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Foundry-Gas Pressing Method

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Abstract
The developed methodology for fundamental research of the casting process with IMSETCHA "Acad. Angel Balevski ". Data from preliminary experiments is used.
A mathematical framework for mathematical modeling of the first-order phase transition in the „Gas Pressing" method is proposed. Below are links to important casting parameters.

Keywords: Mathematical Framework, First-order phase transition, Macro-Level, Parameters

1. Introduction

In IMETCHA „Acad. Angel Balevski" has been established „Foundry Industry" in three directions: 1. Foundry machines based on the Balevski-Dimov counter-casting method [1 and 2]; 2. Pressure metallurgy also based on the Balevski-Dimov back pressure casting method [1 and 3]; 3. Theoretical research led by Correspondent member prof. I. Dimov and prof. D.Sc. I. Nedyalkov from the Institute for Nuclear Researches and Nuclear Energy (INRNE) at the Bulgarian Academy of Sciences. Prof. D.Sc. I. Nedyalkov heads a section: "Mathematical Modeling in Physics and Engineering" at INRNE at the Bulgarian Academy of Sciences. Fundamental experiments and results are presented in many works, some of them being [4, 5, 6, 7 and 8]. The results obtained, apart from articles, were formed in non-commercial mathematical computational products: 1D and 2D products based on the finite difference method and 3D computational products using the finite element method.
It is known that the boundary condition of the cast|mold is of the 4-th order (ideal contact) and depends only on the thermal conduction of the cast (C) and the mold (M) (Boundary Ideal Contact, C|M is Heat Flow from Cast to Mold)

$$\boldsymbol{\lambda_M \nabla T(x,y,z,t)_M^W = \lambda_C \nabla T(x,y,z,t)_C^W}, \qquad (IC_{C|M})$$

where λ, ∇ and T are coefficient of conductivity and temperature gradient (heat flow) at boundary C|M of the cast and mold materials, and index W is work surface of the mold. That's why in the Stefan-Schwartz task the contact temperature is determined. In [4] a new type of bonding is made in the open thermodynamic system (cast-shape) between: the non-stationary temperature field with the stress and deformation fields by the non-stationary thermal resistance of the contact edge cast|mold (work surface of the mold). Boundary Real Contact cast|mold (BRC, C|M) is

$$\boldsymbol{\lambda_M \nabla T(x,y,z,t)_M^W = [\alpha(T_C - T_M)](x,y,z,t)_{C|M}^W = \lambda_C \nabla T(x,y,z,t)_C^W}, \qquad (RC_{C|M})$$

where we have complex non stationary function $[\alpha(T_C - T_M)](x,y,z,t)_{C|M}^W$; the coefficient of the real contact of heat transfer α [5] is

$$\boldsymbol{\alpha(t)} = \eta\left[\frac{\delta_0}{\lambda_0} + \frac{\pi\rho\psi(\eta)}{2\lambda_\mu} + \sum_{i=1}^{2}\left(\boldsymbol{R_l^{F_k}} + \frac{\delta_l^k}{\lambda_l^k}\right)\right]^{-1} + (\mathbf{1} - \eta)\left\{\boldsymbol{\alpha_C} + \boldsymbol{\alpha_R}\left[\frac{\delta_0}{\lambda_0} + \frac{\delta_x}{\lambda_x} + + \sum_{i=1}^{2}\left(\boldsymbol{R_l^{F_k}} + \frac{\delta_l^M}{\lambda_l^M}\right)^{-1}\right]\right\}, \qquad (RC_{C|M})$$

η is relative contact area; δ_0 and λ_0 are thickness and thermal conductivity of the protective coating; $\boldsymbol{\delta_l^{k(M)}}$ and $\lambda_l^{k(M)}$ are the thickness and thermal conductivity of the oxide layers; ψ(η) is

the contraction coefficient; ρ is the radius of contact spot; λ_μ is the geometric mean of the heat conducting materials; α_c is the coefficient of convective heat exchange; α_R is the radiation heat transfer coefficient; $\boldsymbol{R_l^{F_k}}$ is the thermal resistance of the phonon heat transfer between the cast or mold material and the corresponding oxide layer (*l*=1, 2). η is a complex function of statistical distribution, geometry of irregularities and normal tensions in the contact area. An indirect method [6] for evaluation of the coefficient heat exchange on the mold work surface in the cyclic foundry process. In [7] it has been proven that contact pressure and gap are determining factors for contact heat exchange at the cast|mold boundary. Mathematical simulation by Stefan-Schwartz's 3D task and the finite element method of a rapid solidification of metallic eutectic melt from Al-Cu is presented in [8]. The curing front movement speed was obtained for selected values of the heat transfer coefficient at the limit (metal melt)/cooler.
On Fig. 1 shows the general geometric scheme of a gas pressing (GP) method.

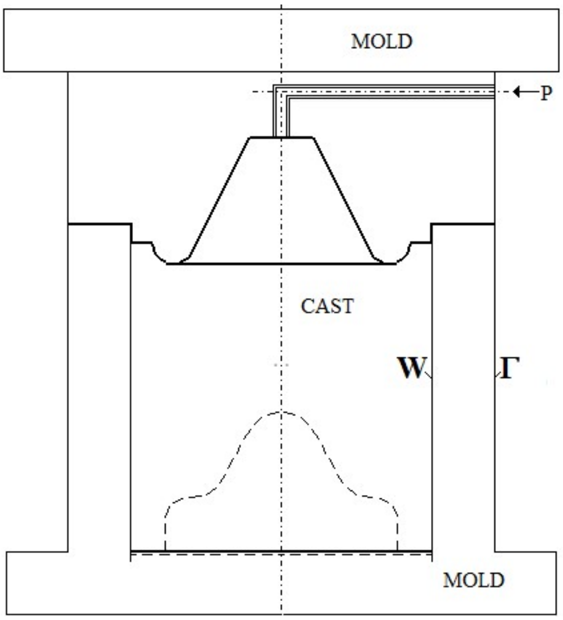


Fig. 1. General geometric scheme of the gas pressing (GP) method: cylindrical CAST, MOLD and boundaries surfaces W (working) and external Γ (mold/environment); P is pressure [9, 10].

To account for the influence of pressure on the crystallization process in "GP" method [9, 10] proposes we use the Clausius–Clapeyron equation (CCE)

$$\boldsymbol{dp/dT = Q_m/[T(v_2 - v_1)]}, \quad \text{(CCE)}$$

where p is pressure; T is temperature; Q_m is the latent heat of melting; $v_{1(2)}$ – relative volume corresponding to a unit mass of phases 1 and 2. The aim of this work is to create a mathematical model of the processes of solidification in casting with the "GP" method.

2. Mathematical model of solidification on the base of the heat conductivity theory by Stefan-Schwartz problem

-3D nonstationary equation of the heat conductivity

$$c_{EF}\rho\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial T^2}{\partial x^2} + \frac{\partial T^2}{\partial y^2} + \frac{\partial T^2}{\partial z^2}\right) \text{ in } V_{OTS}(x,y,z) = V_C(x,y,z) \cup V_M(x,y,z), \quad (1, 1)$$

-initial conditions at τ=0

$T_C(x, y, z, 0)=const_1$ и $T_M(x, y, z, 0)=const_2$, (1, 2)

-boundary conditions at surfaces W and Γ for $\tau \geq 0$

$$W_{C|M}: -\lambda_C \nabla T_{\vec{n}} = \alpha_{W_{C|M}}[T_C(x,y,z,t) - T_M(x,y,z,t)] = -\lambda_M \nabla T_{\vec{n}}, \quad (1, 3, W)$$

$$\Gamma_{M|E}: -\lambda_M \nabla T_{\vec{n}} = \alpha_{\Gamma_{M|E}}[T_M(x,y,z,t) - T_E] \quad (1, 3, \Gamma)$$

-with the conditions for the heat physical coefficients of the cast as follows:

$$\begin{cases} C_L\text{-}\ \lambda_L, \rho_L, c_L & \text{for } T_{EL}(\tau) > \quad T_m + \Delta \qquad 0 < \forall\tau < \tau_L \\ C_L\text{-}\ \lambda_L, \rho_L, c_L + Q_F \frac{dS_F[T(\tau)]}{dT} & \text{for } T_{EL}(\tau) \in [T_m\text{-}\Delta, T_m + \Delta] \quad \tau \in \Delta\tau_{LS} \\ C_S\text{-}\ \lambda_S, \rho_S, c_S & \text{for } T_{EL}(\tau) < \quad T_m\text{-}\Delta \qquad \forall\tau > \Delta\tau_{LS} + \tau_L \end{cases}, \quad (1, 4, a)$$

three time intervals for the state of material of each finite element: liquid time [$0 \div \tau_L$]; time of solidification $\Delta\boldsymbol{\tau}_{LS}$; time of solid state $\tau > \Delta\tau_{LS} + \tau_L$;

$$\lambda_M, \rho_M, c_M \text{ for } T_{EL}(\tau)\ \forall\tau, \quad (1, 4, b)$$

-the function of the heat source is approximated by δ-type function

$$S_F(T) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{T-T_m}{\sigma}\right)^2} \text{ at } (T\text{-}T_m) \in \Delta T(\tau) = [T_m\text{-}\Delta,\ T_m+\Delta], \quad (1, 5)$$

and the condition

$$\int_{T_m-\Delta}^{T_m+\Delta} S_F(T)dT = 1 \quad \Leftrightarrow \quad erf\left(\frac{\Delta}{\sigma}\right) \text{ and at } \frac{\Delta}{\sigma} > 2. \quad (1, 5, 1)$$

Here of the open thermodynamics system (OTS) we have: the heat coefficients λ, c, ρ – thermal conductivity, heat capacity and density for the cast (C) and mold (M); L and S – liquid and solid parts of pure Al; x, y, z – coordinates of (OTS); α_W and $\alpha_{\Gamma M}$ are heat transfer coefficients at the work (*W*) and external (*Γ*) surfaces of the mold; T_m – temperature of firs-order phase transition; $T\text{-}T_m$ – temperature interval of T_m; σ – dispersion of the function S_F; Δ is the associated temperature interval with S_F; $T_{Env.}$ is temperature of environment; $V_{OTS} = V_C + V_M$ is of the sum of cast and mold volumes.

2.1 Technological solidification methodology on the base on [4, 5, 6, 7 and 8] and Fig.2

1. 1D Stefan-Schwartz and termo-elastic tasks are solved in [4], but here we not solved thermo-elastic task, and only solved Stefan-Schwarz's 3D task; **2.** The filling process of the cavity mold is not accounted; **3.** Apply the same (thermal resistances at the work (*W*) and external (*Γ*) surfaces of the mold) i. e. by a heat transfer coefficient $\alpha_W = const_W$ at (*W*) and $\alpha_\Gamma = const_\Gamma$ at (*Γ*) and with condition $\alpha_W \neq \alpha_\Gamma$; **4.** For the real coefficient of heat transfer in [5] we here prepare identification based on works [6 and 7].

I. The information gathered from many experiments is the basis of mathematical models for the Institute's needs. Mathematical models were captured in the 3D case for all of the foundry machines created in our institute.

II. Measurement of the non-stationary phase transition temperature field of first order (solidification) with thermocouples placed in the open thermodynamic system (OTC) cylindrical cast|press-mold (Fig. 2). The use of thermocouples and other sensors in a pressurized volume has been a major challenge, creating an interesting scientific technology.

III. For works [4, 5, 6 and 7] a methodology and developed technology for fundamental physics experiments in counter-pressure die-casting was developed. In Fig. 2 a) is presented the basic idea of fundamental physical experiments on a gas-pressure casting machine VP-type; Fig. 2 b) is the closed chamber system of the mold/press-mold thermodynamic system and the furnace of the machine and the molten pure Al crucible; In Fig. 2 c) show the spatial points of the thermocouple peaks;

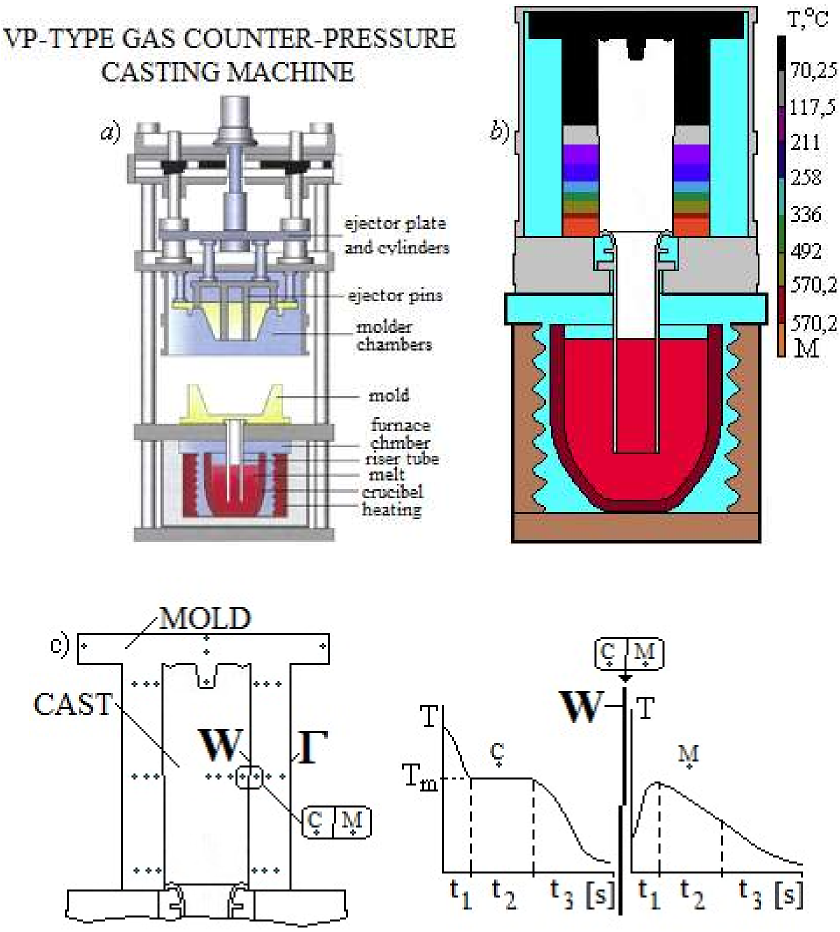
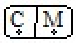


Fig. 2. General geometric scheme of the methodology and technology for fundamental physical experiments in open thermodynamics system (OTS) of cylindrical CAST, MOLD.

Fig. 2. shows general geometric scheme of the methodology and technology for fundamental physical experiments in open thermodynamics system (OTS) of cylindrical CAST, MOLD.
Methodology – measurement of 3D temperature field of the first-order phase transition: 1. the filling process of the cavity mold with liquids of pure metal or Alloy;
a) VP-type gas counter-pressure casting machine. We use the created fundamental methodological, technological and manufacturing experience;
b) Geometrical scheme of the physical experiment: Geometric bodies for fundamental experiments in foundry are: plate, cylinder and sphere. In the figure we present our choice – a cylindrical cast. An important point is the mathematical experiment based on precisely constructed mathematical models (Stefan Schwarz's 3D task (1)). It is known that the technological factor in the foundry is *the initial temperature field of the press-form and thermal resistance at the work surface W. A mathematical experiment is a major tool for developing and modifying technological processes*. In the foundry the main process is the phase transition from the first genus, creating the structure of the new solid phase;
c) A fundamental experiment in the foundry is the study of the temperature field of a first-order phase transition at the macro level; ++++ +++ – thermocouples are used for this purpose. The figure to point at the center of the cross are given places of the tops of thermocouples. Other sensors are also used, which we do not consider here. The information about casting formation is the thermocouples in the mold cavity. Each thermocouple is recorded continuously and a time-temperature curve is obtained with three consecutive time intervals: 1 – change in the temperature of the liquid phase; 2 – retention at the melting point until the end of the first-order

phase transition; 3 – cooling the solid phase. The more thermocouples are in the cast, the more informative the experiment is. Important possibility for identification of the local thermal resistance at the surface W is shown by .

2.2 Mathematical experiment in Foundry

The basic mathematical experiment of foundry is presented in Fig. 3

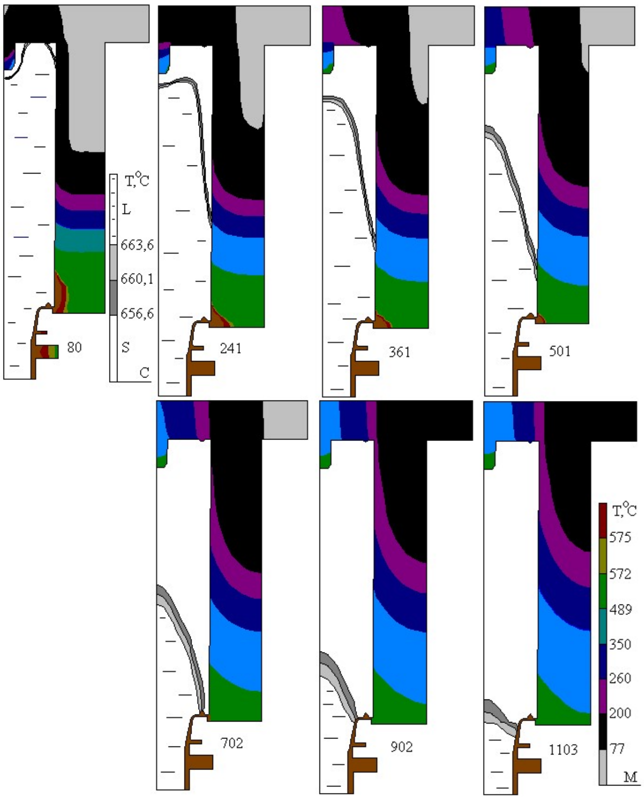


Fig. 3. Mathematical experiments on the base of mathematical model of the theory of heat conductivity Stefan-Schwartz's 3D problem in physics and engineering Foundry. Initial temperature field is show on (Fig.2 *b*) and with simple condition $\alpha_W = const_W$ at (*W*) and $\alpha_\Gamma = const_\Gamma$ at (Γ) and with condition $\alpha_W \neq \alpha_\Gamma$. Technological process of solidification is obtained through *the initial temperature field* of the press mold.

Description of the physical first-order phase transition process at the macro level on Fig.3 is clearly reveals the possibilities for mathematical experiment foundries. Using the possibilities of the mathematical experiment in the gas-pressure casting method is more than necessary. The description of the interfacial boundary surface is necessarily to describe their geometry, which is related to physics, the *equilibrium temperature* is influenced by the curvature. This connectivity is represented by Stefan's well known classical boundary condition

$$\rho Q_m V_n = \lambda_S \frac{\partial T}{\partial n_{|S}} - \lambda_L \frac{\partial T}{\partial n_{|L}},$$

and the Clapeyron-Clausius equation (see CCE) as [12, 13 and 14]

$$\frac{\rho Q_m (T_m - T_e)}{T_m} = \gamma_{SL} \nabla \cdot \underline{n},$$

where T_e is set to the adjusted equilibrium temperature, which takes into account the differences in pressure and density; γ_{SL} is the difference in energy (deposited material)/matrix; $\nabla \cdot n$ is the local curvature.

Conclusion

The article introduced a mathematical framework for the use of mathematical experiments in the Gas Pressing Method (GP) and with different methodological approaches.

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