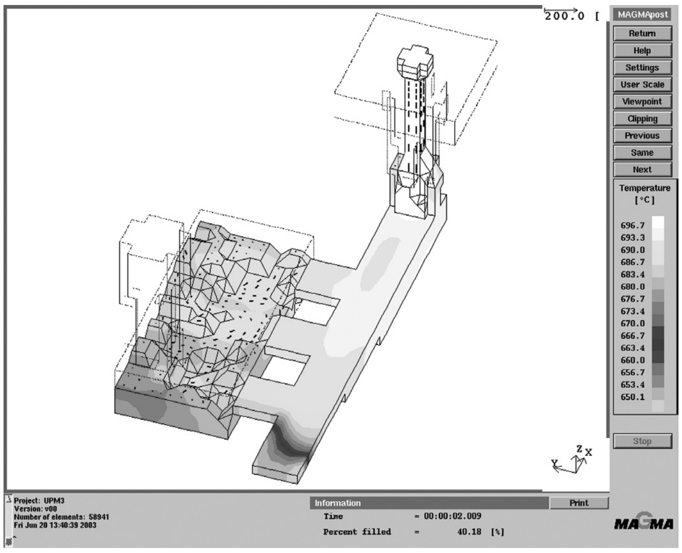

Figure 15: 2.0 second, 40% filled up

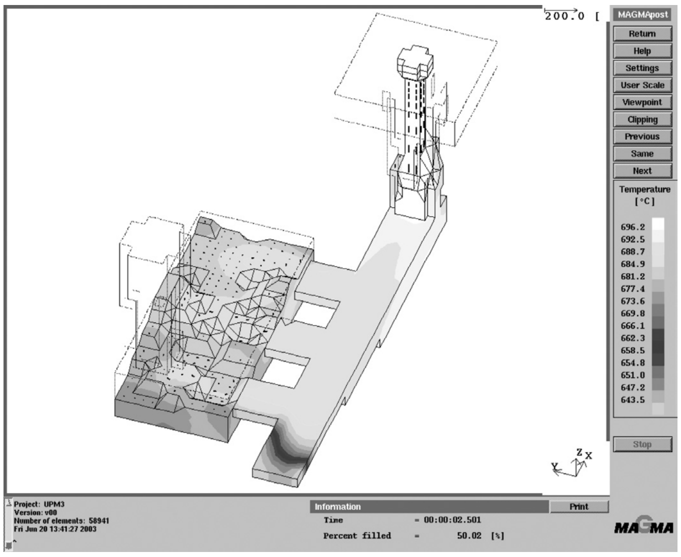

Figure 16: 2.5 second, 50% filled up

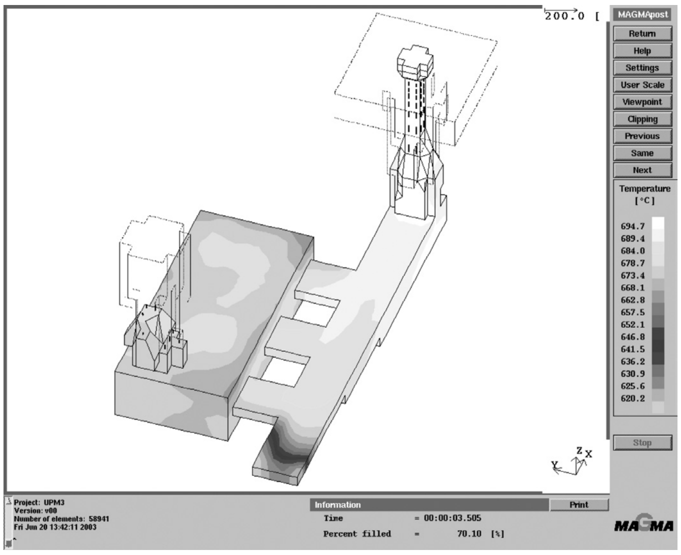

Figure 17: 3.5 second, 70% filled up

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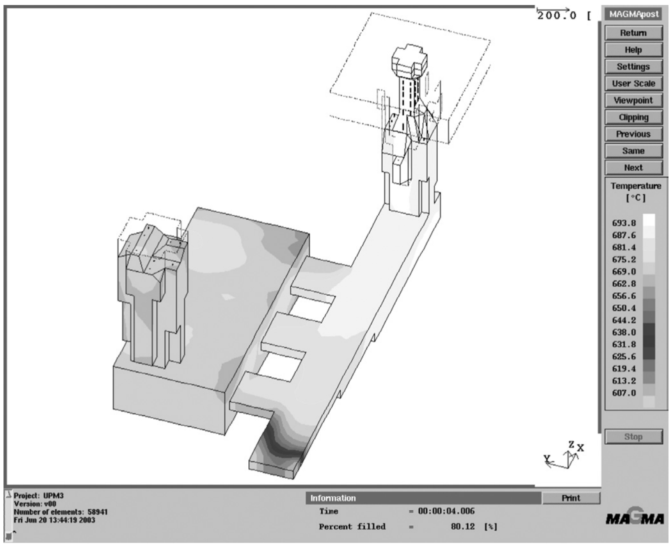

Figure 18: 4.0 second, 80% filled up

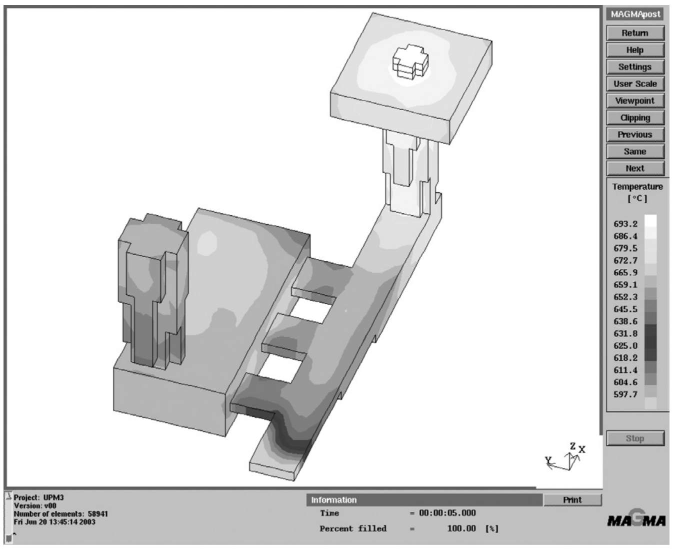

Figure 19: 5.0 second, 100% filled up

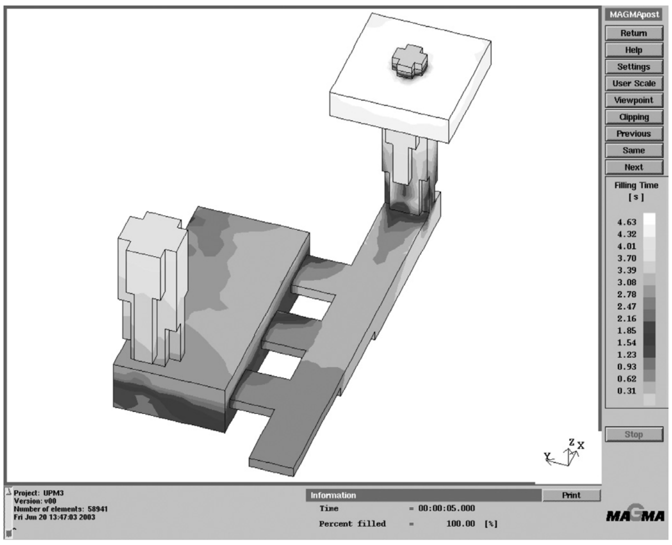

Figure 20: mold filling time.

The variation of filling time for the entire sand mold can be visualized in Figure 20. It can be seen that the stepped runner and gatings were filled up within the first second.

SOLIDIFICATION

Temperature contour of solidification

For the cast material AlSi10Mg, solidification will start when the temperature drops below 595ºC, and fully completed beneath 555ºC. Solidification is a result of *heat transfer* from internal casting to external environment. The heat transfer from the interior of the casting has to go through the routes of [8]:

i) Internal liquid convection above liquidus temperature during mold filling
ii) The solidified metal conduction after complete solidification achieved throughout the bulk of casting
iii) The heat conduction at the metal-mold interface
iv) Heat conduction within the green sand mold
v) Convection and radiation from mold surface to the surrounding

In this section, the authors will be able to compare the simulation results *qualitatively* with experimental data of previous work [1]. First of all, the temperature contours of the

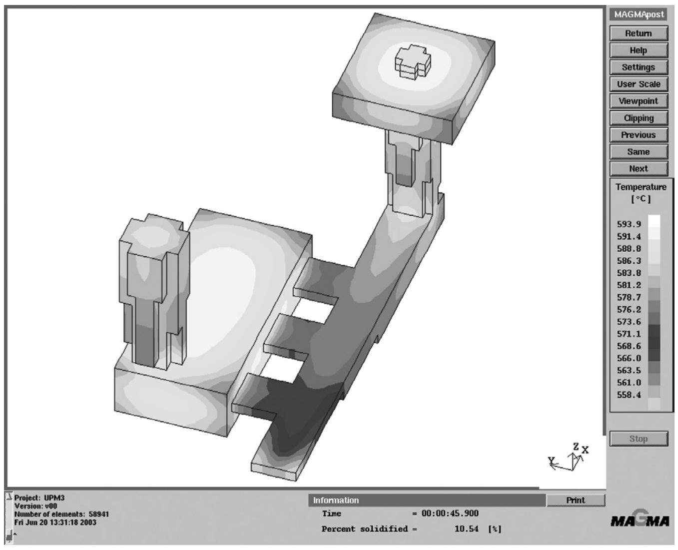

Figure 21: Temperature contour at 10% solidification

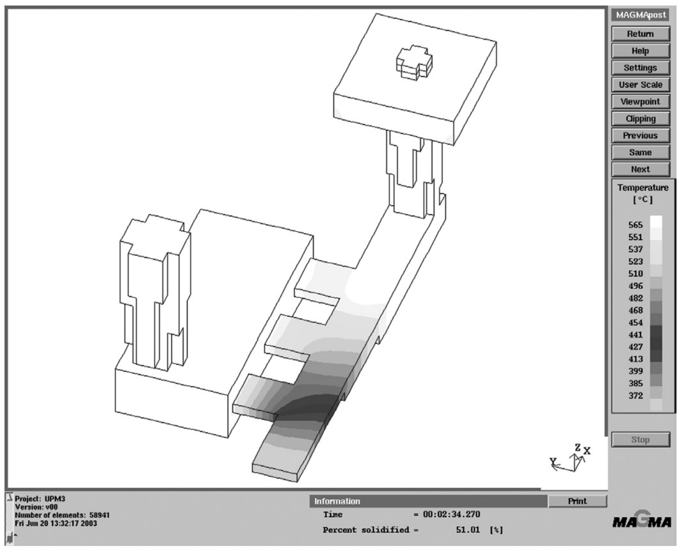

Figure 22: Temperature contour at 51% solidification

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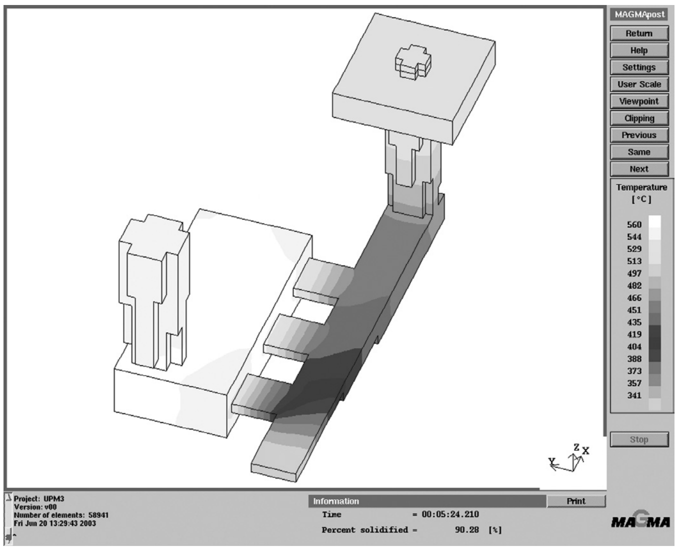

Figure 23: Temperature contour at 90% solidification

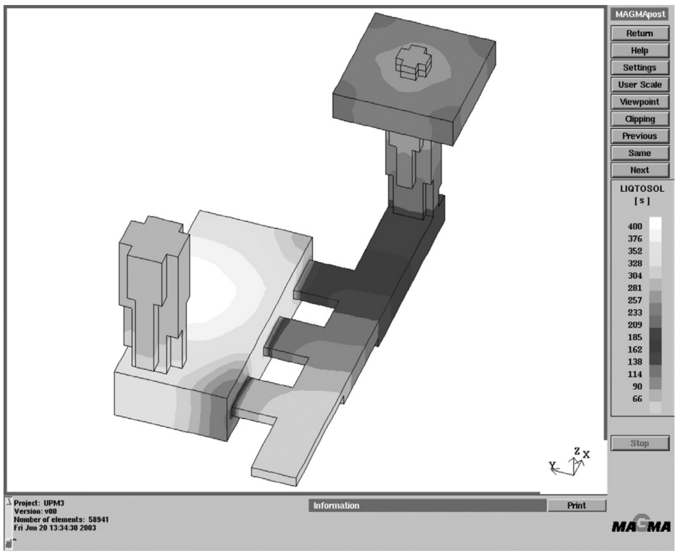

Figure 24: Liquidus to solidus time

casting for different percentage of solidification are given in Figures 21 to 23. Figure 24 shows the time required to reach solidus from the initial temperature of 700ºC.

From Figure 24, it is apparent that directional solidification is achieved in the runner system. The tip of the runner, which has the lowest thickness of 7 mm, solidified faster than other places. After about 60 seconds, the runner tip had completely solidified. Solidification time is proportional to volume to surface area ratio (modulus of casting) [8], therefore the faster solidification rate at the runner tip is expected. The solidification front propagates towards the sprue base from the runner tip. It can be calculated that the mold cavity has a modulus of 10.56 (432000/40920) while the runner tip has a modulus of 2.67 (18900/7080). According to Chvorinov's rule [3,8],

$$t = c\left(\frac{V}{S}\right)^2 \qquad (1)$$

t = solidification time; c is a constan t for a given metal and mould.

The mold cavity which is in the center of the sand mold has comparatively the longest solidification time. This is understandable because according to Fourier's law of conduction, thermal resistance increases with thickness across which heat is to be conducted.

From the casting to the external environment, the heat transfer equation is [9],

$$Q = U\ A\ \Delta T_{overall} \qquad (2)$$

A is the interfacial area between two media. U is called the overall heat-transfer coefficient (or conductance) which has the unit of $W/m^2.K$.

$$U = \frac{1}{\frac{1}{h_1} + \sum \frac{\Delta x}{k} + \frac{1}{h_2}} \qquad (3)$$

For the casting, h_1 is the interfacial heat transfer coefficient between mold and cast, h_2 is the heat transfer coefficient between mold and surrounding. Δx is the thickness of the mold wall and k is the thermal conductivity of mold material. The green sand layer of the cavity is thicker than the runner, therefore a higher Δx will reduce U or increase thermal resistance R, which is the reciprocal of U.

The sand casting model took about 400 seconds to solidify at the center of the cast. A *hot spot* is noticed at the center of the cast, which has the comparatively longest cooling time to solidus. Hot spot may be deprived of liquid metal because its liquid metal can be absorbed into places which solidified earlier and result in defective shrinkage and cavities. Shrinkage at hot spot is also the cause of localized contraction stresses, which will prevail as residual stresses at room temperature. Stresses can lead to three specific phenomena in castings, namely the appearance of cracks, warping of the casting shape and the presence of locked-up stresses which may show up during subsequent use of the casting [3]. For this particular simulation model, it is suggested to shift the feeder to the top of the location of the hot spot so that fresh liquid metal can be supplied to this region to counter-effect volumetric contraction.

Control points temperature tracking

The previous experimental results [1] of control points temperatures are provided in appendix A for qualitative comparison. Figures 25 to 27 are the temperature changes for the casting points. They have the similar shape of temperature changes with respect to time, initial temperature is 700ºC for point 1 at the inlet of hot molten metal introduction, when the molten metal reached points 8 and 9, due to the convection cooling of mold filling, the initial temperature is slightly lower than 700ºC, i.e. 665ºC. The temperatures for these three casting points dropped to between liquidus and solidus temperatures during the solidification process. This is the *mushy zone* where the authors can find the co-existence of solidified metal and liquid metal. The fraction of solid and liquid metal in the mushy zone is a function of time and temperature. When the last drop of liquid metal is crystallized

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into solid, the solidification process is considered complete. Figures 25 to 27 match qualitatively with the previous experimental graphs in appendix A [1].

Other sand points have relatively lower temperatures than the casting points, <100ºC within 500 seconds after pouring. These results also tally qualitatively with experimental work [1]. The thermal conductivity of green sand does not vary significantly with temperature, it is about 0.7 W/m.K for all temperatures. The temperatures of sand points rise steadily from initial room temperature of 20ºC. The simulation stopped after complete solidification was achieved, therefore the authors do not know for how long the sand points temperature will drop back to room temperature. Experimental work shows that even after 100 seconds, the sand points still remain at elevated temperature around 100ºC. The simulation was not carried out until the sands points cool down to room temperature because this is not significant to the evaluation of sand casting process.

Point 6 of Figure 34 is an interfacial point between mold and cast. Its response to temperature is significantly different from the sand and casting points. The temperature rose abruptly from room temperature to 100ºC where it remained for about 90 seconds. After 430 seconds, a peak temperature of about 360ºC was reached. The experimental data [1] also shows an initial leveling of temperature and then rises up to about 500ºC. It is not known how good was the thermocouple positioned at point six in the experiment as it is a sensitive point because volumetric contraction can create a gap between mold and casting and affect temperature recording. Therefore, the graphs of MAGMAsoft simulation and experiment obviously differ from each other. However, compared with other casting points, it is reasonable to conjecture that the experiment had actually measured the casting temperature at point 6 instead of the real interfacial temperature. Interfacial temperature is actually very difficult to measure due to the complicated local heat transfer mechanism. The position of thermocouple tip must be precisely fixed at the interfacial boundary, a variation of 1.0 mm could render it to measure either the sand temperature or the casting temperature.

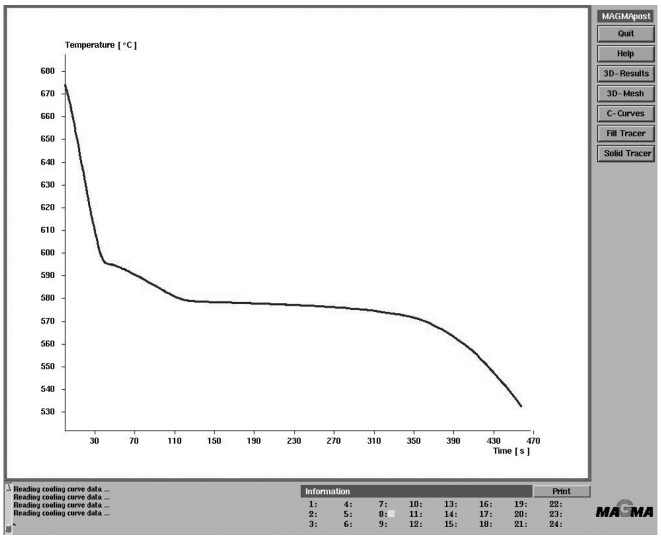

Figure 26: Cast point, P8

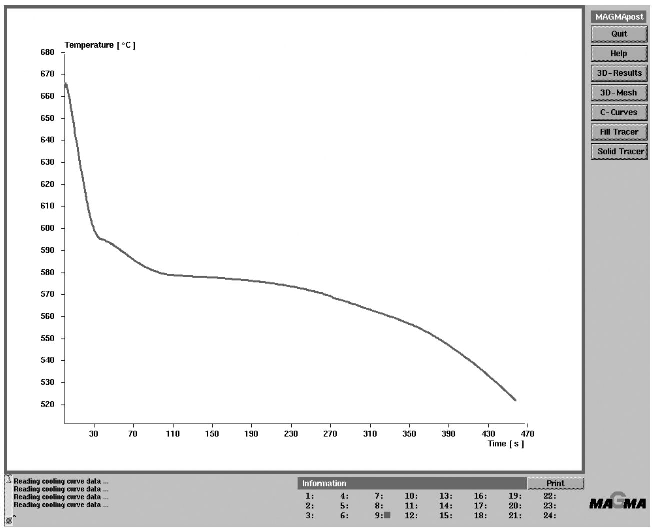

Figure 27: Cast point, P9

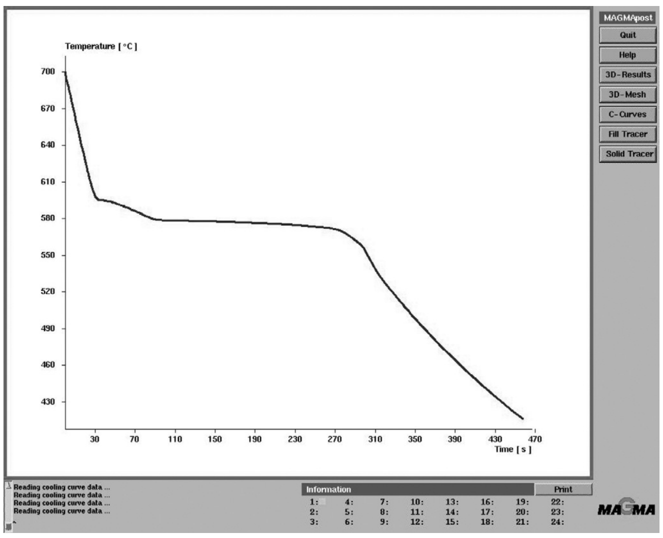

Figure 25: Cast point, P1

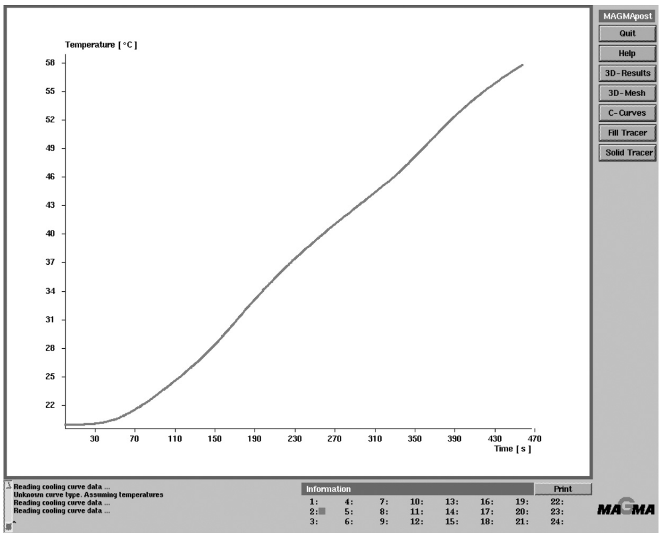

Figure 28: Sand point, P2

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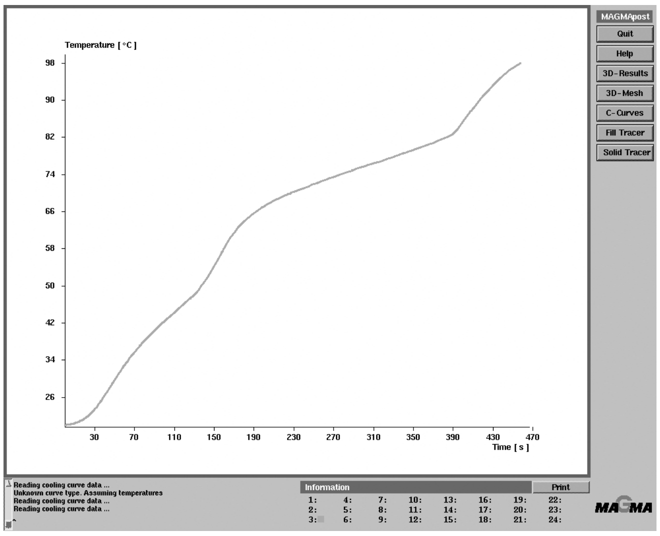

Figure 29: Sand point, P3

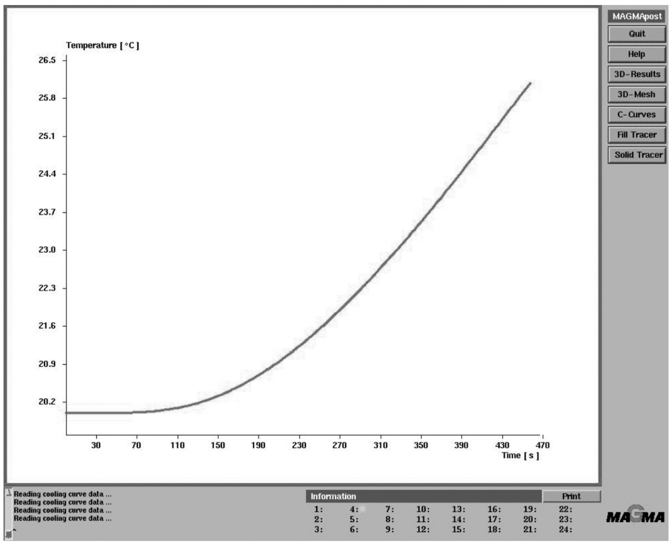

Figure 30: Sand point, P4

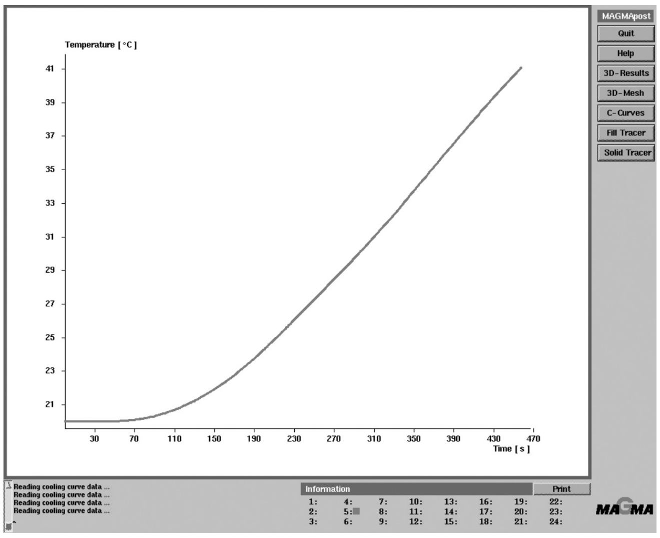

Figure 31: Sand point, P5

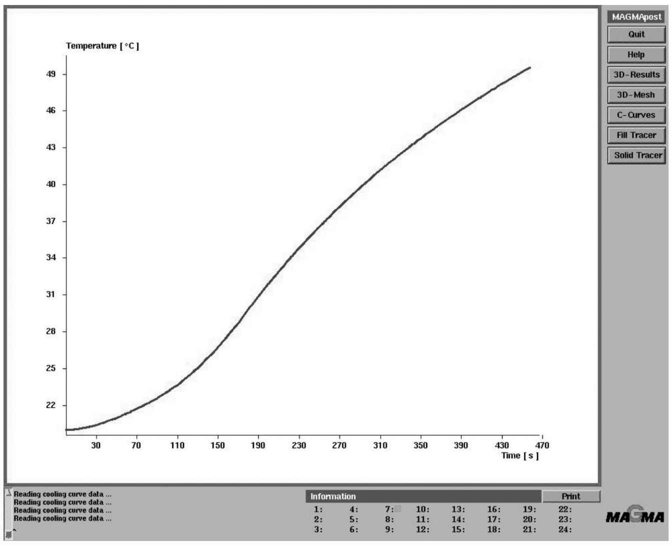

Figure 32: Sand point, P7

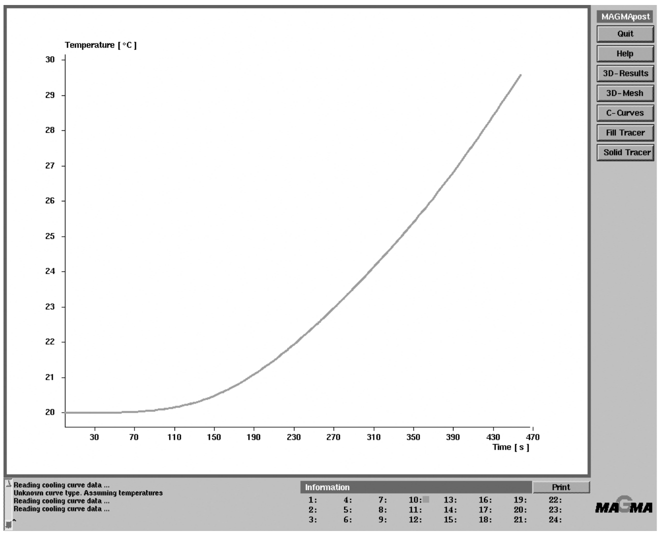

Figure 33: Sand point, P10

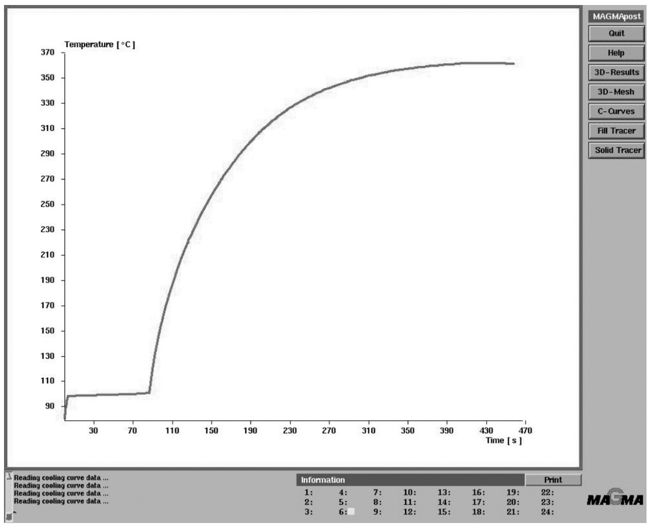

Figure 34: Interfacial point, P6

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CONCLUSION

MAGMAsoft has been validated to be able to produce reliable simulation results that actually reflect the real casting phenomena. The results signify the validity of using MAGMAsoft to perform mold design and casting process simulation. The results of mold filling and solidification would be of high fidelity that can be relied upon to make decisions on designing the mold, feeder, sprue, runner and gating system as well as setting the casting process parameters to achieve the desired casting quality. The success of this validation also serves as a milestone to further utilize and explore the application of MAGMAsoft not only on sand casting, but also on gravity die casting, low pressure die casting and high pressure die casting.

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REFERENCES

[1] C.L. Tan, *Eksperimentasi Analisa Haba Dalam Proses Penuangan Pasir*, Thesis Fakulti Kejuruteraan UPM 2000.

[2] Paul Cleary, Joseph Ha, Vladimir Alguine and Thang Nguyen, *Flow modeling in casting processes*, Applied Mathematical Modelling 26(2002) 171-190.

[3] V. Kondic, *Metallurgical Principles of Founding*, Edward Arnold (Publishers) Ltd. London, 1968.

[4] Edited by John D Beadle, *Castings*, Production Engineering Series, Macmillan Engineering Evaluations,1971.

[5] J. Campbell, *The concept of net shape for castings*, Material and Design 21 (2000) 373-280.

[6] Edited by John R. Brown, *Foseco Foundryman's Handbook*, tenth edition, Butterworth Heinemann, 1994.

[7] Y.Chang and H.Hocheng, *The flowability of bentonite bonded green molding sand*, Journal of Material Processing Technology 113 (2001) 238-244.

[8] J. Campbell, *Castings*, Butterwoth Heinemann, 1991.

[9] K.D. Hagen, *Heat Transfer with Applications*, Prentice Hall International Inc, 1999.

APPENDIX I: PREVIOUS RESEARCH EXPERIMENTAL DATA IN GRAPH