

# Examining and Modelling the Influence of Thermo-Physical Properties of Liquid Metal and Sand Mould on Solidification Time of Pure Al Castings

P.K. Krajewski<sup>1</sup>, K. Magda<sup>2</sup>, P. Stojceki<sup>3</sup>

<sup>1-3</sup>AGH University of Science and Technology. Faculty of Foundry Engineering.

23 Reymonta Street, 30-059 Krakow, Poland

<sup>1</sup>[krajpaw@poczta.fm](mailto:krajpaw@poczta.fm) (corresponding author)

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## Abstract

The paper presents analysis of influence of different variable parameters on time of solidification calculated from analytical solution of the heat exchange in casting-mould system. The analysed variable parameters were: melt overheating, initial mould temperature and ambient temperature; thermo-physical properties of casting (heat of crystallization, specific heat of liquid metal, mass density, temperature of crystallization) as well as thermo-physical properties of the mould material (thermal conductivity, mass density and heat capacity). During the validation experiments the time of solidification of pure Al (99.95%) plate cast into sand mould was measured. Basing on these measurements it was stated that the analytical formulas allow performing the mentioned analysis with enough accuracy. It was also found that complex variability of the molding sand thermal conductivity, especially during the water vaporization, requires analogous analysis by numerical calculations. This allows taking into account corresponding functional dependencies of the variable process parameters.

This paper prepared in frame of M.Sc. P.K. Krajewski's PhD work is connected with scientific activity of the "Kóło Naukowe Zgarek"

## 1. Introduction

Modelling and/or numerical or analytical calculations of the solidification processes require the knowledge of the thermo-physical properties of the examined system casting – mould – ambient when formulating the initial / boundary conditions. These data are, in most cases, mean values of those existing in literature and using them can lead to low accuracy of the calculations. The analysis of the influence of these parameters on time of solidification can be performed using analytical formulas or numerical calculations. The analytical relationship of time of

solidification  $\tau_{SOL}$  for pure metals is usually given in the following form:

$$\sqrt{\tau_{SOL}} = \frac{\sqrt{\pi} \rho_C R_C}{2b_M (T_{CRYST} - T_{AMB})} (L_C + C_C^{liq} \Delta T_{OH}) \quad (1)$$

where:

$b_M$  – coefficient of heat accumulation of mould material is given by the mould thermal conductivity  $\lambda_M$ , heat capacity

$C_M$  and density  $\rho_M$  by:

$$b_M = \sqrt{\lambda_M C_M \rho_M} \quad (2)$$

However, the casting parameters, i.e. mass density  $\rho_c$  and module  $R_c$  can introduce some errors due to their possible inaccuracy. That is why it is reasonable to use measured mass of casting  $M_c$ :

$$\rho_c R_c = \rho_c \frac{V_c}{F_c} = \frac{M_c}{F_c} \quad (3)$$

thus Formula (1) can be written as follows:

$$\sqrt{\tau_{SOL}} = \frac{\sqrt{\pi M_c}}{2 F_c b_M (T_{CRYST} - T_{AMB})} (L_c + C_c^{liq} \Delta T_{OH}) \quad (4)$$

where:

$M_c$ ,  $V_c$  and  $F_c$  are, accordingly, mass, volume and cooling surface of a casting.

## 2. Experimental

During the examinations the mould sand silica quartz – 5 wt.% bentonite (SQ-B sand) was examined using the so called "Casting method" [1-2], whose scheme is shown in Fig. 1.

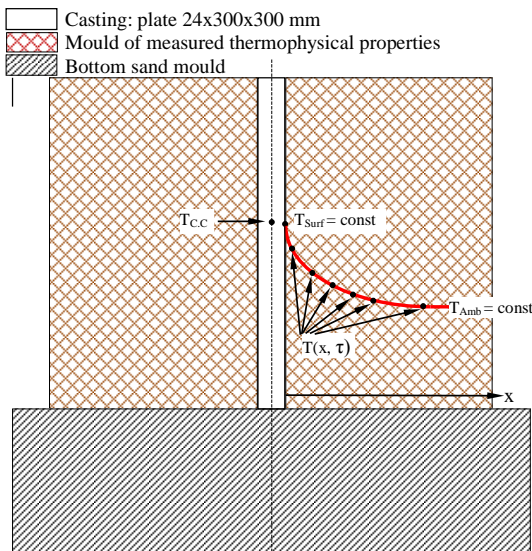


Fig. 1. Scheme of measuring system. Thermocouples location:  $T_{c.c}$  – centre of the casting;  $T_{surf}$  – surface of sand mould ( $T_s$ );  $T(x, \tau)$  – thermocouples located in mould at different distances from the surface;  $T_{AMB}$  – mould temperature unchanged during the solidification of casting (ambient temperature for the casting) [1-2]

The mould was poured with commercial purity aluminium, whose properties are collected in Table 1.

Table 1. Thermo-physical properties and geometrical dimensions of the aluminium castings (purity 99.95% Al) used during the experiments and calculations

Mean density of casting during solidification process, $\rho_c$ , [kg/m <sup>3</sup> ]	2540
Heat capacity in liquid state, $C_c^{liq}$ [J/(kgK)]	1290
Latent heat of fusion, $L_c$ [J/kg]	398000
Overheating, $\Delta T_{OH}$ , [K]	40
Measured temperature of crystallization, $T_{CRYST}$ , [°C]	656,3
Temperature of ambient, [°C]	31,75
Dimensions of plate-shape casting, [m]	0,162x0,162x0,016
Measured mass of casting, $M_c$ [kg]	1,052
Measured density of sand mould, $\rho_M$ [kg/m <sup>3</sup> ]	1372
Mean thermal conductivity of sand in temperature range 100-450 °C, W/(m K)	0,554 [3-4]
Mean heat capacity of sand in temperature range 100-450 °C, J/(kg K)	1278 [3-4]

## 3. Results and discussion

### 3.1. Comparison of solidification time measured and calculated

To check the validity of the Formula (3) the first series of experiment was devoted to evaluating the time of solidification from cooling curve. An exemplary result is shown in Fig. 2.

As it appears from Fig. 2 the time of solidification equals 186.5 s, while the time calculated from Formula 3, using parameters collected in Table 1, equals 172.9 s. The relative difference equals only – 7.3 %. This entitles us to use the relationship (1) in the following analysis aimed at evaluating the influence of thermal properties of the system casting –mould on solidification process.

### 3.2. Influence of casting process and casting material parameters

#### 3.2.1. Melt overheating

Among the parameters of the casting process the most important ones are: melt overheating and initial mould temperature. In Figs 3 and 4 there are shown measured times of solidification of the Al poured into similar moulds (assumed the same density and composition) practically without overheating and with overheating of 40K. It can be seen that overheating significantly influences the experimental time of solidification, which increases by about 20%.

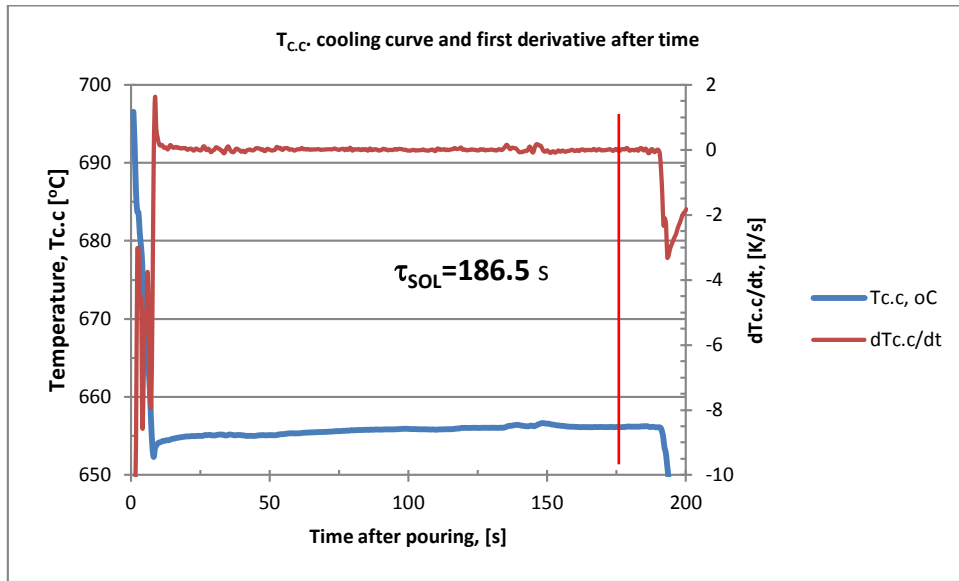


Fig. 2. Measured time of solidification of pure Al plate solidifying in the mould SQ-B [4]

Table 2. Comparison of times of solidification measured and calculated

Time of solidification, [s]		Relative difference, [%]
Measured – $\tau_{sol,m}$	Calculated – $\tau_{sol,c}$	$RD = \frac{\tau_{sol,c} - \tau_{sol,m}}{\tau_{sol,m}} * 100$
186.5 s	172.9 s	-7.3

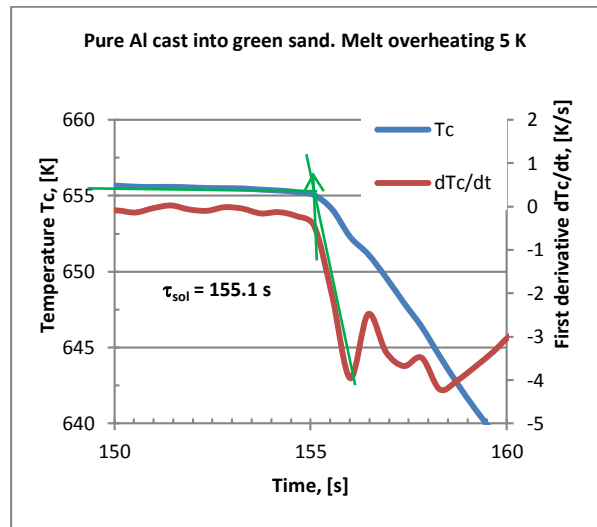
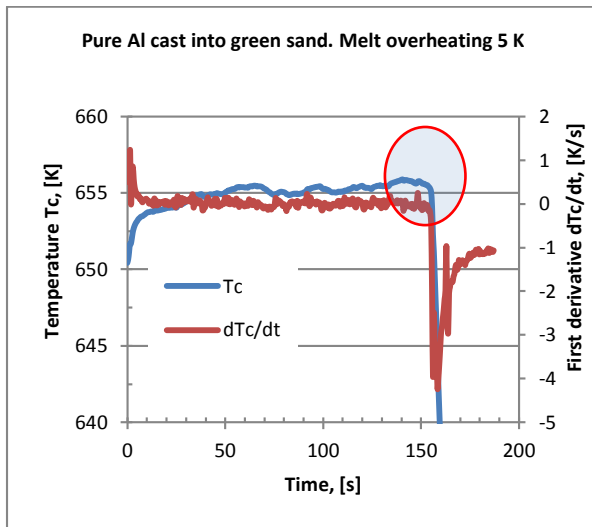


Fig. 3. Cooling curve with first derivative after time and time of solidification of Al casting poured with small overheating of 5 K

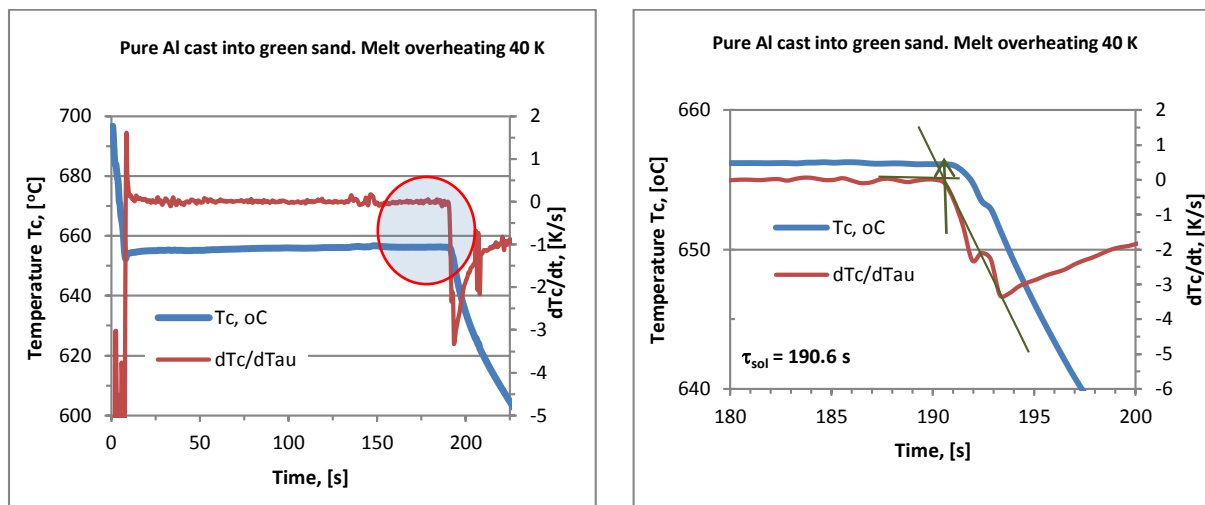


Fig. 4. Cooling curve with first derivative after time and time of solidification of Al casting poured with overheating of 40 K

### 3.2.2. Thermo-physical properties of casting material

The analysis was performed using the Q parameter, being a part of Formulas (1) and (3):

$$Q = \frac{(L_C + C_C^{liq} \Delta T_{OH})}{(T_{CRYST} - T_{AMB})} \quad (5)$$

where  $L_C$ ,  $C_C^{liq}$  and  $T_{CRYST}$  were changed in ranges shown in Table 3. Other parameters were constant and taken as follows:

casting:  $\rho_C = 2500 \text{ kg/m}^3$ ;  $R_C = 0.008 \text{ m}$ ;  $\Delta_{OH} = 40 \text{ K}$ ;  
 mould:  $\lambda_M = 0.8 \text{ W/(m K)}$ ;  $\rho_M = 1400 \text{ kg/m}^3$ ;  $C_M = 1080 \text{ J/(kg K)}$ ;  $T_{AMB} = 20 \text{ }^\circ\text{C}$

Table 3. Influence of Q parameter on time of solidification – TauSol. The last column presents changes calculated in relation to the standard parameters given in bold italics in row No. 5

No.	$L_C$ [J/kg]	$C_C^{liq}$ [J/(kgK)]	$T_{CRYST}$ [°C]	Q [-]	TauSol [s]	Change [%]
1.	390000	1282	656.4	0.4780	124.87	-2.45
2.	392000	1284	657.4	0.4790	125.66	-1.84
3.	394000	1286	658.4	0.4799	126.44	-1.23
4.	396000	1288	659.4	0.4808	127.23	-0.61
5.	<b>398000</b>	<b>1290</b>	<b>660.4</b>	<b>0.4818</b>	<b>128.01</b>	<b>0.00</b>
6.	400000	1292	660.4	0.4834	129.20	0.93
7.	402000	1294	660.4	0.4851	130.39	1.86
8.	404000	1296	660.4	0.4868	131.59	2.80
9.	406000	1298	660.4	0.4884	132.79	3.74

### 3.3. Influence of mould material parameters

The second group of parameters influencing course of the solidification process are thermo-physical properties of the mould material, i.e. thermal conductivity, mass density and heat capacity. All these coefficients are combined in the heat accumulation

coefficient  $b_M$  – Formula (2). The influence of  $b_M$  changes on the time of solidification is significant as it is shown in Fig. 7. However, changes of the mould density and heat capacity during the solidification are rather in a narrow range, thus the main contribution comes from the thermal conductivity, which is shown in Fig. 8.

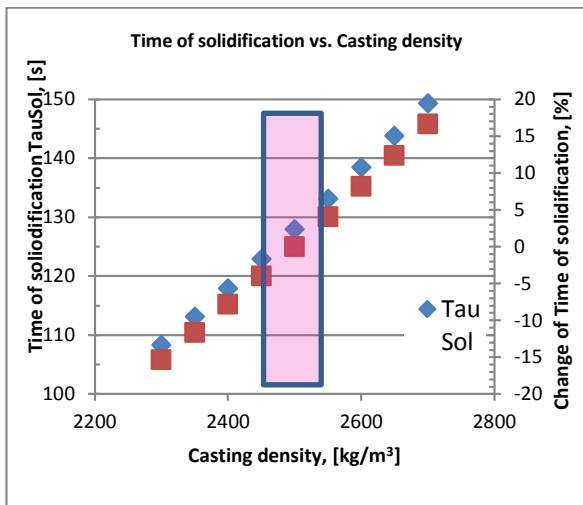


Fig. 5. Influence of assumed casting density on calculated time of solidification

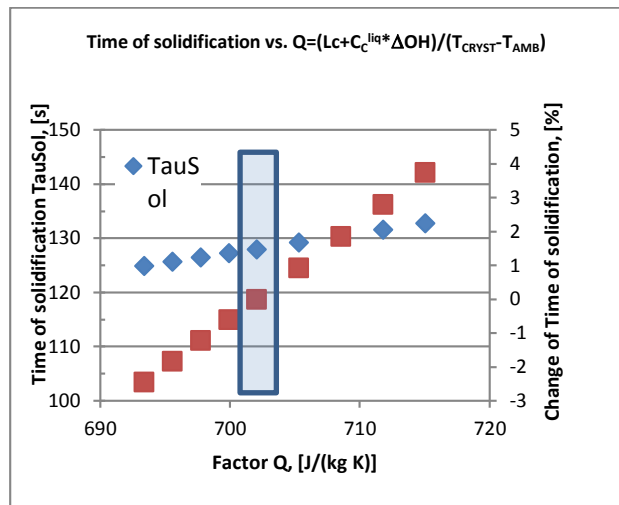


Fig. 6. Influence of parameter Q on calculated time of solidification

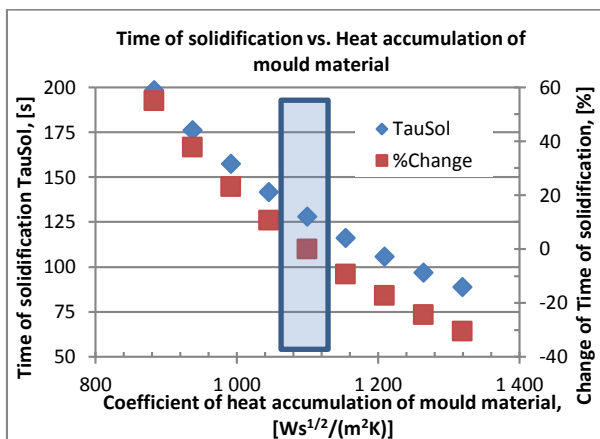


Fig. 7. Influence of mould material heat accumulation coefficient on time of casting solidification

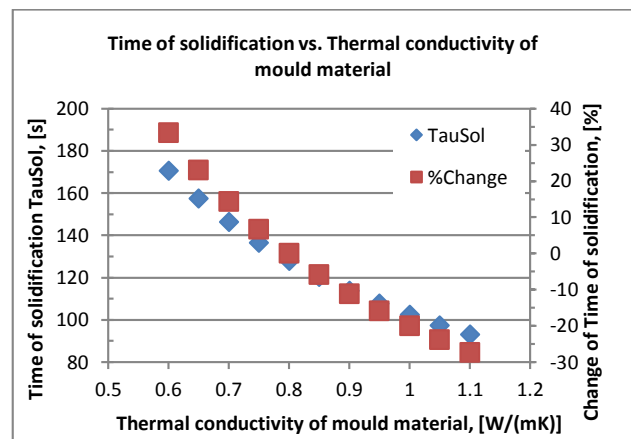


Fig. 8. Influence of mould material thermal conductivity on time of casting solidification

## 4. Conclusions

Basing on the performed examinations and calculations the following conclusions can be drawn:

1. Among the thermo-physical properties the most important is coefficient of thermal conductivity. It is well known, that it strongly depends on temperature changes as well as on mass density changes. However, those relationships are, in most cases, not determined yet. There is need to perform extended examinations of the thermo-physical properties, at least for the main groups of materials which build the systems casting – mould.
2. The examinations should focus on changes of the thermo-physical properties together with temperature changes and mass density changes. The final aim of these examinations is

obtaining data which allow to predict needed values of thermo-physical properties, basing, for instance, on the mass density parameter of sand-moulds in a foundry plant, which is comparatively easily measured.

3. The examinations performed using the "Casting method" show, that the dependence: *thermal conductivity of sand mould vs. temperature* is not simple, especially during the initial period of heating a mould by a casting, when water vaporization proceeds - Fig. 9.
4. From the analysis of the relationship shown in Fig. 9 it is clear that during modelling the solidification processes numerical methods should be employed, which will allow introducing real mathematical dependencies of the processes parameters and improve accuracy of the calculations.

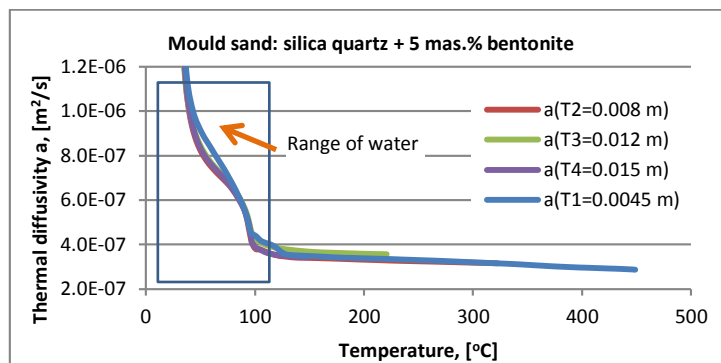


Fig. 9. Relationship *thermal diffusivity coefficient vs. temperature* of the examined sand mould [4]

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# Badania i modelowanie wpływu właściwości termofizycznych ciekłego metalu i formy na czas krzepnięcia odlewu Al

## Streszczenie

Praca dotyczy analizy wpływu właściwości termofizycznych układu odlew – forma odlewnicza, na przykładzie odlewu płyty z czystego Al (99.95%), odlanego do formy piaskowej. Na podstawie pomiarów czasów krzepnięcia ustalono, iż analityczne zależności z wystarczającą dokładnością umożliwiają przeprowadzenie oceny wpływu zmiennych parametrów procesu (temperatura przegrzania metalu, początkowa temperatura formy, temperatura otoczenia), zmiennych właściwości termofizycznych metalu (ciepło krystalizacji, ciepło właściwe w stanie ciekłym, gęstość masy odlewu, temperatura krystalizacji) oraz zmiennych właściwości termofizycznych formy odlewniczej (gęstość masy, ciepło właściwe i przewodnictwo cieplne) na zmianę czasu krzepnięcia wytypowanego odlewu. Stwierdzono również, iż skomplikowany charakter zmienności współczynnika przewodzenia ciepła masy formierskiej, szczególnie w okresie odparowywania wody, wymaga przeprowadzenia analogicznych analiz za pomocą obliczeń numerycznych, umożliwiających wprowadzenie odpowiednich funkcyjnych zależności ww. zmiennych parametrów procesu.

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