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Use of Low Vacuum for High Pressure Casting

Nikolai YACHKOV, Jordan GEORGIEV, Anna MANEVA, Stefan BUSHEV

Institute of Metal Science, Equipment and Technologies
with Hydro- and Aerodynamics Center „Acad. A. Balevski",
Bulgarian Academy of Sciences, Sofia, Bulgaria
e-mail: iatchkov@abv.bg, anna13@abv.bg, stbushev@abv.bg

Abstract
In this work, an experimental circuit for the use of vacuum is used to fill the cavity of the casting mold under the conditions of high pressure casting. The resulting castings have a good replica surface and a higher density. A mathematical model of Stephen-Schwartz's task to assess the temperature field of a solidification droplet on metal substratum.

Keywords: vacuum, feelin, high pressure, experimental schema, solidification of droplet on metal substratum

1. Introduction

Basic definitions of A. Balevski in [1]:

Metal science is a science of the relationship between structure and properties, as well as the influence that thermal, mechanical and other impacts have on the structure and properties of metals and alloys. (A, MS)

Such a combination of mechanical and technological (and in some cases, physical and chemical) properties, which no pure metal possesses, whatever mechanical and thermal treatment it is subjected to; (A, 1)

Such a combination of mechanical and technological (and in some cases physical and chemical) properties, which does not have any cast of pure metal, regardless of the mechanical and thermal treatments it undergoes. (A, 2)

The structure of metals and alloys is: an ideal crystal lattice, but defects are polycrystalline (grains – diameter, orientation) and carry the working properties (A, 1, 2). (A, 3)

The processes of elastic and plastic deformation influence on the polycrystalline structure of metals and alloys. S. Vodenicharov makes an extended definition of toughness [4]:

Toughness – the ability of the metal structure (construction) to resist dynamic impact loads with one or several overcutя generating stresses; Measure – the amount of energy needed to destroy a sample body at a given temperature; Two types of toughness: with cut and toughness against destruction of a monolithic body. (A, 4)

The structure is obtained in the fundamentals processes the phase transitions [10]: The phase transition is passing from one phase to another, respectively from one physical state to another. Description of the phase transition under of singularities is introduced of Ehrenfest [11]. Singularities [12] is a term in science that is generally described as a state of unification of certain features of the object under investigation to the extent that the character of the object is radically changed. Types of singularity [12]: Gravitational singularity – a point of zero volume and of infinite density; Mathematical singularity – a state in which a mathematical object is not defined; Mechanical singularity – position or configuration of a mechanism or machine, from where the subsequent behavior cannot be predicted.

Each physical state is related to any of the four main types of forces in nature: 1. Gravitational interaction is the weakest, it connects individual parts of the planet, planets and stars in a system, stars in galaxies; large-scale events in the universe; 2. Electromagnetic interaction holds electrons in atoms, connects atoms to molecules and crystals; 3. The strong interaction, connects nucleons, unites protons and neutrons in the nuclei of all chemical elements, acts at very small distances, i.e. the predominant kind of interaction in nuclear physics and high energies; 4. Low interaction, acts between light particles and does not create a steady state.

The physical state of matter is determined by the structure that carries the working properties of the substance. The most common aggregate states are: solid, liquid, gas and plasma. Other aggregate states are known: 1. Quark-gluon plasma, exists at extremely high temperature and/or density; 2. Bose-Einstein Condensation: occurs at very low temperatures; the particles have the same: zero velocity, the same mass, energy and charge all other parameters - so the particles are indistinguishable. This is the fifth state of matter – the state of a single super atom.

The phase transitions between physics states are:

$$\text{GAS} \xrightleftharpoons[\text{recombimation}]{\text{ionisation}} \text{PLASMA}$$

$$\text{LIQUID} \xrightleftharpoons[\text{condensation}]{\text{evaporation}} \text{GAS}$$

$$\text{SOLID} \xrightleftharpoons[\text{desublimation}]{\text{sublimation}} \text{GAS}$$

$$\text{SOLID} \xrightleftharpoons[\text{solidification}]{\text{melting}} \text{LIQUID}$$

$$\text{BOSE-EINSTEIN'S CONDESATE} \xrightleftharpoons[\text{decondensation}]{\text{condensation}} \text{SOLID}$$

Fig.1 Physic states and phase transitions.

In the casting has solid and liquid state. Ehrenfest’s classification is of thermodynamics point of view [10÷12]: 1. The first-order phase transition is one in which the first derivatives of thermodynamic potential change in jump; 2. The second-order phase transition is one in which the second derivatives of the thermodynamic potential change jump.

Casting and heat treatment are the economically most advantageous physical processes for producing articles with a particular microstructure, working properties and complex geometry. In the casting phase transition of first order is the transition $Solid \xleftrightarrow{transition} Liquid$ (Fig. 1); the phase transition of second order is $Solid \xleftrightarrow{transition} Solid$ [5] (heat treatment). For economics of Bulgaria the materials science, machine building and electronics are very important branches.

In Bulgarian academy of sciences at Academician Angel Balevski Institute of Metal Science, Equipment and Technologies with Center for Hydro and Aerodynamics, Sofia is developed [3]: *fundamental machine casting branch on the base the invention of Balevski-Dimov: METHOD FOR CASTING UNDER PRESSURE, author's certificate №187/26.01.1961.* An example is the [14]; with this method are cast thick plates [3].

The most common casting method is pneumatic piston machine [6] and have important development of the work [8].

Aim of this work is the use of *vacuum* mold at filling.

2. Vacuum use at filling – material science.

The science fundament of the material science are metal science [1] and solid state physics [2]. The general subject is: the materials work properties are consequence of the structure formation processes [1, 2 and 6]. For this reason the fundamental physicals and technological processes of the material science are: phase transition of firs order (casting) and phase transition of second order.

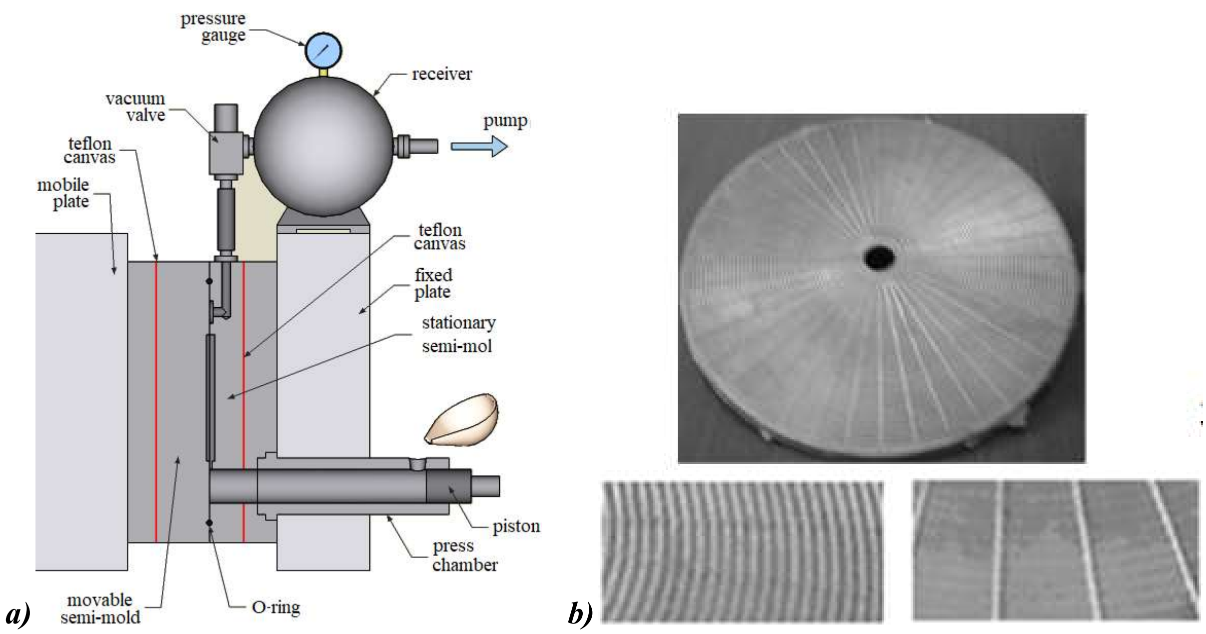
In the specific casting conditions of standard pneumatic piston machine [8] used of vacuum is at the filling process for reducing and removing the gases from the mold cavity. Vacuuming achieves: reduction of gas porosity especially in thick casting places; improved copy of the surface of the parts and dimensional accuracy without chip breaking; production of aluminum alloys with a thickness of 0,6 to 1 mm. The use of vacuum prolongs the process and is used for aluminum castings requiring: thinner walls; high quality casting surface and polishing; need for additional heat treatment; welding of aluminum castings.

The vacuum technology is on the basis of vacuum physics [13]; and in SI unite is [13]: 1 torr = 133 Pa (= 133 Nm^{-2}) and 760 torr = 101,325 Pa = a standard atmosphere pressure.

Table 1. Vacuum types distributed at intervals [13].

VACUUM	PRESSURE [mbar]
Low (rough)	Atmospheric pressure to 1 mbar
Medium	1 to 10^{-3} mbar
High (HV)	10^{-3} 10^{-8} mbar
Ultrahigh (UHV)	10^{-8} 10^{-10} mbar
Extreme high (EHV)	Less than 10^{-10} mbar

In [8] was used low (rough) vacuum 0,2÷0,3 mbar. This is a general force P that is represented by Zhukovsky's formula: $P = C\rho_L f_{Mech.} V_{max}^2 2^{-1}$ $P = C\rho_L f_{Mech.} V_{max}^2 2^{-1}$, where C – geometric coefficient equal to 1/3 of the gas bubble; ρ_L – metal melt density; $f_{Mech.}$ – the cross-sectional area of the bubble in the ejection plane; V_{max} is maximum speed the cross section of the flow [8]. The experimental schema is [8] on Fig.2:



C) 1  2  3 

Fig.2 Experimental schema Vacuum in filling of MB-250 and view of cast and surface details [8 and 15]: a) The scheme is executed on a machine MB 250 - the receiver and control valves are mounted on the fixed plate, allowing the shortest distance between the mold and the receiver. For connection is used a special vacuum hose; b) Ripple plate type casting with surface details for pressing abrasive discs standard casting under high pressure [15]; c) Different feeling velocity [8]: 1 – min; 2 – middle; 3 – turbulent.

The facility (Fig. 2a) [8] provided a necessary and controlled vacuum; the vacuum reduces the filling speed, improve appearance and quality of castings; improves appearance and quality of castings; quality castings may be of less thickness, mechanical properties have been improved, the stabilization of the mechanical properties in small limits significantly improves the overall structural strength of the parts. The comparative analysis between the castings (Figures 2b and 2c) presents the influence of the vacuum factor on the high pressure casting process.

3. Material science – theory of phase transitionof macro-level and casting methodology.

The casting methodology on the base of work [6] and influence on the phase transition of first order of macro-level solidification. The base inters is the quality (A, MS, 1÷4) polycrystalline structure which develop of classical Taman's criterion K in the view of [1] and the law of the square root X:

$$\text{К} = f(\text{КР}/\text{КЦ}) \text{ and } \text{X} = \text{К}\sqrt{\tau}, \qquad (\text{К, X})$$

where K is the crystal size; КЦ is the rate of formation of crystallization centers; КР is the rate of crystal growth with increasing degree of overcooling; X, K and τ are solidification size, coefficient of solidification and time. The scheme of the grains formation in freezing metal is the classical crystallization theory introduced on (p. 25, Fig. 25 [1]).
Schema of Flemings [6] heat balans (heat out = heat to, (HB)) movable elementary volume v_{el} in the flow of liquid metal with heat capacitance c_L, density ρ_L and coefficient α of heat to

$$\left\langle Heat\ from\ v_{el}^L = heat\ to\ v_{el}^L \,\middle|\, c_L \rho_L v_{el}^L \dot{T} = -\alpha(T - T_m) s_{el}^L \right\rangle, \qquad (\text{HB})$$

where T is temperature; $\dot{T}$ is time derivative of temperature; T_m is temperature of melting (melting point). Some notes – we present important parameters and formulas about (K, X), we present important formulas, grouped by the labels as follows: for the processes (K, X) we have thermodynamic driving force (TDF) like (K, X, LTS); (K, X, Move v_{el}^L) is moving of liquid volume with processes (K, X); Base parameters: dimensionless overcooling ΔU, local time of solidification t_f, the time t_r to pass the liquid volume v_{el}^L of road with velocity v, measure for the flow of liquid metal L_f, t_l – swirl distraction time, the criteria of Graskov (Gr), Prandtl (Pr) and Hartmann (M); Formulas are in a *methodological order*: ΔU, t_f, t_r,, t_l, Gr, Pr, M and Dates:

$$\Delta U = (c_S \Delta T)/Q_m, \qquad (\text{К, X, TDF})$$

$$t_f = \Delta T_S / GR, \qquad (\text{К, X, LTS})$$

$$t_r = l/v,$$ (К, X, Move v_{el}^L)

$$t_{f|vol} = (\rho_S Q_m S)/[2\alpha(T_M - T_m)],$$ (К, X, v_{el}^L)

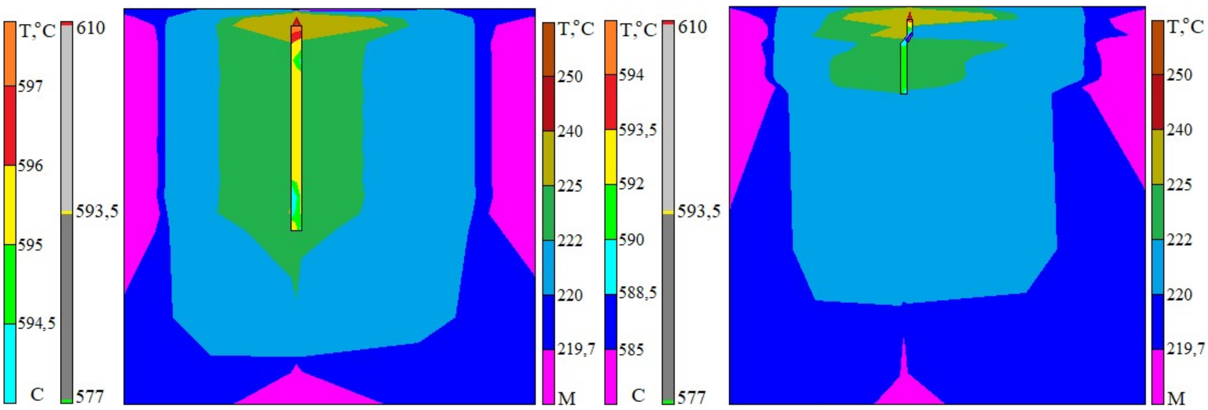
$$L_f = \rho_S S\left(Q_m + Q_{suph}^{melt}\right)/[2\alpha(T_M - T_m)],$$ (К, X, L_f)

$$Gr = g\beta\Delta T L^3 v^{-1}, Pr = \mu c_p v^{-2} = va^{-1} \mathrm{Pr} = \mu c_p v^2 = va^{-1},$$ (К, X, Gr, Pr)

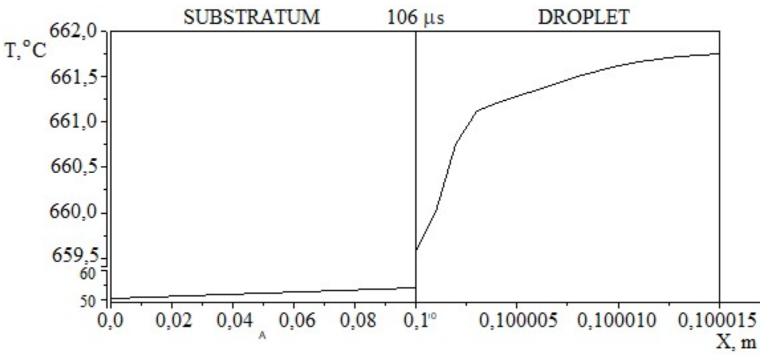
$$M = BL\sqrt[2]{\sigma/\mu},$$ (К, X, M)

$$R_a = GrPr,\ R_a \le 10^8,\ R_a > 10^8,\ M\ is \gg 1,$$ (X, К, Dates)

where Q_{suph}^{melt} is melt superheated; Q_m is latent heat of melting; c_S is coefficient of heat capacitance of solid phase; ρ_S is density of solid phase; ΔT is undercooling; ΔT_S – temperature interval of non-equilibrium solidification; G is temperature gradient; R is growth velocity; (GR) is velocity of cooling; l is distance of displacement with velocity v; S is cross section; L is characteristic length; g is acceleration of gravity; β is thermal coefficient of volume changes; c_p – relative heat capacity at constant pressure; ν – coefficient of kinematic viscosity; B – magnitude of the magnetic field; μ – dynamic viscosity; σ – electrical conductivity. $\partial g_L/\partial C_L = -(1-\beta)/(1-k)\,[1 + (v\nabla T)/\varepsilon](g_L/C_L)$First technology interest is keeping of max part of Q_{suph}^{melt} after feeling like ideal case or the based case feeling before the start of solidification. The mathematical model of Stefan-Schwartz of work [15] is shown the feeling of ripple plate with max size (see Fig. 2). On Fig. 3a are shown numerical results temperature field of solidification of Ripple plate (see Fig. 2) with sizemax and sizemin to compare; and on Fig. 3b is shown temperature field of solidification droplet on the substratum:



a) solidification (size MAX ;size MIN) in the moment of time t = 0,8 s; date: T_{cast}^0 = 640° C, T_{Mold}^0 = 220° C; $\alpha_{C|M}$ =2800 w/m2 K; α_M =25 w/m2 K; cast: λ_S =209,275 w/m K, λL =104,675 w/m K; c_S =1130,085 J/kg K, c_L =1088,23 J/kg K; ρ_S =2540 kg/m^3, ρ_S =2380 kg/m^3, Q_m = 401819 J/kg, T_S =577o C, T_L =610° C; mold: λ_M =54,28 w/m K; c_M =486 J/kg K; ρ_M = 7900 kg/m^3; date: T_{cast}^0 = 760,1° C, T_{Mold}^0 = 50° C; $\alpha_{Sub|Drop}$ =56000 w/m^3 K; λ_S =209,275 w/m K, λ_L = 104,675; c_S =1130,085 J/kg K, c_L =1088,23 J/kg K; ρ_S =2540 kg/m^3, ρ_L = 2380 kg/m^3, Q_m = 401819.J/kg K, T_m=660,1 ° C, λ_M =385 w/m K; c_M = 1090 J/kg K; ρ_M = 8930 kg/m^3;



b) Temperature field – solidification of droplet from pure Al on the substratum from pure Cu at different scales for convention;

Fig.3 Numerical results of solidification ripple plates with max and min size and droplet.

The results on Fig. 3 introduce the possibility of the mathematical model for mathematical experiments. We use not commercial products develop in our institute. Computational mathematics and physics is develop and covered all fundamental science fields. In our institute is work also with MAGMA soft which has been perfected in recent years 1996-2017 [24]. Perfection is most often a complicated process than creating a new computing product. Improvement is: Development of mathematics and computational mathematics; Development of mathematical physics and theoretical physics; Estimates for the use of new fundamental results: for fundamental research or for applied research. For example, work [19] presents the precise development and application of the method of mathematical experimentation in various fields: metallurgy, laser physics, ecology and finance.

It is well known, that the polycrystalline structure is carrying the working properties of the castings (see Fig.2). The local solidification (crystallization) time LCT with the DAS analysis by the formula: **LCT[s] = (DAS[μm]/10)^3**; and acceptable deviation work properties (WP): δ ≥ (Rp02 [MPa]; Rm [MPa]; A5 [%]; HB [MPa]); and local scale $\boldsymbol{l_{scale}}$ **[μm]** → number pixels ⇔ 1 pixel [μm] are experimental technological data (ETD)

LCT[s], δ and l_{scale}. (K, X, ETD)

The scheme in Fig. 2*a* provides **vacuum and pressure** in high pressure casting [8]. The coefficient of heat transfer at the surface mold/cast decreases significantly in the conditions of low vacuum. At the contact melt/mold it is α = 1100 w/m^2 K but the same coefficient of atmospheric pressure is α = 3000 w/m^2·K [15]. The solidification interval is [577^o÷610^o·C] but in that moment temperature is smaller in the max and min size of cast (see Fig. 3*a*). The result of Fig. 3b is very important because it represents the capabilities of the mathematical model – solidification of a droplet of X=0,02m, Y=0,01m, Z=0,000015m on a substratum of X=0,02m, Y=0,01m, Z=0,1m thickness. (K, X, ETD) give the scale with which is prepared to use a numerical network for the Stefan-Schwarz problem in 3D space. Thus, we can use developed interaction of: non-commercial software in our institute [15, 16] and commercial products MAGMASOFT [27] and the new knowledge [11, 13, 17, 20, 21, 22, 23].

4. Industry 4.0 – material science and knowledge

The Industry 4.0 [28] is technological revolution without asking; or like change of paradigm (Kuhn); revolution is connect with substantially new knowledge in relation to: problem (staging), idea, approach (method), principle, object, result [25]. Paradigm: generally means a pattern (model) of thinking – specifically in a scientific discipline or in another epistemological

context; Epistemology: origin scope and peculiarities of knowledge; Ontology: research and understanding of the being, reality, and being in general. Heuristics is understood both as approach and as teaching [24]. We adopt for [8] a detailed and critical scientific approach to developing a new theoretical or mathematical model based on [11, 24 and 25] on Fig.4: I) Paradigm $\xleftrightarrow{complex}$ $\overset{\text{complex}}{\longleftrightarrow}$Epistemology $\xleftrightarrow{complex}$ $\overset{\text{complex}}{\longleftrightarrow}$Ontology;
II) Heuristics↔Multi-scale↔Mathematical Logical↔Mathematics ↔Physics; III) Defining the open physical system (OPS)↔New theoretical or mathematical model, where $\xleftrightarrow{complex}$ $\overset{\text{complex}}{\longleftrightarrow}$ means complex interaction (singularity, probability, and stochastics); ↔ means complex interaction (with evaluation of singularity, probability, and stochastics).

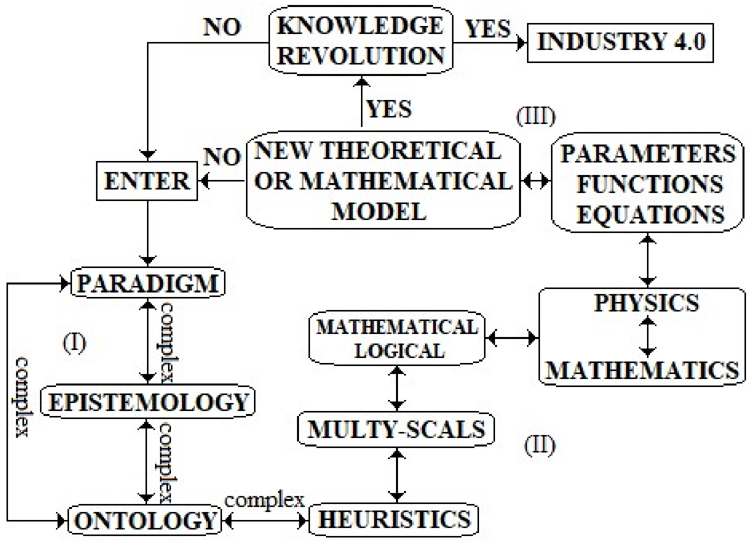


Fig. 4 Bloc diagram of complex methodology – Detailed and critical scientific approach to developing a new theoretical or mathematical mode based on [11, 24, 25, 26], where $\xleftrightarrow{complex}$ is complex interactions (singularity, probability and stochastics); ↔ is complex interaction (with evaluations of singularity, probability and stochastic): I. Model of thinking (Paradigm); Origin scope and peculiarities of knowledge (Epistemology); Research and understanding of the whole reality (Ontology); II. Heuristics is understood both as approach and as teaching; Multy-scales is description at different scales: macro-scale km ≥ l ≥ 1μm, nano-scale 1μm > l ≥ 1nm, Å-scale 1 nm > l ≥ Å; mathematical logical: axioms, prove of lemmas and theorems; Pure mathematics, interaction mathematics and physics and mathematical and theoretical physics; III. Definitions of Open physical system: parameters, functions, equations and mathematical fields; New theoretical or mathematical model; Evaluation of the new theory or mathematical theory or model of revolutionary new knowledge, which is necessary of the Industry 4.0.

The first-order phase transition is represented by the Taman criteria and the task of Stephen-Schwarz and interacts with the methodology of [6] for the filling processes of the casting mold cavity which is represented only by the indications of the corresponding equations with the following scheme:
It is well known, that vacuum decrease the coefficient of heat transfer α at the work surface of the mold [16]. The result of Fig. 3 *b* is complement of the works [15 and 16]. The general description of phase transition of first order is Stefan-Schwartz's tasks (see Fig. 2): 1. For the full volume of the cast and mold; 2. For the minimal volume of the cast according of concrete scale.

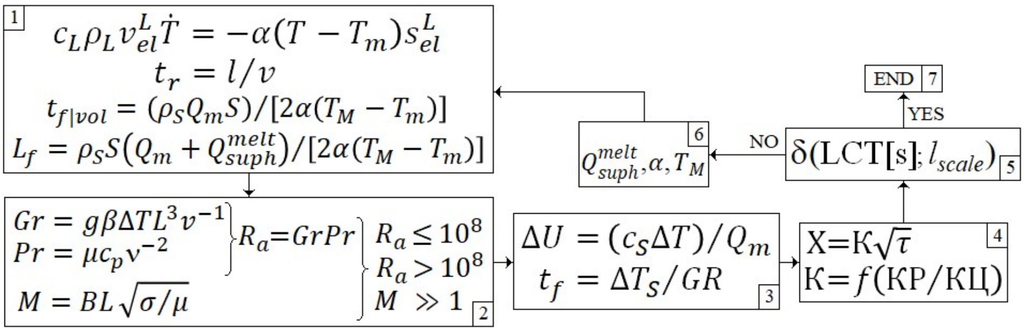


Fig. 5 Bloc diagrams of local (in volume of droplet v) solution by the micro- Stefan-Schwartz problem (see Fig. 3 b) in the feeling with vacuum before applied of high Pressure: 1 – base equations (see & 3); 2 type conditions of hydrodynamics; 3 – thermodynamics driving force for local time of phase transition of 1-st order; 4 – solidification and crystallization; 5 – deviation of local micro-structure and scale (work properties); 6 – change the control parameters; 7 – finished analyze (or product (cast)). Here the volume of droplet v_{el}^L is our open physical system.

In [10] is discuss Ehrenfest classification according singularity [12] of the phase transitions from modern point of view. The historically analyze show, that the classification and description of the phase transitions is need from great part of modern knowledge. The study metals and alloys properties in the metals physics is reason to creating of quantum mechanics for description the connection structure – properties. Today the physics of metals is obligatory subject in the university [9]. The metal science [1] and the solid state physics [2] are complement one another methodologically for example the alloys (solution of inculcate and replacement) are described atomic point of view with quantum mechanics. In [7] the theoretical model of structure formation in the casting process is on the base of classical theory of crystallization and Stefan-Schwartz's task. The modern theory of quantum solids matter [17] is applied like general theory of phase transition, electrons in metals, strong electron correlation and many other interesting science areas. In work [21] the condense matter physics is introduced like a theoretical laboratory for investigation of the quantum physics and the statistical physics. The author sees the physics of condensed matter as an infinite playground for physicists to explore strange quantum and statistical effects. At work [22], the author views solid state physics as the condensed matter physics and as the greatest achievement since the discovery of quantum mechanics. The properties of materials and, more generally, systems with multilevel freedom from fundamental to technological applications are determinants of solid state physics as the largest physics. The solid state physics (or condense matter physics) has contributed most to the technological development of the industrialized countries. Contemporary metallurgy expands with a related subject Material Science and Engineering [23]; quantum theory is introduced in a classical approach with modern results and knowledge. Understanding [17, 21, 22] that the condensed substance (solids) consists of atomic nuclei (ions) located in a regular (elastic) lattice and electrons is the reason to introduce Hamiltonians describing nuclei and electrons. We combine the ideas from [17, 18, 19, 20] with the ideas from [17, 21, 22, 23] we accept the methodologically schema:

3D Stefan-Schwartz task – Modern numerical methods – Quantum theory – Theory quantum solids.

In the above methodologically schemes it is important for our institute to be used in parallel with MAGMASOFT a commercial software product for the quantum theory of solid state for example CASTEP. CASTEP is also interesting in computing replica of materials in non-destructive control.

Regardless of the use of commercial software, knowledge is developed through mathematics, mathematical physics, computational mathematics and physics. This determines the enormous variety of computing products created on the basis of the commercial software needed for the new Revolution Industry 4.0 (28).

Conclusions

An experimental scheme was developed for the use of low vacuum for high pressure casting. The resulting castings have a very good surface impression and higher density.
3D Mathematical model of phase transition of first order by combine Stefan-Schwartz problem with different max- and min-scales (droplet).
The modern scientific investigation require to work with full knowledge, which complicate the methodology of the scientific research.

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