A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 59 2014 Issue 4
DOI: 10.2478/amm-2014-0238

P.K. KRAJEWSKI*, G. PIWOWARSKI*, P.L. ŻAK*, W.K. KRAJEWSKI*

EXPERIMENT AND NUMERICAL MODELLING THE TIME OF PLATE-SHAPE CASTING SOLIDIFICATION VS. THERMAL CONDUCTIVITY OF MOULD MATERIAL

EKSPERYMENT I MODELOWANIE NUMERYCZNE CZASU KRZEPNIĘCIA ODLEWU PŁYTY W FUNKCJI PRZEWODNICTWA CIEPLNEGO MATERIAŁU FORMY

The paper presents results of measuring thermal conductivity of sand mould material and time of castings solidification evaluated from cooling curves and from Nova Flow & Solid numerical calculations. During the experiments pure Al (99,95%) plate was cast into the sand moulds. The analysed variable parameter in numerical calculations was mould thermal conductivity of fixed value taken from the range 0.5-0.9 W/(mK). Other mould parameters (initial temperature, mass density, heat capacity) and thermo-physical properties of liquid and solid casting were taken invariable. Basing on the measurements it was stated that thermal conductivity of the moulding sand has complex temperature variability, especially during the water vaporization and the obtained dependence should be used in the numerical calculations to improve their accuracy.
Keywords: castings, sand mould, thermal conductivity, solidification, numerical modelling

Artykuł prezentuje wyniki pomiarów współczynnika przewodzenia ciepła materiału formy piaskowej oraz czas krzepnięcia odlewu oszacowany z krzywej stygnięcia i obliczony numerycznie za pomocą Nova Flow & Solid. W czasie eksperymentów odlew w kształcie płyty wykonywano z czystego aluminium (99,95%). Zmienną w obliczeniach była przewodność cieplna materiału formy z zakresu 0,5-0,9 W/(mK). Pozostałe parametry formy (temperatura początkowa, gęstość masy i pojemność cieplna) oraz właściwości termofizyczne ciekłego i zakrzepłego metalu były stałe. Na podstawie eksperymentów stwierdzono, że temperaturowa zależność przewodności cieplnej formy nie ma prostego przebiegu, szczególnie w okresie odparowywania wilgoci, a uzyskana w części eksperymentalnej temperaturowa zależność powinna być stosowana w obliczeniach numerycznych w celu polepszenia jakości obliczeń.

1. Introduction

The amount and rate of heat transferred from a solidifying melt to foundry mould and ambient determines the structure and properties of the casting. Nowadays designing of the casting technology uses numerical simulation of the heat and mass exchange processes. Simulation of the solidification processes requires knowledge of several boundary parameters, among others, the thermo-physical parameters of the system casting – mould – ambient [1].

For a mould these are: coefficient of thermal diffusivity, coefficient of heat capacity, coefficient of thermal conductivity and mass density. For a casting these are mainly: densities of liquid and solid state, liquid and solid heat capacities and heat of solidification.

The solidification and feeding processes depend on grain-size of the casting, which can be controlled by heterogeneous nucleation and/or or by the intensity of cooling [2,3]. The latter strongly depends on the mentioned thermo-physical properties of the mould [4]. In foundry practice, in many cases shape castings solidify in sand-moulds. Thermo-physical properties of sand moulds strongly depend on temperature changes, unfortunately these relationships are in most cases unknown. Moreover, the available software packages have mean values of those existing in literature and using them can lead to low accuracy of the calculations. Thus, there is a need of establishing the temperature dependencies of the mentioned thermo-physical properties as well as a need of performing a confrontation: experimental results vs. numerical calculations of the solidification process. Many different methods of measurements of the thermo-physical properties are available in literature, e.g. [5-20] and their describing is beyond scope of this paper.

2. Experimental

In this experiment pure Al plate was cast into wet green-sand mould. During the experiment temperature field of the mould as well as cooling curve of the solidifying casting were registered. The details of the experiment are shown in Figure 1 and are already described in detail in [21-25].

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF FOUNDRY ENGINEERING, 23 REYMONTA STREET, 30-059 KRAKOW, POLAND

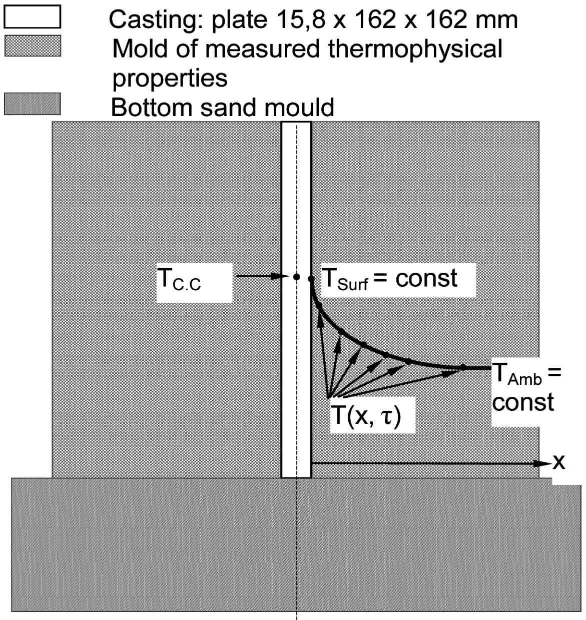

Fig. 1. Scheme of measuring system. Thermocouples location: $T_{C.C}$ – centre of the casting; T_{Surf} – surface of sand mould; $T(x,\tau)$ – thermocouples located in different distances from the surface; T_{Amb} – mould temperature unchanged during the solidification of casting (ambient temperature for the casting) [21]

The sand mould with mounted thermocouples is shown in Figure 2 while Figure 3 shows the same mould with solidified Al plate inside. The material properties of the casting – mould system used during calculations are collected in Table 1. The measured time of solidification was confronted with the one calculated from the analytical formula (1), [24,25]:

$$\sqrt{\tau_{SOL}} = \frac{\sqrt{\pi} M_C}{2F_C b_M \left(T_{\mathbf{CRYST}} - T_{Amb}\right)} \left(L_C + C_C^{liq} \Delta T_{OH}\right) \quad (1)$$

M_C and F_C – mass and cooling surface of casting; b_M – coefficient of heat accumulation of mould material is given by the mould thermal conductivity λ_M , heat capacity C_M and density ρ_M:

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

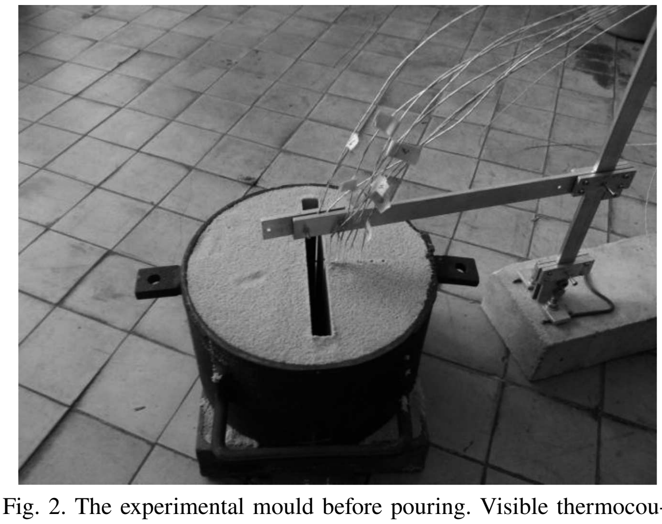

Fig. 2. The experimental mould before pouring. Visible thermocouples mounted in the mould cavity and in the mould body

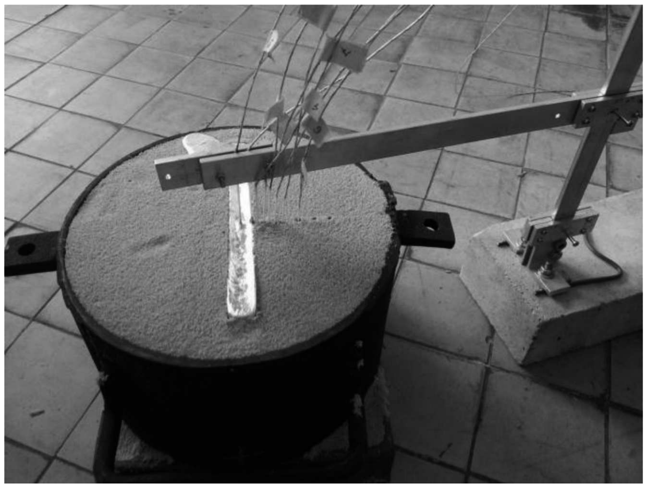

Fig. 3. The mould from Figure 2 cast with pure aluminium

Combining relationships:

$$b = \sqrt{\lambda C \rho} \quad a = \frac{\lambda}{\rho C} \quad (3)$$

one can easily calculate required coefficients as follows:

$$\lambda_M = b_M \sqrt{a_M} \quad C_M = \frac{b_M}{\rho_M \sqrt{a_M}} \quad (4)$$

where: a_M – heat diffusivity coefficient of the mould material.

TABLE 1

Thermo-physical properties and geometrical dimensions of the Al casting (purity 99.5% Al) and density of the mould used during the calculations

Property – Symbol/Unit	Value
Liquid density – ρ_{LC} / kg/m^3	2 400
Solid density – ρ_{SC} / kg/m^3	2 660
Heat capacity in temperature range of crystallization – $C_{liq-sol}$ / J/(kgK)	960 – 1 170
Heat capacity in liquid state – C_C^{liq} / J/(kgK)	1 086
Latent heat of fusion – L_C / J/kg	398 000
Melt overheating – ΔT_{OH} / K	40
Measured temperature of crystallization – T_{CRYST}/ °C	656,27
Dimensions of plate-shape casting / mm	160×160×15,8
Liquid state thermal conductivity – λ_L / W/(mK)	100
Solid state thermal conductivity – λ_S / W/(mK)	125 – 165
Measured density of sand mould – ρ_M / kg/m^3	1 372
Initial mould temperature T_{Amb} / °C	32
Measured time of solidification in experiment – τ_{sol} / s	186

The a_M heat diffusivity coefficient can be determined from the registered temperature field of the mould described by error function [7,8]:

$$\frac{T_{x,\tau} - T_{Surf}}{T_{Amb} - T_{Surf}} = erf(u); \text{ where } u = \frac{x}{2\sqrt{a_M \tau}} \quad (5)$$

3. Results and discussion

The temperature dependence of the investigated green-sand is shown in Figure 4. From Figure 4 it can be seen that the coefficient of thermal conductivity takes value from the range 1.6-0.7 W/(mK) during the first period of the mould heating by the solidifying casting. During this period also water evaporation and vapour transport from the mould surface-layer to the mould body takes place. Then its value stabilizes and linearly decreases to about 0.55 W/(mK).

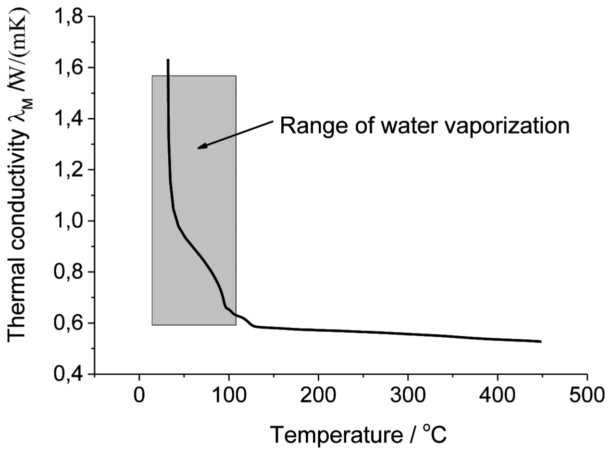

Fig. 4. The relationships: thermal conductivity vs. temperature obtained for the examined sand in the Casting Method experiment [21]

As mentioned before the same material data were used in numerical calculations by Nova Flow & Solid. The obtained cooling curves during the numerical modelling are shown in Figure 5 while time of solidification for different values of the sand thermal conductivity is shown in Figure 6.

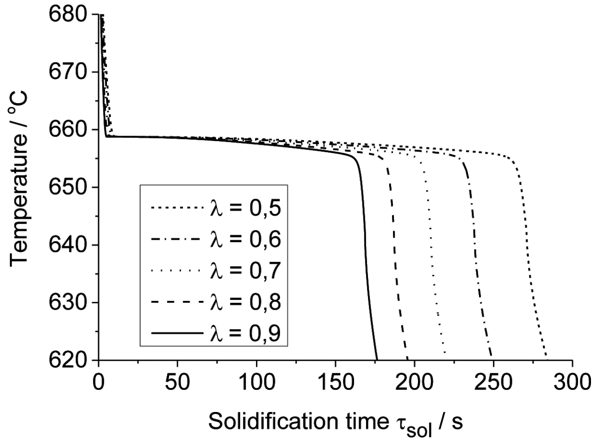

Fig. 5. Cooling curves of the aluminium plate obtained in Nova Flow simulation for different values of the sand λ_M thermal conductivity

The time of solidification from the experiment is 186 s while by Nova Flow & Solid it is 260 s for the sand thermal conductivity $\lambda_M = 0.5$ W/(mK) and 230 s for the sand thermal conductivity $\lambda_M = 0.6$ W/(mK). Thus, it can be concluded, that using mean values the sand thermal conductivity in numerical calculations introduces significant inaccuracy in relation to the value obtained in the experiment, as it can be seen in the last column of Table 2.

TABLE 2

Time of solidification τ_{sol} by Nova Flow & Solid for different values of the mould mean λ_M thermal conductivity coefficient

λ_M / W/(mK)	τ_{sol} / s	τ_{sol} / s	Error / %
	NovaFlow	Experiment	–
0.5	260.2	186.0	39.9
0.6	228.9		23.1
0.7	202.3		8.8
0.8	180.3		-3.1
0.9	162.7		-12.5

Finally, it should be taken into account that only real temperature dependence of thermo-physical properties can ensure high accuracy of the numerical calculations.

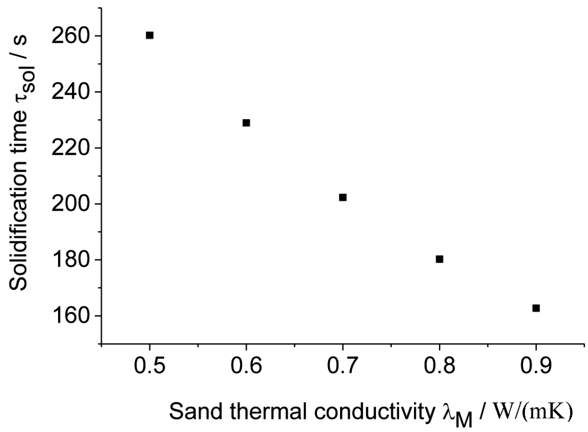

Fig. 6. Time of solidification τ_{sol} for the sand thermal conductivity value λ_M = 0.5 - 0.9 W/(mK) (Nova Flow & Solid)

4. Conclusions

Basing on the presented results the following conclusions can be drawn:

The Casting Method (CM) allows obtaining temperature dependence of the thermo-physical properties.

The CM is performed in real conditions of the poured sand mould, i.e. in contact with molten metal, under hydrostatic pressure of the molten metal during initial period of the metal cooling as well as in condition of the water evaporation from the wet mould.

Using mean values of the sand thermal conductivity in numerical simulations / calculations can lead to very high inaccuracy, for instance the time of solidification may be 20-40% longer than the real one.

Finally, it should be concluded that only real temperature dependence of thermo-physical properties, e.g. measured by the Casting Method, can ensure high accuracy of the numerical simulations and calculations.

Acknowledgements

The authors are grateful to the NCN – Polish Science National Centre for financial support under grant Preludium 5 No. UMO-2013/09/N/ST8/00256.

REFERENCES

[1] M. Copur, M.N. Eruslu, Metalurgija **53**, 2, 149-154 (2014).
[2] W.K. Krajewski, A.L. Greer, Materials Science Forum **508**, 281-286 (2006).
[3] W.K. Krajewski, Materials Science Forum **508**, 615-620 (2006).
[4] S. Neves, W. Schäfer, P.N. Hansen, International Journal of Thermophysics **23**, 5, 1391-1399, September 2002.
[5] Y. Jannot, A. Degiovanni, G. Payet, International Journal of Heat and Mass Transfer **52**, 1105-1111 (2009).
[6] Y. He, Thermochimica Acta **436**, 122-129 (2005).
[7] C.P. Cam, Thermochimica Acta **417**, 1-4 (2004).
[8] S. Chudzik, Infrared Physics & Technology **55**, 73-83 (2012).
[9] J. Svidro, A. Dioszegi, J. Toth, Journal of Thermal Analysis and Calorimetry **115**, 331-338 (2014).
[10] D. Emadi, L.V. Whiting, M. Djurdjevic, W.T. Kierkus, J. Sokolowski, Metallurgija – Journal of Metallurgy (Serbia) **10**, 91-106 (2004).
[11] M. Velièka, R. Pyszko, M. Pøíhoda, J. Molínek, Metalurgija **48**, 4, 277-280 (2009).
[12] G. Solenicki, I. Budij, D. Ciglar, Metalurgija **49**, 1, 3-7 (2010).
[13] P. Tervola, International Journal of Heat and Mass Transfer **32**, 8, 1425-1430, August 1989.
[14] Sang II Park, J.G. Hartley, KSME Journal **10**, 4, 480-488, December 1996.
[15] K. Kubo, I. Ohnaka, T. Fukusako, and K. Mizuuchi, The journal of The Japan Foundrymen's Society **55**, 362-368 (1983).
[16] K. Kubo, K. Mizuuchi, I. Ohnaka, and T. Fukusako, Proc. 50th Intl. Foundry Congress, Cairo **6**, 1-12 (1983).
[17] K. Kubo, K. Mizuuchi, International Foundry **50**, 5, 1-21 (1983).
[18] K. Kubo, I. Ohnaka, T. Fukusako, and K. Mizuuchi, The journal of the Japan Foundrymen's Society **53**, 627-634 (1981).
[19] S.I. Bakhtiyarov, R.A. Overfelt, D. Wang, International Journal of Thermophysics **26**, 1, 141-149, January 2005.
[20] A.I. Vejnik, Theory and calculations of solidification of castings in ceramic mould, Maszgiz, Moscow 1954 (in Russian).
[21] W.K. Krajewski, J.S. Suchy, Materials Science Forum **649**, 487-491 (2010).
[22] P.K. Krajewski, Z. Zovko-Brodarac, W.K. Krajewski, Archives of Metallurgy and Materials **58**, 847-849 (2013) (Part 1).
[23] P.K. Krajewski, A. Gradowski, W.K. Krajewski, Archives of Metallurgy and Materials **58**, 1149-1153 (2013) (Part 2).
[24] P.K. Krajewski, G. Piwowarski, W.K. Krajewski, Materials Science Forum **790-791**, 452-457 (2014).
[25] P.K. Krajewski, J.S. Suchy, G. Piwowarski, W.K. Krajewski, Thermo-physical properties vs. temperature of selected foundry sands, Proceedings of the 71st World Foundry Congress Advanced Sustainable Foundry, 21-24 May 2014, Bilbao, Spain (on USB Memory Flash).

Received: 20 January 2014.