ANALYSIS BY MATHEMATICAL MODELLING OF UNIDIRECTIONAL SOLIDIFICATION OF ALUMINIUM

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The paper presents some results regarding the simulation of the unidirectional solidification process by mathematical modelling. The program analyzes the influence of casting geometry, initial and pouring temperatures, boundary conditions, materials thermal properties. Three types of cooling plates were takenconsidered: copper, aluminium, and cast iron. By processing the results of modelling data some interesting information related to the variation of the solidified layer thickness in time according to the casting temperature and cooling plate type were obtained.

Keywords: unidirectional solidification, aluminium, mathematical modelling, cooling plate

1. Introduction

Solidification of metallic melts is a complex process with major implications on the quality of castings. Frequently, before the thermal treatment, in castings appear three areas: a narrow layer of fine and uniform equiaxed crystals on the alloy-mould surface separation (formed in heterogeneous germination conditions), an area where dendritic crystals developed perpendicular to the wall of the mould (columnar crystals) and a zone of large equiaxed crystals (in the center of cast).

Depending on chemical composition and solidification conditions it can be obtained a macrostructure with two zones or even a single one. Generally, it follows to obtain fine equiaxed crystals on the whole section of castings. Columnar crystals are undesirable because it leads to a strong anisotropy of mechanical properties. However, in the case of parts such as turbine blades or drill bits, this anisotropy is advantageous.

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These dendritic crystals can be obtained by unidirectional solidification. Consequently, tensile strength, elongation, impact ductility, and creep resistance are superior in the direction of crystal orientation. To obtain this structure the following conditions must be fulfilled: unidirectional heat flow, large temperature gradient in the melt, a plane liquid - solid interface, and local high solidification velocity. By unidirectional solidification it can obtains a fibrous structure with anisotropic properties.

Besides the traditional methods of analysis, mathematical modelling of solidification process provides to the manufacturers useful information on the quality of castings. Also, simulation reduces the time needed to start a mass production as a result of eliminating the experimental phase, materials and energy consumptions, rejected castings, labour costs etc [1-5].

2. Experimental results and discussions

To simulate the unidirectional solidification process of technical aluminium, SimCADE v.2.0, a computer program, was used. The program analyzes the influence of casting geometry and solidification conditions (initial and pouring temperatures, boundary conditions, and thermal properties of materials) on the isothermal lines [6]. To solve the heat transfer equation, the finite element method is used.

The following equation was used to describe the heat flow during solidification:

$$\frac{\partial}{\partial x}\left[\lambda(T)\frac{\partial T}{\partial x}+\lambda(T)\frac{\partial T}{\partial y}\right]=\rho c_{ps}\frac{\partial T}{\partial t}, \qquad (1)$$

where: T is the temperature, λ - the thermal conductivity, ρ - the density of metallic materials, c_{ps} – specific heat, t – time.

Initial and boundary conditions:

$$T = T_0,\ t = 0; \qquad (2)$$

$$\lambda\left((\frac{\partial T}{\partial x}n_x+\frac{\partial T}{\partial y}n_y\right)+\alpha\left(T-T_0\right)=0,\ \forall P(x,y)\in S_\alpha, \qquad (3)$$

attached to equation (1) lead to the mathematical model (T_0 is the temperature at the initial moment; α - the heat transfer coefficient on the surface S_α).

During the solidification process, the latent heat acts like an external source of heat.

Simulation of solidification process was performed considering cylindrical samples (ϕ30x150 mm) cast from technical aluminium in temporary mould (quartz sand of Valeni and furan resin Kaltharz type). A metal plate, acting as a cooler, was placed at the bottom of the mould to ensure the conditions for unidirectional solidification (Fig. 1). Cooling plates (150x150x50 mm) of aluminium, cast iron and copper were used.

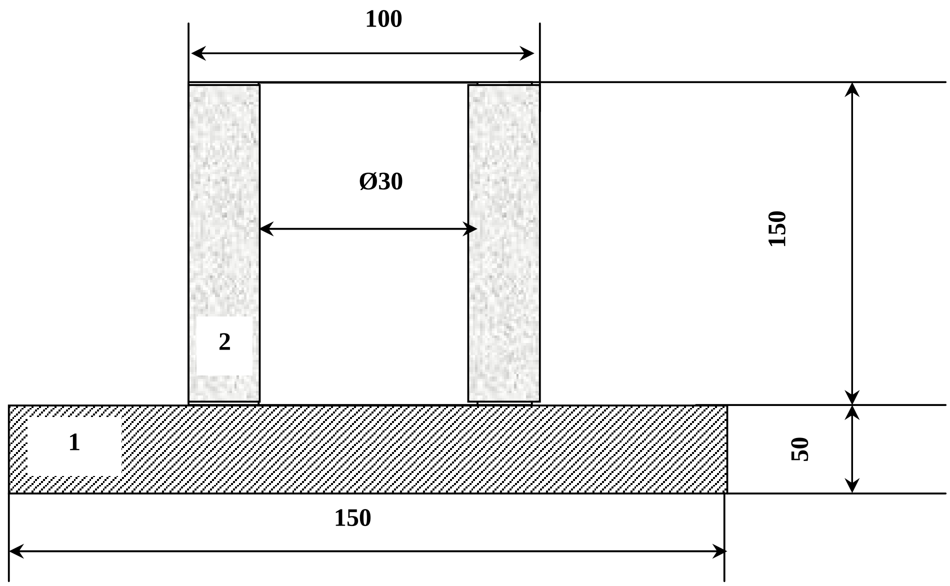

Fig 1. Mould - cooling plate ensemble.

The following parameters were used for the mathematical modelling [6]:

- chemical composition of the technical aluminium (98% Al, 0.7% Si, 0.22% Mg, 0.10% Mn, 0.16% Cu, 0.19% Zn, 0.58% Fe, other elements – remainder)
- thermal conductivity of technical aluminium, $\lambda = 207$ W/(m·K)
- casting temperature: $T_{c1} = 700$°C; $T_{c2} = 750$°C; $T_{c3} = 800$°C
- heat accumulation (diffusivity) coefficient of the mould, $b_f = 1200$ $Ws^{1/2}/(m^2 \cdot K)$
- heat accumulation coefficient for cooling plates, $b_{f\text{Al}} = 24800$ $Ws^{1/2}/(m^2 \cdot K)$, $b_{f\text{Cu}} = 34400$ $Ws^{1/2}/(m^2 \cdot K)$, $b_{f\text{Cast Iron}} = 13500$ $Ws^{1/2}/(m^2 \cdot K)$

Solidification isotherms for cooling plates at casting temperatures are presented in Figures 2…4.

Solidified layer thickness was determined by direct measurements on solidification isotherms. The time is ranging between 10…30 s, depending on the casting temperature. The results are presented in Table 1.

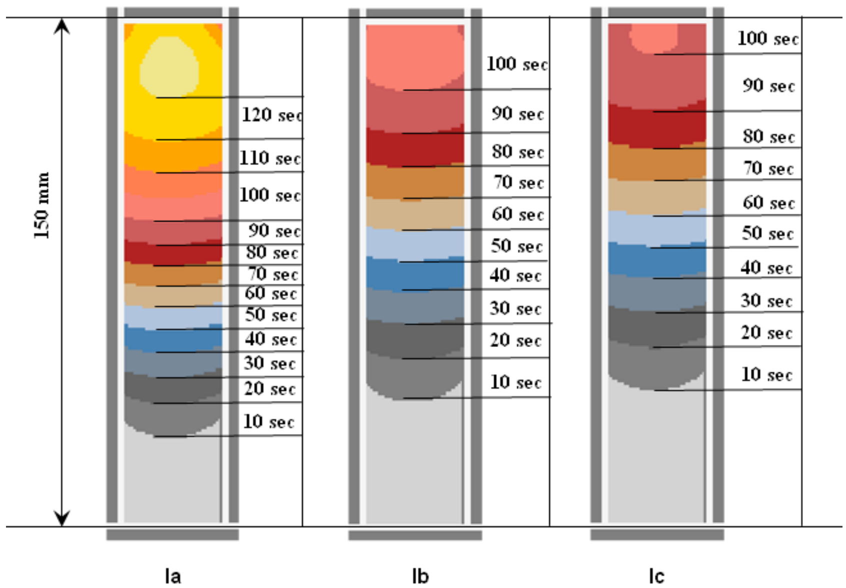

Fig. 2. Solidification isotherms for T_c=700^{o}C: Ia – cast iron chill; Ib – aluminium chill; Ic – copper chill.

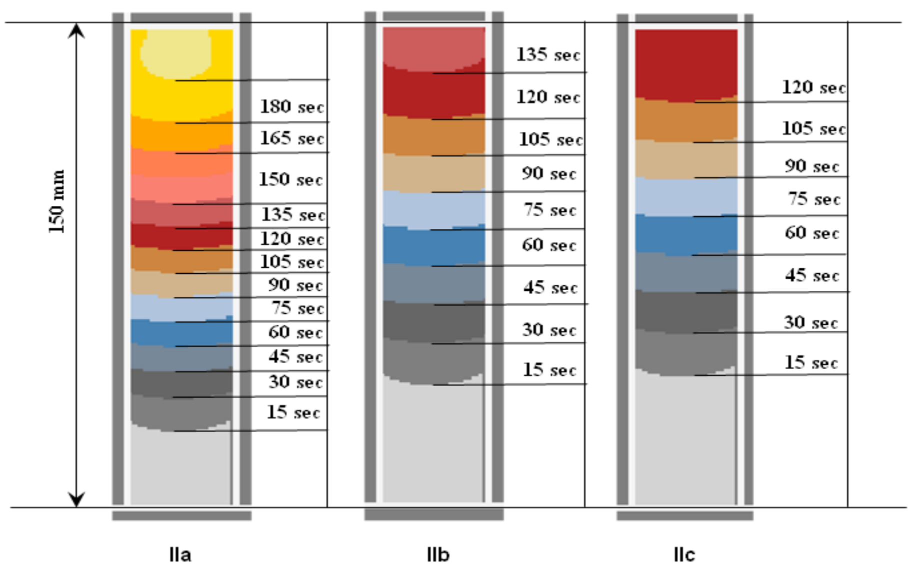

Fig. 3. Solidification isotherms for T_c=750^{o}C: IIa – cast iron chill; IIb – aluminium chill; IIc – copper chill.

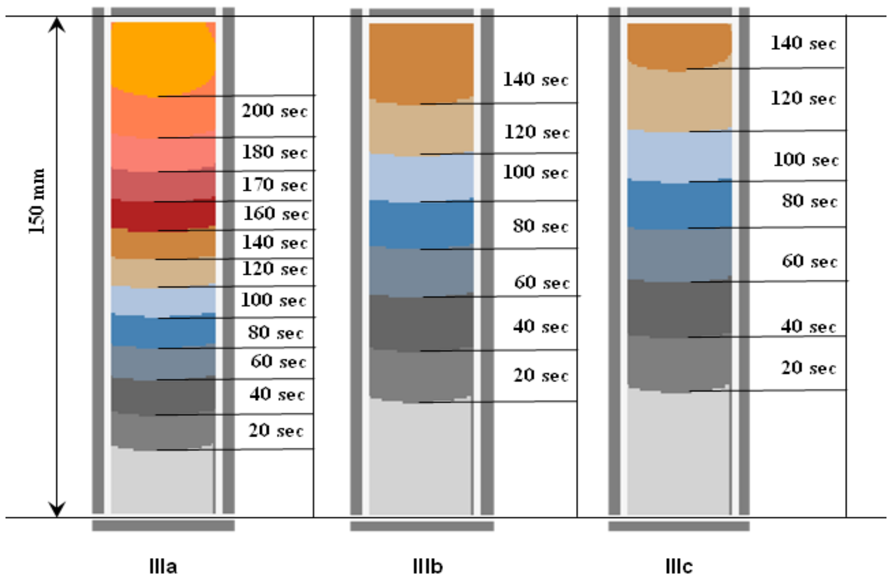

Fig. 4. Solidification isotherms for T_c=800°C: IIIa – cast iron chill; IIIb – aluminium chill; IIIc – copper chill.

Table 1

The thickness of the solidified layer

T_c = 700°C				T_c = 750°C				T_c = 800°C			
X, mm				*X*, mm				*X*, mm			
t, s	Cast Iron	Al	Cu	*t*, s	Cast Iron	Al	Cu	*t*, s	Cast Iron	Al	Cu
10	26.2	32.1	37.9	15	23.3	33.5	36.4	20	20.4	33.5	37.9
20	36.4	48.1	52.4	30	33.5	46.6	51	40	30.6	48.1	53.9
30	43.7	58.3	62.6	45	40.8	61.2	65.5	60	33.5	65.6	68.5
40	51	72.8	77.2	60	49.5	74.3	77.2	80	49.5	80.1	85.9
50	58.3	81.6	87.4	75	56.8	85.9	88.8	100	59.7	94.7	99
60	65.5	91.8	96.1	90	64.1	90.3	101.9	120	67	107.7	115
70	72	101.9	107	105	71.4	109.2	112.1	140	77.2	122.3	133.9
80	78.2	110.7	120.1	120	80.1	119.4	133	160	84.5		
90	86.5	122.3	129.2	135	85.9	138.3		180	93.2		
100	93.6	136.8	147.1	150	93.2			200	103.4		
110	104.9			165	109.2			220	112,1		
120	112.1			180	117,9						
130	125.2										

Analyzing the obtained data, it results how the casting temperature, chill type and time influenced the solidified layer thickness.

It was determined that at 800°C casting temperature, after 60 s, the melt is solidified in a proportion of 22% for cast iron chill, 43% for aluminium chill and 45% for copper chill. Also, after 120 s, at the same temperature, the melt is solidified in a proportion of 44% for cast iron chill, 71% for aluminium chill and 76% for copper chill.

Mathematical modelling of unidirectional solidification for the samples poured at 700°C on aluminium or copper cooling plate shows as a melt completely solidified. However, cooper chill has the strongest effect on the process. After 100 s, the solidification isotherms indicate that the sample is solidified in a proportion of 98%, compared with 91% for aluminium cooling plate.

The variation of the solidified layer thickness in time according to the casting temperature and cooling plate type are presented in Figures 5…7.

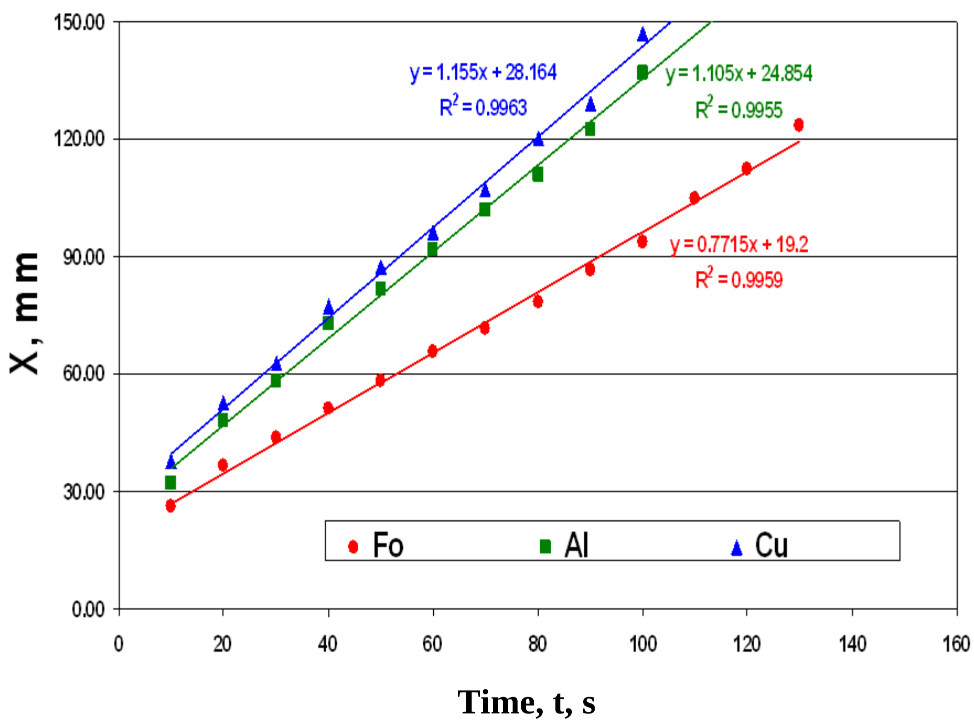

Fig.5. Influence of cooling plate on the thickness of solidified layer for 700°C casting temperature, (Fo- cast iron, Al- aluminium, Cu- copper).

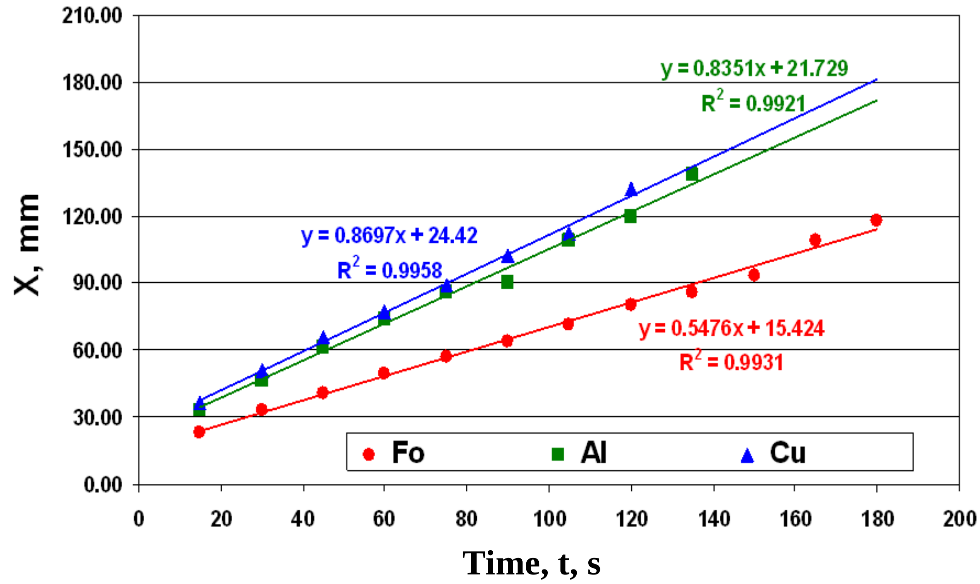

Fig.6. Influence of cooling plate on the thickness of solidified layer for 750°C casting temperature. (Fo- cast iron, Al- aluminium, Cu- copper).

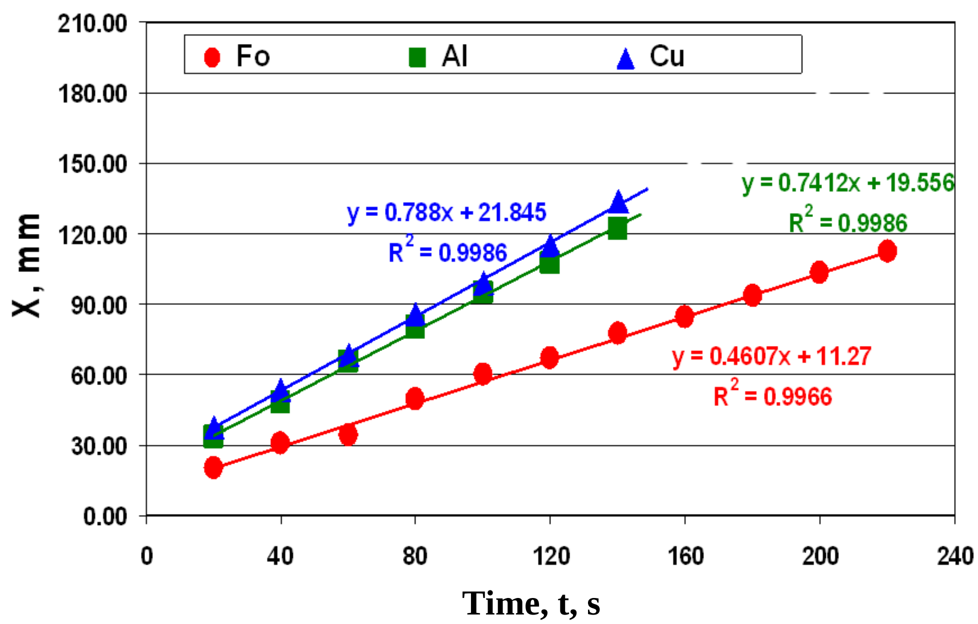

Fig.7. Influence of cooling plate on the thickness of solidified layer for 800°C casting temperature. (Fo- cast iron, Al- aluminium, Cu- copper).

Analyzing the modelling data, it results that the casting temperature and thermal properties of the cooling plate significantly influence the kinetics of solidified layer thickness. There are also shown the limits of influence for these technological parameters.

3. Conclusions

Regardless of the process characteristic parameters (casting temperature and time), it is found that the copper cooling has the strongest influence on the thickness of the solidified layer. The copper cooling plate, due to its thermal properties characteristics, embedded in the heat accumulation coefficient, absorbs and conducts faster the heat from the metallic melt in the environment.

The modelling adopted could be used successfully to study the process of unidirectional solidification. On the other hand, it results which are the main technological conditions that must be established to obtain a desirable effect.

R E F E R E N C E S

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