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Temperature measurement during solidification of thin wall ductile cast iron. Part 2: Numerical simulations

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Abstract

Temperature measurements in castings are carried out with thermocouples (TC's), which are inserted in the melt. The TC influence solidification of the casting, especially in thin wall castings where the heat content of the melt is small compared to the cooling power of the TC.

A numerical analysis of factors influencing temperature measurement in thin walled castings was carried out. The calculations are based on and compared with experiments presented in part 1 of this paper.

The analysis shows that the presence of the TC has only a minor influence on the microstructure of the casting. The influence is restricted to a volume within 2mm from the TC. Measured cooling curves will have the right shape. In a 2 mm plate the measured temperature was 17 °C below the true temperature in the melt. However, the cooling curve provides important information about nucleation and growth during solidification.

Keywords

Temperature measurement; Thermocouple; Thin walled casting; Numerical simulation

1. Introduction

Measuring temperature in castings is an important tool for investigation of the solidification process. Temperature measurement is normally done using thermocouples (TC's). Placing a TC in a casting will however change the thermal field and thus influence the solidification process, especially in thin walled castings. The question is how large this influence is and if the measured temperature gives a correct picture of what happens during solidification.

In part 1 the theory of temperature measurement with TC is given combined with results from experiments with temperature measurement in plate thickness of 2.8 to 8 mm [1]. Based on results from the experiments a number of numerical simulations have been performed in order to evaluate how different parameters influence temperature measurement in thin walled castings.

2. Simulation

2.1 Input parameters

Magmasoft® 4.2 including the MAGMAiron module [2] was used for the simulation. In this module it is possible to set parameters related to inoculation and chemical composition of the alloy, so that the nucleation conditions during solidification are equivalent to those found in the experiments. In that way indication of nucleation of phases, under cooling and eutectic solidification will be shown correctly on the cooling curves. The experiment described in part 1 was the background for the simulation. In order to reduce calculation time a number of simplifications were done. Only the plate and not the complete gating system was included in the simulation. For the same reason the width of the plate was reduced to 10 mm and replaced by adiabatic boundaries. In order to simulate the effect of melt flow past the thermo couple during filling a feeder of 20 x 35 mm was placed on top of the plate to get a flow around the TC similar to what is found in the experiment. The filling time was between 1.8 s for the 2mm plate up to 2.3 s for the 8mm plate. The geometry is shown in Fig. 1. The distance, d, is the depth the ceramic tube penetrates into the casting. Normally the naked TC wire will be placed in the centre of the casting plate. As the length of this part of the wire will be about 1 mm the distance, d, can be calculated by: $d = t/2 – 0.5$, where t is the plate thickness.

In the software round shapes are approximated with a mesh of cubic cells. This means that the small, round cross section of the TC wire in the model becomes square. Therefore the TC wire dimension in the model was 0.2 x 0.2 mm corresponding to a diameter of about 0.2mm. The ceramic tube was 1.4 x 1.4 mm in the model corresponding to a diameter of about 1.6 mm. From the enmeshment of the geometry the TC wire had a thickness of 1 cell.

A number of cooling curves were recorded from the simulations, these are shown in Table 1. CC1 is placed in the middle of the TC wire just outside the ceramic tube and CC2 is placed in the melt in the middle of the cell nearest to CC1. The other cooling curves are placed in the middle of the plate at different distance from the TC. CC3-5 are localed at the same height and placed horizontal from the TC. CC6 is placed 10 mm below the TC, near the inlet. As previously discussed in part 1 the measured temperature T_m will be the temperature on the surface on the TC. T_m will therefore be defined as an average of CC1 and CC2.

An important factor is the heat transfer coefficient (HTC) between melt and TC. From the heating time of TC used in the experiments the HTC was found to be around 25000 $Wm^{-2}K^{-1}$ [1]. This HTC value could be explained by the presence of an oxide layer, which will stick to the TC when the melt hits the TC during filling of the mould. This oxide layer will however be dissolved or ripped away from the TC during the continuous filling of the mould. As the oxide layer disappears again it can be assumed that there will be very good thermal contact between melt and TC wire. The HTC between the TC wire and melt will therefore be given a very high number (10^{10} $W\ m^{-2}K^{-1}$). The HTC along the rest of the TC wire and the HTC at interfaces of the other materials involved are of less importance. Values are listed in Table 2.

The thermal properties of the material in the simulation are given in Table 3. The casting material is ductile iron as in the experiments. The material properties for mould and casting are taken from the database in Magmasoft. As these properties depend on the temperature the values in the tables are an average for the actual temperature interval. The thermal properties of TC wire and ceramic tube are constant.

2.2 Results

In the following the results from the simulations are presented. In general it was found that the presence of a TC had minor influence on the graphite nodule count in the casting. Only the volume within a distance of maximum 2 mm from the TC was affected, see Fig. 2. The difference is however small, the increase is about 100 nodules mm^{-2} compared to a level of about 800 nodules mm^{-2}. It can therefore be assumed that presence of TC will not have an influence on the CC5 placed 4 mm from the TC. CC5 will therefore be the reference curve when comparing measured temperature with solidification temperature. The temperature difference between temperature in the casting and the measured temperature, ΔT_{c-m}, will be defined as the average temperature difference between CC5 and T_m during solidification at CC5.

The simulated temperature curve for simulation 1 (2mm plate) are shown in Fig. 3 and the corresponding differentiated curves dT/dt are shown in Fig. 4. The shape of both temperature and dT/dt curves are very similar to each other except for the last part of the solidification at around 11 seconds, see Fig. 4. This small difference can be explained by a difference in local solidification time due to a little faster cooling around the TC. This similarity was found in the results from all the simulations.

Details from the simulations are given in Table 4.

2.2.1 Influence of plate thickness

Simulations with different plate thickness have been performed, where the TC was placed in the centre of the plate (simulation 1-4). Different inlet temperature was used for the different plate thicknesses as in general the temperature loss during filling will be higher in the thinner plates compared to the thicker plates.

The difference between the measured temperature and the CC3-6 are shown in Fig. 5 and Fig. 6 for the 2 mm and 8 mm plate respectively. The temperature difference is large, more than 20 °C in the first few seconds. As soon as solidification begins the difference decreases and reach a more stable value. The differences are more stable for the 8 mm plate compared to the 2 mm plate. This can be explained by the difference in solidification time, where there will be longer time for the temperature to equalize in the 8 mm plate. This also explains why $\Delta T_{c\text{-}m}$ for the 8 mm plate is 2.7°C and for the 2 mm plate it is 16.9°C. The temperature difference seems to be inversely proportional with the thickness of the plate.

2.2.2 Influence of inlet temperature

Each plate thickness was simulated with different inlet temperature, similar to the conditions in the experiments [1]. A simulation was performed of a 2 mm plate with the same inlet temperature as in the 8 mm plate: 1320°C. Here $\Delta T_{c\text{-}m}$ was 16.1°C compared to 16.9°C when inlet temperature was 1240°C (simulation 5 and 1). This difference can be explained by a higher inlet temperature, which gives a little longer solidification time. The effect is however small compared to $\Delta T_{c\text{-}m}$ of 2.7°C with the 8mm plate. But it indicates that $\Delta T_{c\text{-}m}$ is relatively insensitive to the pouring temperature.

2.2.3 Influence of melt flow passing the TC

The preheating during filling was thought to have an influence on the temperature measurement so as to reduce $\Delta T_{c\text{-}m}$. To test this a simulation was performed on a 2 mm plate without a feeder (simulation 6). This reduced the filling time from 1.8 s to 0.2 s. This gave a $\Delta T_{c\text{-}m}$ of 20.7°C instead of 16.9°C. So preheating of the TC during filling has an influence on temperature measurement. More important is however that an oxide layer can be formed on the TC when the first melt hits the TC during filling. If the oxide layer is not dissolved again during the continuous filling there will be reduced thermal contact between TC and melt and the $\Delta T_{c\text{-}m}$ will been even larger.

2.2.4 Influence of thermal properties of TC wire and ceramic tube

In order to see the influence of thermal properties four different simulations were performed on the 2mm plate. Tests were made where the thermal properties of the thermocouple were changed, so that either thermal conductivity (λ) was reduced by 50 % or the heat capacity (ρc_p) was decreased by 50 %. Similar chances were done to the thermal properties of the ceramic tube, see simulation 7-10. Reducing the λ for the TC wire reduced ΔT_{c-m} to 14 °C while reducing ρc_p for the TC wire only had a negligible effect. For the ceramic tube reducing λ or ρc_p had almost the same effect, giving a ΔT_{c-m} of 15.1 and 15.8 °C respectively.

2.2.5 Influence of oxide layer on TC wire

In the case where there is an oxide layer envelope the TC wire close to the ceramic tube the measuring point will be at the end of the oxide layer where the melt is in electrical contact with the TC wire. A simulation was performed on a 2 mm plate where the HTC between the TC wire and the melt was changed (simulation 11). At the first 0.4 mm of the wire outside the ceramic tube the HTC was 25000 $Wm^{-2}K^{-1}$ as the oxide layer was still present. On the remaining TC wire the HTC was still high, 10^{10} $Wm^{-2}K^{-1}$. The position of CC1 and CC2 was changed with 0.4mm too. The presence of a oxide layer gave a ΔT_{c-m} of 9.0°C instead of 16.9°C

2.2.6 Influence of diameter of TC wire

Two simulations were performed where the TC wire was 0.4 x 0.4 mm, corresponding to a diameter of about 0.5 mm (simulation 12 and 13). Here the ΔT_{c-m} for the 2mm plate was 30°C compared to 16.9°C for the smaller TC wire and for the 8mm plate it was 7.1 compared to 2.7 for the smaller TC wire.

2.2.7 Influence of placement of TC

Two simulations were performed where the distance, d, (see Fig. 1) was reduced to see if it had an influence on the cooling curve if the TC was placed closer to the surface. One simulation with 4 mm plate where d = 0.5mm compared to d = 1.5 and one simulation with 8 mm plate where d = 1.5 mm compared to 3.5 mm (simulation 14 and 15). For the 4 mm plate the ΔT_{c-m} was now 15.4 °C compared to 8.7 °C and for the 8 mm plate the ΔT_{c-m} was 7.7 °C compared to 2.7 °C. All these temperature differences are between the measured temperature and the temperature in the middle of the plates. There will however also be a temperature gradient within the plates. Taking this into account ΔT_{c-m} would be 12.1°C for the 4 mm plate and 4.2°C for the 8 mm plate, in both cases larger compared to when the TC was placed in the middle.

2.2.8 Influence of geometry of casting

Cylindrical geometries are commonly used instead of plates to investigate solidification of cast alloys. Two simulations were therefore performed where the plate casting was replaced by a cylinder with diameter of 5 or 9 mm (simulation 16 and 17). The solidification time of these cylinders corresponds to a 2 and 4 mm plate respectively. The adiabatic boundary was removed and the cylinders were completely surrounded by the mould. The feeder was the same as for the plates. The cylinder with diameter of 5 mm had a ΔT_{c-m} of 12.3°C compared to 16.9°C for the 2 mm plate. The cylinder with diameter of 9 mm had a ΔT_{c-m} of 5.0°C compared to 8.7°C for the 4 mm plate.

2.3 Discussion of simulation results

In sand moulds the cooling of a casting is governed by how fast the heat can be extracted from the casting, or in other words the thermal properties of the mould. Increasing of either the heat conductivity (λ) or the heat capacity (ρc_p) of the mould will increase the cooling rate of the casting. As both the TC wire and the ceramic tube have a larger λ and ρc_p than the mould (see Table 3) there will be a larger cooling rate around the TC compared to other places in the casting. Especially the TC wire has a higher λ in comparison to both the mould and ceramic tube. Looking at the temperature profile in the TC wire it can be noted that the TC wire is relatively quickly heated up to a temperature above 600 °C in the few millimetres close to the casting, while the ceramic tube and mould heats up more slowly, see Fig. 7. Because of the high λ there will be a higher heat flow through the TC wire compared the surroundings but the wire will also be cooled by the surroundings. As the wire is relatively small there will be almost a steady state flow of heat from the casting through the TC wire to the surroundings of the wire the first 5 mm from the surface of the casting into the mould. This explains why reducing λ of the TC wire will have a large effect because the heat flow is governed by λ. On the other hand as the volume of the TC wire is very small the effect of changing ρc_p will be small. The effect of increasing the diameter of the TC wire can be explained by an increase in the heat flow through the wire because of the increase of the cross section.

Another important factor seems to be the distance, d, that the ceramic tube penetrates into the casting. Reducing d will increase the temperature difference $\Delta T_{c\text{-}m}$ more than what can be explained by the temperature gradient in the plate. Another way to study the effect of the distance, d, is to change the casting geometry from a plate to a cylinder with the same solidification time. When measuring the temperature in the centre of both plate and cylinder there will not be an effect from temperature gradient in the melt on $\Delta T_{c\text{-}m}$. In this way the distance d can be increased and by that the effect on $\Delta T_{c\text{-}m}$ is reduced. The effect of increasing the distance d can also be explained by the temperature profile of TC wire and ceramic tube. The temperature profile of the ceramic tube will be close to the surroundings. When a longer part of ceramic tube is in contact with the melt it will give a longer path for the heat to flow through the TC wire or in other words: Less cooling of the melt through the TC wire.

The simulations have shown that the measured temperature will give correct and useful information of what happens during the solidification process. The shape of the measured temperature curve will be the same as from a casting that not is affected by the presence of a TC. There will be some displacement between the measured and unaffected temperature curve during the solidification, but the variation of the displacement during solidification is small and could also be called a parallel shift. The size of the parallel shift can change; depending on different factors such as plate thickness, presence of oxide layer on TC wire or thermal properties of TC wire and ceramic tube.

3. Discussion

It was concluded from the experiment that placing a TC in the casting did not change the microstructure of the casting significantly [1]. The simulation showed a small change within the first 2 mm from the TC by an increase in nodule count. The increase in nodule count was however so small that it will be difficult to detect it in reality.

The simulations showed that in the 2mm plate the temperature difference $\Delta T_{c\text{-}m}$ was about 17 °C. This could explain how the thin plates in the experiment could solidify without carbides even though the measured temperature during the solidification was below the eutectic metastable temperature.

In the experiment there was some parallel shift between the measured temperature in plate A and B. Some of this can be explained by the accuracy of the measured temperature but not all of it. From the results of the simulations a number of other explanations can be found. It could be small variations in the distance d that the ceramic tube penetrates into the casting, which from the manufacturing process can vary ± 0.3 mm. It could be variation in amount of residual oxide layer envelope the TC wire. But regardless of the reasons for the parallel shift the displacement of the temperature curve from plate A and B was constant showing the same history of the nucleation and growth morphology during the solidification process. And this is also what the simulations have shown. The parallel shift can for different reasons have different size, but the measured temperature curve will still give some useful information about the solidification process.

Temperature curves recorded from thin walled castings can therefore give information about nucleation and growth during solidification process. The actual temperature level will however be lower than the actual temperature in unaffected castings and it is therefore important to be careful when comparing measured temperatures, especially when comparing between different plate thicknesses. For the 2 and 4 mm plate however the simulations shows that the temperature difference $\Delta T_{c\text{-}m}$ is nearly the same for if the distance d = 0.5mm, showing that it is possible to compare these two different plate thicknesses.

Looking at the $\Delta T_{c\text{-}m}$ it will be better to use cylinders instead of plates as the casting geometry. However when examining the microstructure of a casting a cross section is normally cut out of the casting and polished. The area to examine should have a certain size. It can therefore be difficult only to be content with the area just around the TC. Having a plate it can therefore be advantageous to cut a couple of millimetres from the TC and by that get a large area along the centreline of the plate where it can be assumed that the microstructure is the same. For a similar investigation in a cylinder, it is necessary to carefully cut and polish of the casting sample in order to be sure that the examined area is in the middle of the casting. Therefore it can be more easy to use plates rather than cylinders as casting geometry.

4. Conclusion

- The simulations have shown that placing a thermocouple (TC) in thin wall casting will only have a small influence on the microstructure very close to the TC. 2mm from the TC the microstructure seems to be unaffected. This also corresponds with what found in experiment.
- The measured temperature curve will have the correct shape compared to temperature in unaffected melt during the solidification process.
- The measured temperature will however be lower than in the unaffected casting. There will be a parallel shift between the measured temperature and the temperature in unaffected casting.
- Temperature measurement with TC in thin wall castings will therefore give reliable information about nucleation and growth during solidification taking into account that the measured temperature will be lower than in unaffected casting.
- The size of parallel shift will depend on different parameters. For a 2 mm thick plate using Ø0.2 mm TC wire the measured temperature will be about 17°C too low compared to unaffected melt.
- The size of the parallel shift seems to be inversely proportional with the thickness of the casting plate.
- Decreasing the thermal conductivity or the diameter of the TC wire will decrease the size of the parallel shift. The heat capacity of TC had only a very little influence on temperature measurement.
- Decreasing the thermal conductivity or heat capacity of the ceramic tube will decrease the parallel shift.
- Increasing the distance the ceramic tube penetrates into the casting will decrease the parallel shift.

References

[1] K. M. Pedersen and N. Tiedje: Temperature measurement during solidification of thin wall ductile cast iron. Part 1: Theory and experiment. Measurement, in press, doi:10.1016/j.measurement.2007.05.002.

[2] Magmasoft 4.2, Service Release 2, Manual. MAGMA Giessereitechnologie GmbH, Germany. 2004.

Figures and tables

Table 1 Placement of cooling curves during simulation

Point	Placement
CC1	In thermocouple
CC2	Melt, nearest to CC1
CC3	Melt, 1 mm from thermocouple
CC4	Melt, 2 mm from thermocouple
CC5	Melt, 4 mm from thermocouple
CC6	Melt, 10 mm below thermocouple

Table 2 HTC used in the simulations

Interface	HTC ($Wm^{-2}K^{-1}$)
Melt – mould	1000
Melt – ceramic tube	1000
Melt – TC wire	10^{10}
Ceramic tube – mould	500
Ceramic tube – TC wire	200

Table 3 Thermal properties of materials

	Thermocouple wire	Ceramic tube	Mould: Silica_dry (an average)	Casting: GJS-600 (an average)
λ ($Wm^{-1}K^{-1}$)	25	2	~0.65	~22
ρ ($kg\ m^{-3}$)	8600	2600	~1520	~6900
C_p ($J\ kg^{-1}K^{-1}$)	500	850	~1000	~800
ρC_p ($Jm^{-3}K^{-1}$)	4.3×10^6	2.21×10^6	~1.52×10^6	~5.52×10^6
Low λ ($Wm^{-1}K^{-1}$)	2.5	0.2		
Low ρC_p ($Jm^{-3}K^{-1}$)	2.15×10^6	1.105×10^6		

Table 4 Performed simulations including the temperature difference between the temperature in the casting and the measured temperature

Simulation	Plate thickness (mm)	Modification	Inlet temperature (°C)	Distance d (mm)	Temperature difference ΔT_{c-m} (°C)
1	2		1240	0.5	16.9
2	4		1260	1.5	8.7
3	6		1300	2.5	4.7
4	8		1320	3.5	2.7
5	2	Increased inlet temperature	1320	0.5	16.1
6	2	Without feeder	1240	0.5	20.7
7	2	TC wire: Low λ	1240	0.5	14.0
8	2	TC wire: Low ρC_p	1240	0.5	16.9
9	2	Ceramic: Low λ	1240	0.5	15.1
10	2	Ceramic: Low ρC_p	1240	0.5	15.8
11	2	Special HTC	1240	0.0	9.0
12	2	TC wire Ø0.5mm	1240	0.5	30.4
13	8	TC wire Ø0.5mm	1320	3.5	7.1
14	4	Reduces d	1260	0.5	15.4
15	8	Reduces d	1320	1.5	7.7
16	Ø5	Cylinder instead of plate	1240	2.0	12.3
17	Ø9	Cylinder instead of plate	1260	4.0	5.0

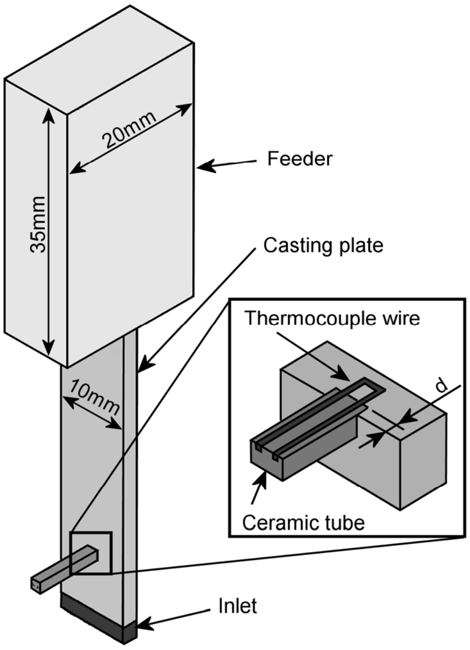

Fig. 1 Layout for simulation

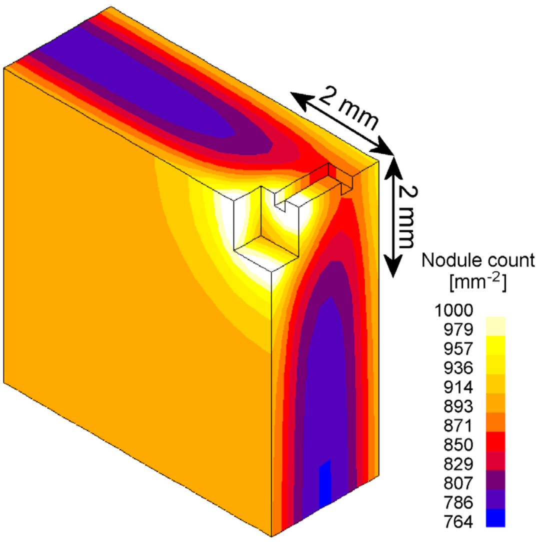

Fig. 2 Nodule counts near the thermocouple in 2 mm plate

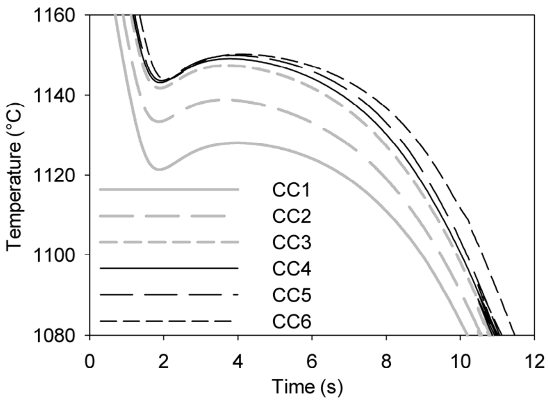

Fig. 3 Temperatures from simulation 1, 2mm plate

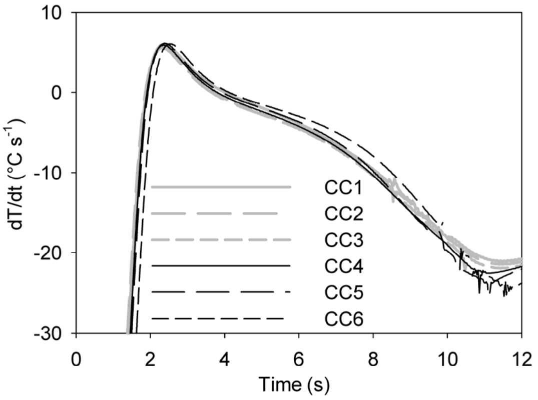

Fig. 4 Differentiated temperature from simulation 1, 2mm plate

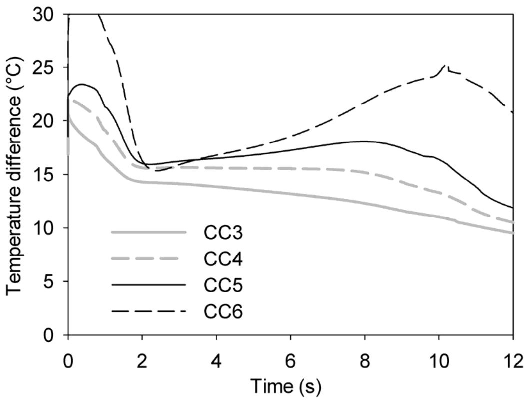

Fig. 5 Temperature difference between surface of TC and CC3-6, from simulation 1 (2 mm plate)

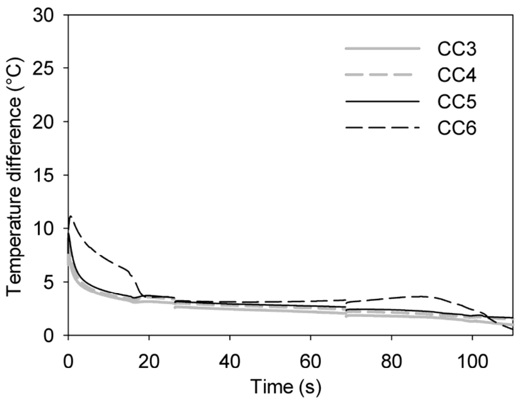

Fig. 6 Temperature difference between surface of TC and CC3-6, from simulation 4 (8 mm plate)

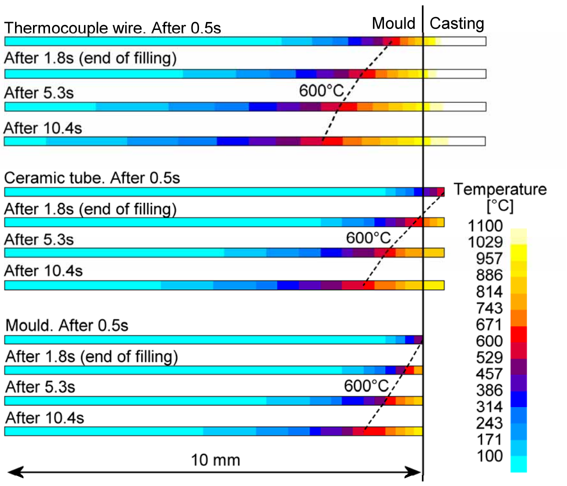

Fig. 7 Temperature profile in TC wire, ceramic tube and mould, 2mm plate (simulation 1)