SOLIDIFICATION ON SURFACE

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Abstract: This article uses mathematical mathematical models of tasks by Stefan and Stefan-Schwarz describing the technologies of IMSCHA "Acad. A. Balevski ". Described are processes for solidifying a drop (droplet) over a surface of a metal substrate. Processes of solidifying of metal melts in the form of spheres having a radius of 50 nm are described. The temperature fields of the open thermodynamic system drop / substrate system are presented. The influence of the change of specific parameters from the hardening process is represented by the type of the temperature field of the OTS.

Keywords: Stefan and Stefan-Schwartz problem, drop (droplet) on the surface of substrate, temperatures curves

1. Introduction – основен процес

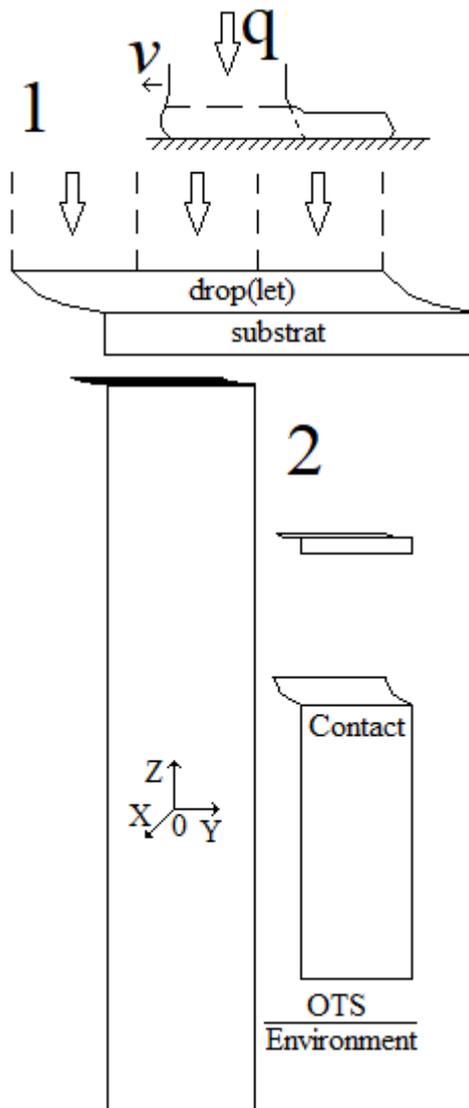In Fig. 1 is shown the solidification on surface process:

Fig. 1 Geometric idea by cross section of the open thermodynamic system (OTS) – drop (let) solidification on surface of the substrate: 1 – Physics: drop and flow of melt, v and q are velocity and stream; 2 – different size of system.

Figure 2 presents our results [20], supplemented by new ones. These are time-temperature curves of solidification of spheres of different materials with a radius R = 50 nm:
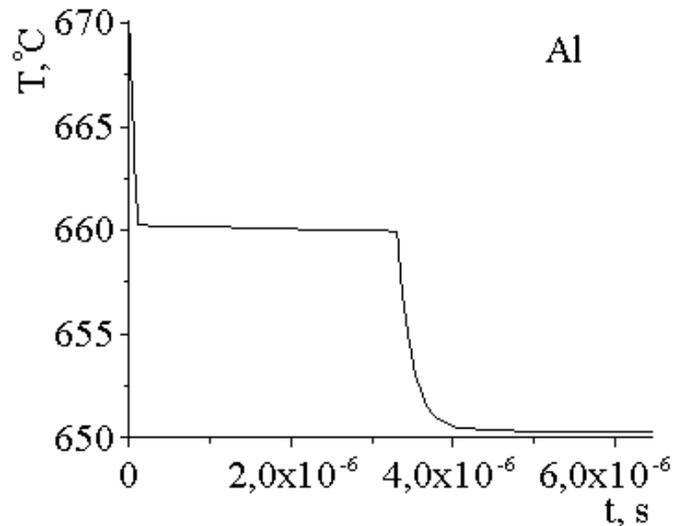

Pure Al: $T_m = 660, 1\,^o\,C$, latent heat of fusion at T_m is $Q_m = 401,819\ kJ/m^3$, heat conductivity $\lambda_S = 209\ w/(m^3.K)$ $\lambda_L = 104.675\ w/(m^3.K)$, heat capacity $c_S = 2540\ kJ/(kg.K)$ $c_L = 2380\ kJ/(kg.K)$, density $\rho_S = 2540\ kg/m^3$, $\rho_L = 2380\ kg/m^3$, index S – solid, index L –liquid;
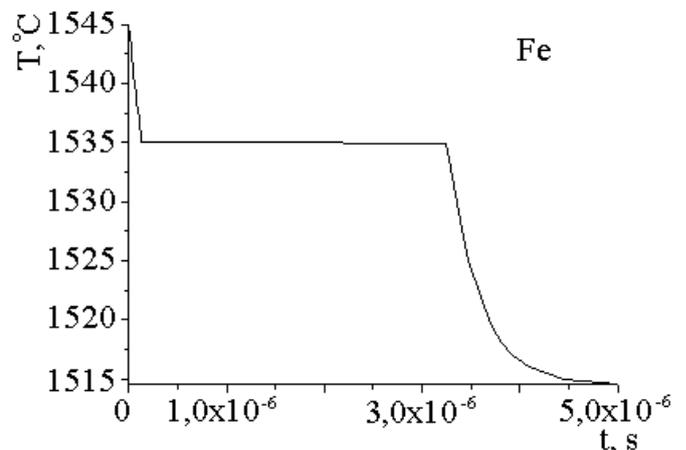
Pure Fe: $T_m = 1535\,^o\,C$, $Q_m = 272\ kJ/m^3$, $\lambda_S = 33\ w/(m^3.K)$ $\lambda_L = 29\ w/(m^3.K)$, $c_S = 447\ kJ/(kg.K)$ $c_L = 800\ kJ/(kg.K)$, $\rho_S = 7400\ kg/m^3$, $\rho_L = 7145\ kg/m^3$;
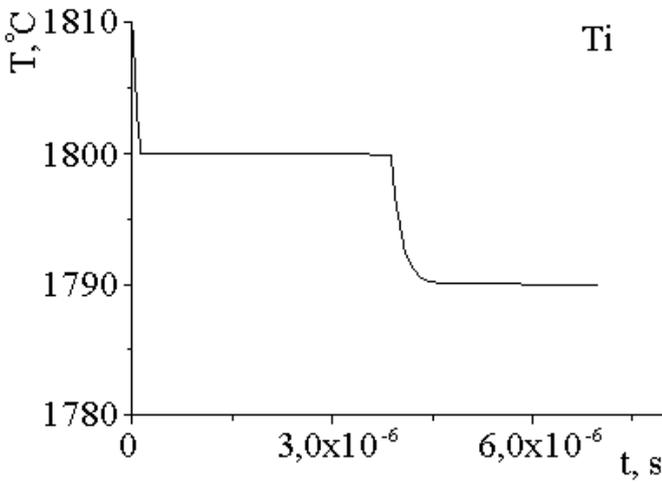
Pure Ti: $T_m = 1800\,^o C$, $Q_m = 376,810\ kJ/m^3$, heat conductivity $\lambda_S = 22.5$ $w/(m^3.K)$ $\lambda_L = 18\ w/(m^3.K)$, heat capacity $c_S = 523\ kJ/(kg.K)$ $c_L = 628$ $kJ/(kg.K)$, density $\rho_S = 4540,6\ kg/m^3$, $\rho_L = 4500\ kg/m^3$, index S – solid, index L –liquid;
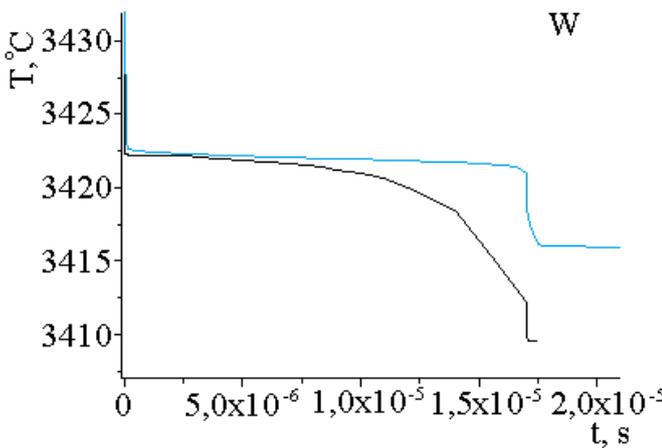
Pure W: $T_m = 3422\,^o C$, $Q_m = 255,390\ kJ/m^3$, $\lambda_S = 196\ w/(m^3.K)$ $\lambda_L = 76,2$ $w/(m^3.K)$, $c_S = 150,7\ kJ/(kg.K)$ $c_L = 152,8\ kJ/(kg.K)$, $\rho_S = 19300\ kg/m^3$, $\rho_L = 19200\ kg/m^3$. Important: the difference between the two curves is due to the precision of defining the parameters of the mathematical model of the heat source in Stephen's task [].
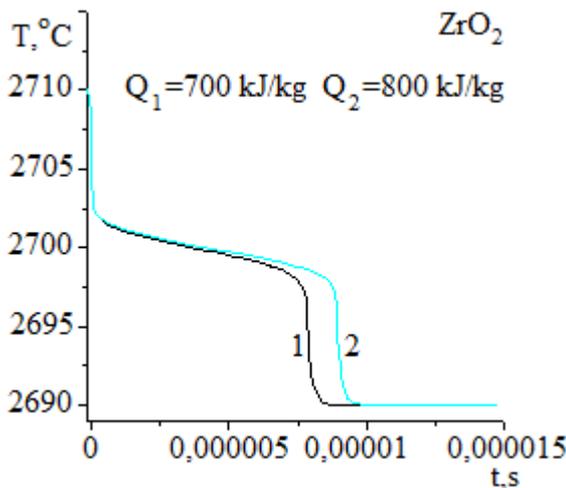
Material ZrO: $T_m = 2700\,^o C$, $Q_m = 700 \div 800\ kJ/m^3$, $\lambda_S = 1.95\ w/(m^3.K)$ $\lambda_L = 2.44\ w/(m^3.K)$, $c_S = 730\ kJ/(kg.K)$ $c_L = 730\ kJ/(kg.K)$, $\rho_S = 3300\ kg/m^3$, $\rho_L = 3200\ kg/m^3$; curve 1 - $Q_m = 700\ kJ/m^3$; 2 – $Q_m = \div 800\ kJ/m^3$ [14].

Fig. 2 *Solidification of different materials – spheres of different materials with a radius R = 50 nm.*

Mathematical models are based on the tasks of Stefan and Stefan-Schwarz, created and realized through non-commercial software products at IMSETCHA "Acad. A. Balevski "BAS [2, 3, 4,

5 and 6]. The process of solidification (phase transition of first order) is fundamental in material science for obtaining structures bearing different working properties of the respective materials [1, 6]. The aim of this work is the calculation process of solidification a drop on different sizes on the surface of a metal substrate.

2. *Numerical solutions - Stefan-Schwarz tasks*

In Fig. 3 are introduced solidification temperature field by Finite elements method (FEM) of this task (see Fig.1):
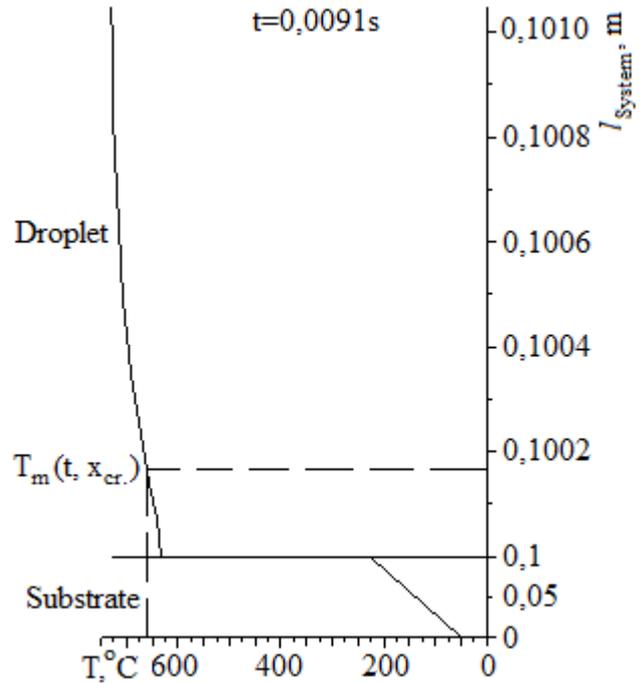
Stefan-Schwartz temperature field: The geometry space of FEM is 3D but the temperature task in the direction of axis 0Z is 1D;
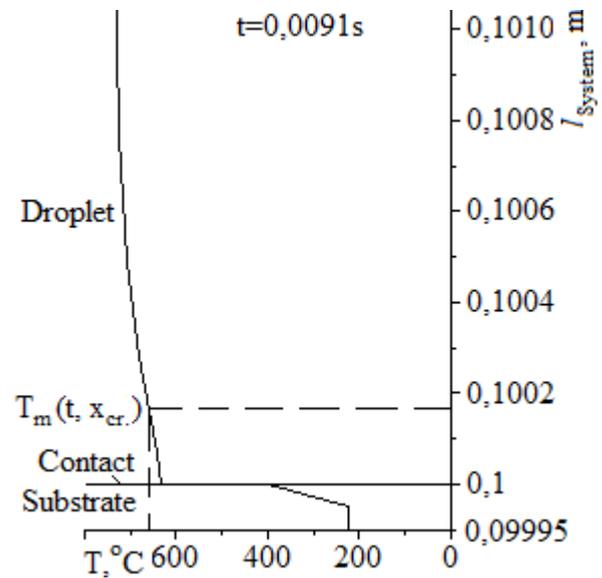
Important: ccontact heat exchange with the temperature difference at the surface of the drop-substrate contact;
Fig. 3 *Stefan-Schwartz temperature great OTS with size (substrate $x_{max}=0,02$, $y_{max}=0,02$, $z_{max}=0,1$) [m] and (drop $x_{max}=0,02$, $y_{max}=0,02$, $z_{max}=0,00105$) [m].*

The results of Fig. 3 present the possibilities of computational mathematics and physics of non-stationary field of solidification (phase transition of first order) on a macro-scale. The technological parameters of the phase transition of first order i.e. the process of formation of the polycrystalline structure on a macro-scale.

The technological parameters of the hardening process are known for a long time or for the phase transition of the first

generation. We choose the parameter: the initial temperature field of the corresponding OTS $T(x, y, z, t = 0)$ and the coefficient of heat transfer at the contact surface α_c (see Fig. 1 and Fig. 2). In Fig. 4 we present the influence of these two parameters on the temperature field of the drop only:
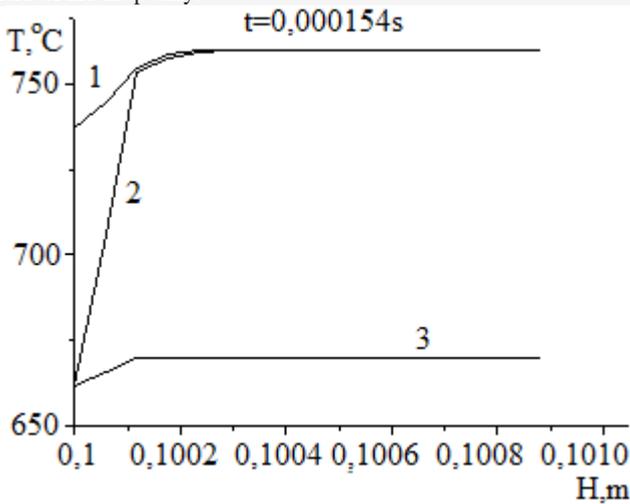

Fig.4 Comparative analysis by the type of temperature field only at the drop by changing the initial melt temperature and by changing the coefficient of contact heat transfer: $T_{drop}(x,y,z,0) = 760, 1\ {}^oC, \alpha_c = 56000\ w/m^2s\ {}^oC;$ 2 $T(x,y,z,0) = 760,1\ {}^oC\ \alpha_c = 560000\ w/m^2s\ {}^oC;$ 3 $T(x,y,z,t=0) = 670,1\ {}^oC\ \alpha_c = 56000\ w/m^2s\ {}^oC.

From Fig. 4 clearly shows the influence on the type of the temperature field at time t = 0 0091s.

The thermophysical properties of the substrate have a definite effect on the phase transition of first order. For this reason, the following figures shows the influence of the temperature field in the droplet and the substrate in a small OTC with dimensions ($x_{max} = 0,00002$ m, $y_{max} = 0,00002$ m, $z_{substrate\ max} = 0,1$ and $z_{droplet} = 0,00105$ m):

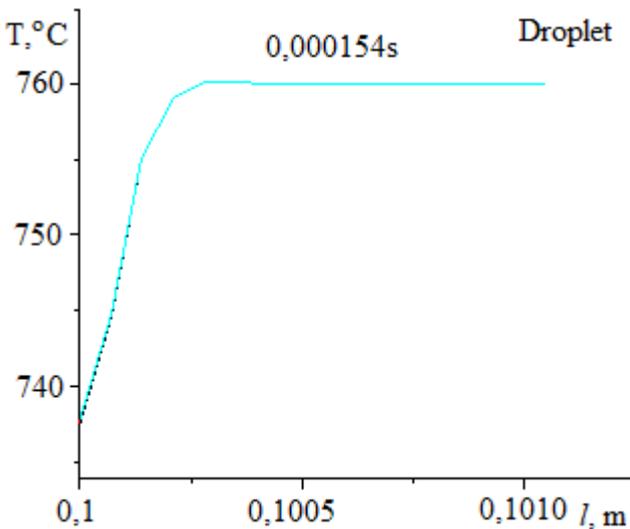*Fig. 5 Temperature fields of the droplet at time t = 0.000154s steel (black line) and aluminum (blue line) substrates. Initial conditions are: $T_{drop}(x, y, z, 0) = 760, 1\ {}^oC, \alpha_c = 56000\ w/m^2s\ {}^oC;$ 2 $T(x, y, z, 0) = 760,1\ {}^oC.$ The minimal effect is very clearly seen even at start time t = 0,000154s.*

Here, we note that the thermophysical parameters of the substrate are part of the macro-level influence parameters.

Important: Your own substrate is related to modern technology called 3DPrinter.

On the following figure 6 presents a comparative analysis of the temperature fields of the OTC in substrates with different heat-physical properties (aluminum and steel substrates):
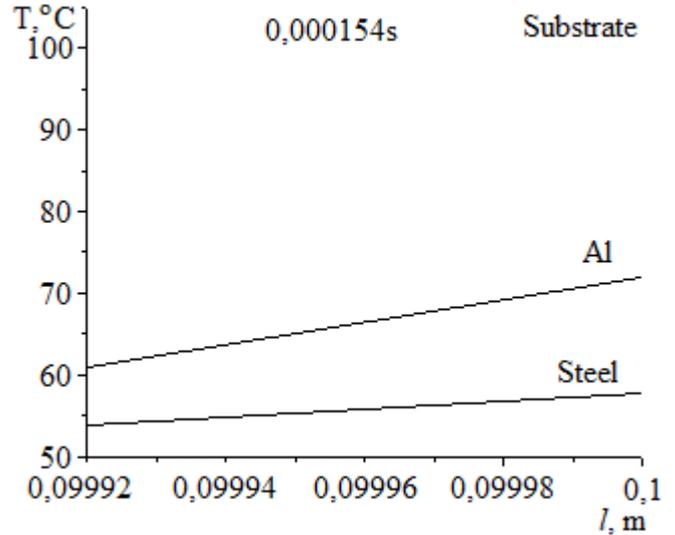

Fig. 6 Comparative analysis of temperature fields in substrates with different thermophysical properties in the case of Al and Steel. Initial conditions are: $T_{drop}(x, y, z, 0) = 760, 1\ {}^oC, \alpha_c = 56000\ w/m^2s\ {}^oC;$ 2 $T(x, y, z, 0) = 760,1\ {}^oC.$ The minimal effect is very clearly seen even at start time t = 0,000154s.

From Fig. 6 shows the significant difference with the direct relationship to the contact heat exchange, namely the influence of the surface temperature of the contact substrate/droplet.

The results obtained relate to different technological processes. Stefan Schwarz's main task allows him to develop as a connecting task with mathematical and mathematical physics tasks. The latter are related to lower levels. These ideas have been developed in various studies by many authors.

Stephen-Schwartz's task is the natural aggregate mathematical approach to describe technological processes in phase transitions of first and secondary order. Material science has evolved as an interdisciplinary field of study [7, 8, 9 and 10]. The next figure presents the multi-scale linking possibility of heat conduction theory and mathematical modeling [2, 3, 4, 5, 6, 11, 12 and 13]:

LEVELS OF DESCRIPTION OF PHASE TRANSITION OF FIRST AND SECONDARY ORDERS
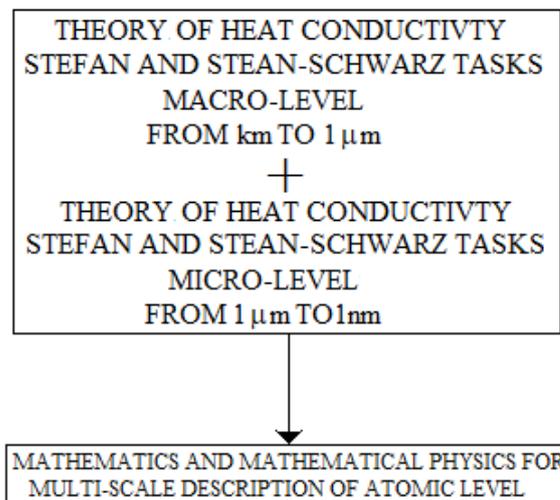
Fig. 7 Multi-scales description of phase transition of first and secondary orders by Stefan-Schwartz tasks + Mathematics and mathematical physics.

According to the principles of material science [7, 8, 9 and 10] and mathematical modeling [2, 3, 4, 5, 6, 11, 12 and 13], a methodology for Basic Knowledge is proposed: Methodology for Basic Knowledge is proposed: 1. General evaluation of the structure (on the meso-level) and the properties of the material; 2. Select a section of mathematics and mathematical physics for multi-scale

description; 3. A specific mathematical model of the structure, with the working properties, the technological process, the work and the life of the material. A very important point is the use of this methodological frame work for the additive capabilities of the 3Dprinter [15, 16 and 17] technology i.e. *3Dprinter interaction with die casting and heat treatment*. 3Dprinter + die casting + heat treatment are an essential task of Industry 4.0 [1]. Mathematical modeling in Industry4.0, in our view, is close to pure mathematics [6]. Such an assumption canal so be accepted on the basis of works [2, 3, 4, 5, 6, 11, 12, 13, 18 and 19]. The 3Dprinter technology has a great application (from food, medicine and weapons) and is an incentive for its mathematical modeling [17 and 18].

Additive manufacturing AM [15] is a concept that covers: casting, separation of metal turning, milling, plastic deformation, welding, forging and electroerosity processing heat treatment. But at the end of the 20th century new technologies for depositing materials such as micro-casting [21] and spraying were developed at Stanford University and Carnegie Mellon University [22]. 3DPrinter modifies the AM concept by expanding its idea of sequentially adding and linking material sequentially, following a three-dimensional profile of the blank, with automated control [15].

Significant results have been achieved with 3D printer technologies [23, 24 and 25]. The reason for the powerful entry of a 3D printer is the good price that falls great convenience to work with full control of the technology. This makes the 3D printer actually leading the Industry 4.0 revolution [1].

3. Conclusions

The obtained results represent the broad application of Stefanov type tasks in macro and nano-scale areas.

4. References

1. K. Schwab, The fourth industrial revolution, Hermes, Plovdiv, 2016. ISBN 978-954-26-1630-6

2. S. Bushev, M. Dimitrov, N. Miloshev, S. Stefanov, N. Stoichev, V. Todorov. Generalized Description of Microphenomena and Processes for Use in Various Technological Systems, Proceedings of Mini-symposium "MICRO-FLOWS" 10th Jubilee National Congress on Theoretical Applied Mechanics, 13 – 16 September, 2005, Bulgaria, 408-413.

3. S. Bushev, N. Stoichev, M. Dimitrov, N. Miloshev, Stefan's problem in modeling the metals rapid solidification, Proc. of Fifth International Congress Mechanical Engineering Technologies'06, September 20-23.2006, Varna, Bulgaria, 8-11.

4. S. Bushev, Computational physics – casting and heat treatment, Proceedings of "Fifth National Conference with International Participation Materials Science, Hydro- and Aerodynamics and National Security'2015", 22-23, October, 2015, Sofia, 170-177, ISSN 1313-8308.

5. S. Bushev, N. Stoichev, N. Miloshev, M. Dimitrov, V. Todorov, Temperature Field and Crystallization During Solidification of Liquids, Journal of Materials Science and Technology, v. 18, 2010, No 4, 228-239.

6. S. Bushev, Industrial mathematics –phase transitions, scattering, structures, Innovations, year V, ISSUE 2/2017, Sofia, 57-63. ISSN PRINT 1314-8907

7. W.D. Callister, Jr., Fundamentals of Materials Science and Engineering, 2001, John Wiley & Sons, Inc., Fifth Edition, CD-ROM. ISBN 0-471-39551-X

8. Materials science -Wikipedia,

https://en.wikipedia.org/wiki/Materials_science

9. Material science,

https://bg.wikipedia.org/wiki/Материалознание (In Bulgarian)

10. The Ten Principles of Material Handling–Material Handling Institute (MHI)

www.mhi.org/downloads/learning/cicmhe/.../10_principles.pdf

11. Mathematical Modeling Handbook II: The Assessments, The Consortium for Mathematics and Its Applications Bedford, MA 01730, 2013, USA,

www.comap.com/product/samples/MHBII-DRAFT.pdf

12 S. Heinz, Mathematical modeling, Springer-Verlag Berlin Heidelberg, 2011.

13. K, Velten, Mathematical Modeling and Simulation: Introduction for Scientists and Engineers, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2009. ISBN: 978-3-527-40758-8

14. *https://www.azom.com/properties.aspx?ArticleID=133*

15. 3DPrinter *www.etiket.bg/bg/news-view/40.html*

16. 3D printers for direct printing in metal (In Bulgarian)

www.spacecad.bg/printeri-za-metal

17. Second National Forum "3D Printing - the Precursor of the 4th Industrial Revolution", March 16, 2017, Sofia, Bulgaria, (In Bulgarian), *www.computerworld.bg/50916_aditivnoto_proizvodstvo_i_3d_pech atat...*

18. I. Akinola, Modelling the Stereo-lithography Process, Electrical Engineering, Stanford University, iakinola@stanford.edu

19 A. Anastasiou at al., 3D Printing: Basic concepts Mathematics and Technolodies... - Semantic Scholar,

https://pdfs.semanticscholar.org/.../7486320e82081935ac20bc...

20. S. Bushev, Material science theory in Industry 4.0 for phase transition technologies, 12th Annual Meeting of the Bulgarian Section of SIAM "BGSIAM'17", December 20.-22, 2017, Sofia, 20-21.

21. C. H. Amon, and al. Shape Deposition Manufacturing With Microcasting: Processing, Thermal and Mechanical Issues. // Journal of Manufacturing Science and Engineering 120 (3). 1998. *https://pdfs.semanticscholar.org/7a7a/6961f6dac7861db7de51e768 0e9990a09e85.pdf*

22. Beck, J.E. и др. Manufacturing Mechatronics Using Thermal Spray Shape Deposition. // Proceedings of the 1992 Solid Freeform Fabrication Symposium. 1992.

https://pdfs.semanticscholar.org/c27c/50c0061aac1b842636cf5d0a d711195f5fb6.pdf

23. Military aircraft "Tornado" with metal parts, printed in 3D, made a successful test flight, www.bnr.bg/.../voenen-samolet-tornado-s-metalni-chasti-otpechatani-s-3d-printer-e-napravil-.

24. General Electric: https://bg.id-forex.com/general-electric-aircraft-engine-on-3d-printer

25. www.geomedia.bg/.../5251-„airbuse"-with-first-in-the-world-aireplkane-printed-of-3d-pr...