DOI: 10.17277/amt.2018.01.pp.022-035

From Information and Additive Technologies to Self-Reproduction of Machines and Organisms

M.L. Kheifetz

Department of Physical-Engineering Sciences, National Academy of Sciences of Belarus, 66 Praspekt Nezavisimasti, Minsk, 220072, Republic of Belarus

Corresponding author: Tel.: +375 (17) 284-03-77; fax: +375 (17) 284-03-75. *E-mail:* mlk-z@mail.ru

Abstract

The analysis of the state and prospects of the development of additive technologies for computer aided manufacturing has been carried out. This analysis allowed demonstrating a new paradigm of computer aided manufacturing evolution – the transition to self-reproduction of machines and their parts, as well as organisms.

A diagram of logical connections in the process of additive manufacturing has been proposed, which is a state machine that can be used to build a 3D printer enabling to "grow" products of complex shapes and structures, as well as for additive synthesis of its composite material.

A prospective approach, considering additive methods as synergetic energy technologies, ensuring self-organization of surface phenomena in the formation of structures of layers of different materials has been developed. It is proposed to use this approach to select sources of energy and material for discrete or continuous process medium of the additive processing method. Conditions for stabilization of the thickness of formed layers related to the processes of self-organization of surface phenomena and design features of products have been discussed.

Keywords

Computerized production; additive technologies; self-reproduction machines; finishing machine; cellular automaton; layered synthesis; synergetic technologies; self-organizing.

As stressed by N. Wiener, K.-E. Shannon and other famous scientists [1, 2], machine analogues of a living organism always reflect the spirit of the times. For many years, automata have been considered as an organism or an idealized machine. The theory of automata does not study their internal structure, but features of external manifestations [3, 4].

Elements of the body or machine are considered as automata if their internal structure is not necessarily open, but they are supposed to respond in certain ways to certain specific stimuli [4].

Finite automata and models of self-reproduction

A "black box" having a finite number of discrete internal states is called a finite automaton. Usually the machine also has a finite number of possible input and output signals, and its state and output signal at any time depends on the state and input signal at the previous time [5].

In terms of logic, an automaton that could perform precisely defined operations, which A.-M. Turing attempted to determine. The Turing machine is a "finite state machine" equipped with an "endless tape" with instructions recorded at its final site [1, 4].

Despite the fact that biological systems are composed of unreliable components, they are highly reliable and capable of self-healing. D. von Neumann showed how to make a machine that would function properly, even if some of its parts failed. This can be achieved by introducing redundancy into the machine, for example, by replacing both one circuit and its elements with several elements connected in parallel [4, 5]. As a result, he assumed that the simplest possible description of the operations peculiar to the brain could be performed in the form of a *diagram* reflecting all its possible connections.

Von Neumann was the first to consider methods of creating *self-reproducing automata*. He showed that if the machine is equipped with the appropriate program of actions and placed in the *environment* consisting of the same parts as the machine itself, then, by searching for the necessary parts, it will ensure self-reproduction [1, 4].

John von Neumann showed in his model of *self-reproduction* how to create a fairly complex machine in a simple environment with a large number of not very diverse parts or with a small number of states. He concluded that the instructions given to the machine how to reproduce itself could not be complete because of logical contradictions. Instructions should describe not only the machine, but also themselves, and there must be a plan for constructing the machine, etc. This can be avoided if we have two machines, each of which treats the construction plan in its own way [1, 4].

Further John von Neumann turned to an abstract mathematical model of a purely logical nature. As a "storage" he chose the environment in the form of a plane divided into square cells. In each such cell, he placed one of the elementary components – a machine with a finite number of states. Such machines have neither inputs nor outputs, but only a certain number of admissible states. Each machine is deterministic and synchronous, and the state of each cell depends on the state of its own and neighboring cells at the previous time [1, 4]. Such a system, consisting of a mosaic space, **cellular machines**, admissible states, transition rules is called *a mosaic structure*. In turn, *a configuration* in the structure is the final block of cells whose states are given.

Within the environment there are **configurations of cells** (square cell structures or cells shaped differently), and they can be made self-reproducing. Cells that are at rest are raw materials, while a cell separated from the whole configuration cannot suddenly activate. The machine "reaches out" to the surrounding raw materials only through local actions. As a result, it all comes down to constructing a mosaic structure of individual cells with a small number of different states, as well as selecting the **transition rules** and the subsequent organization of these cells in a configuration that can reproduce similar ones. The solution of such problems is similar to the compilation of computer programs [4, 6].

To solve them, John von Neumann had each configuration included a universal Turing machine. On this basis, he developed the parts for a self-replicating configuration consisting of a multitude (about 200 thousand) cells with a large but limited number of allowed states (29 was considered) [4, 6].

However, not every configuration can replicate a similar one. There are configurations that cannot occur except for the initial moment, that is, they cannot be produced from other configurations using the specified transition rules. J.W. Tukey proposed the term "Garden of Eden" for blocks of cells that do not have any previous states. Since these configurations *are not reproduced* by any other configurations, they cannot also reproduce themselves [1, 4].

One of the **conditions for the existence** of such configurations is the ability to perform erasing operations. *Erasing* is an irreversible process, from which the present can arise. In the case of a mosaic structure, one must be sure that information relating to past states is actually erased, and not transferred to neighboring states. In mosaic structures, the configuration can be considered erased if there is another such that, together with it, they are mutually erasable. In the mosaic structures possessing erasable configurations, there are configurations of states "Garden of Eden" [1, 4].

The configuration corresponds to a machine that can be described as joining certain parts, but which cannot be created from them. Since this is a machine that cannot be reproduced, it must be a machine that cannot reproduce itself [1, 4, 6].

Purpose and objectives of the study. Thus, the self-reproduction of machines should be considered from the point of view of computerization of production activity, and 3D-printers, printing machines, their units and parts should be designed as computer peripheral devices built on the same architecture as computers.

Therefore, for modeling 3D-printing, first of all, it is necessary to:

1) create a **diagram** of connections in the processes of self-reproduction of products, which is a *finite state machine*;

2) transform the proposed finite state machine into a **cellular machine** with a limited number of *states and transition rules*;

3) form **configurations from cells** of the final block of cellular machines for various processes of self-reproduction of items;

4) consider the *mosaic structures* formed by different cell configurations, depending on their states and **transition rules**;

5) determine *configurations not capable of reproducing themselves* and establish their **conditions of existence** in a mosaic structure.

Additive computer technologies

Modern additive technologies implement a new "*bottom-up*" paradigm proposed by R. Feynman in 1959 instead of or in addition to the "*top-down*" paradigm. The essence of additive technology lies in the laminate synthesis or solid freeform fabrication of products by "digital models" without using a form-building tool. The creation of the product shape occurs by adding material, in contrast to traditional technologies based on the removal of "excess" material [7, 8].

There are two main groups of additive methods: 1) the ones with the "preliminary formation of a layer" of material using Bed Deposition (**BD**) technologies, implying the existence of a certain platform on which the material and product are grown layer-by-layer; 2) "direct deposition of the layer" of the material on the complex surface of the product using Direct Deposition (**DD**) technologies [9, 10].

At present, additive production methods are classified as follows in accordance with ISO / ASTM 52900-15 (ASTM F2792-12a) [7]:

– *Vat Photopolymerization*;
– *Material Jetting*;
– *Material Extrusion*;
– *Powder Bed Fusion*;
– *Binder Jetting*;
– *Sheet Lamination*;
– *Directed Energy Deposition*.

Classifications by the principles of making products without form-building equipment include "traditional" methods created more than 30 years ago [11, 12]:

– *StereoLithography Application* (**SLA**);
– *Solid Ground Curing* (**SGC**);
– *Fused Deposition Modeling* (**FDM**);
– *Selective Laser Sintering* (**SLS**);
– *Direct Shell Part Creation* (**DSPC**);
– *Laminated Object Manufacturing* (**LOM**)

as well as other methods that are not widespread in industry today.

Layered synthesis technologies are widely used in industry worldwide; thus, application of new additive technologies for creating layers and shaping products using different combinations of materials and energy sources is quite promising. This, in turn, sets the task of distributing the components of materials and energy flows not only over a given contour or surface, but also in depth from the surface of the product, as well as by the nature of the pulses of energy and material supply.

Thus, when designing the technology of additive synthesis, both the methods of shaping components from composite materials, using energy flows and material components, and methods of automation and control of operational prototyping and manufacturing processes are used.

Modeling of additive technologies

To denote the processes of additive technologies the following concepts [13, 14]:

– *Solid Freeform Fabrication*;
– *Laminate Synthesis*; *Rapid Prototyping*;
– *3D-Component Forming*

are used.

The following concepts are often associated with additive methods: "direct deposition" (DD-technology) and "bed deposition" (BD-technology), as well as "intermediate" and "final" synthesis of the material of the product. Therefore, the question arises of determining the interrelationship between the processes of forming products and differentiating the concepts used.

For the self-reproduction of objects, according to the von Neumann model [4], the following machines are required: C – "construction plan copyist"; O – "construction plan executor"; S – "starting device" (includes C and O at the appropriate time); B_{C+O+S} – "automaton construction plan" (describes all elements of the model). As a result, the whole automaton is expressed symbolically C+O+S+B_{C+O+S}. After the initial launch, S gets to its disposal the automaton construction plan as a whole B_{C+O+S}, C copies it and O in turn follows it for constructing C, O, and S.

Thus, the procedure is as follows [14, 15]:

– launch (S) is direct access to the flows of matter and energy;
– plan retrieval (B_{C+O+S}) is self-tuning of the reproduction program;
– copying of the plan (C) is transfer of the information flow;
– the construction of the automaton (O) is the self-organization of its structure.

The study of the processes of additive technology as a function of the aggregate state of the initial material, the dimensions of the flows of the forming medium (Table 1), and the sequence of technological operations [16, 17] made it possible to present a set of processes of solid freeform fabrication of products in the form of a logical connection diagram (Fig. 1)

The diagram is a directed closed graph and describes an automaton with a finite number of states [13, 15]. The vertices of the graph represent the processes of additive production of products and

Table 1

Additive technologies for part manufacturing

Operations	Medium dimensions	Formation processes for aggregate states of a process medium		
		Solid	Liquid	Gaseous
1	Δd^{3}	Pressing, sintering of powders and other particles	Formation of layers by cladding, inclusions of molten particles	Formation of layers by implantation and deposition of vapor, gas and plasma
	$d\Delta d^{2}$	Winding, sintering of fibers and wires	Formation of layers by casting, melting of surfaces and coatings	–
1′	Δd^{3}	Layered formation of surfaces with powders and other particles	Layered formation of surfaces with drops of solutions and melts	Layered formation of surfaces by vapor deposition, gas and plasma deposition
	$d\Delta d^{2}$	Layered formation of stackable surfaces with fibers and wires	Layered formation of stackable surfaces by jets of solutions and melts	–
2	$d^{2}\Delta d$	Layered joining of sheet two-dimensional billets from low-melting, burnable materials	Layered surfacing, melting of fusible, fast setting materials	Layer deposition of vapor, gas and plasma streams of low-melting burnable materials
2′	$d^{2}\Delta d$	Layered pressing, sintering of formed shells from materials of a part	Layered casting for models of dissolved and melted materials	Layer deposition of vapor, gas and plasma flows of the material
3	d^{3}	Sintering, welding of formed workpieces	Casting on models of dissolved and melted materials	Deposition and implantation of vapor, gas and plasma materials of the part
4	Δd^{3}	Pressing, sintering of powders and other particles of low-melting, burnable materials	Forming with drops of solutions and melts of low-melting fast-hardening materials	Deposition of vapor, gas and plasma materials of the part
	$d\Delta d^{2}$	Winding, sintering of fibers and fusible wires of burnable materials	Shaping with a jet of solutions and melts of low-melting fast-hardening materials	–
4′	Δd^{3}	Pressing, gluing of powders and other particles to create shell molds	Creation of shell molds by deposition from solution and inclusions of molten particles	Deposition of vapor, gas and plasma to create shell shapes
	$d\Delta d^{2}$	Winding, gluing fibers and wires to create shell molds	Creation of shell molds by a jet of solutions and melts	–
5	$d^{2}\Delta d$	Joining of sheet two-dimensional workpieces, layers from the materials of the part	Dipping, layer-by-layer casting on the surface and melting of the part material	Layer deposition and implantation of vapor, gas and plasma flows of the materials of the part
6	d^{3}	Assembly of three-dimensional workpiece parts	–	

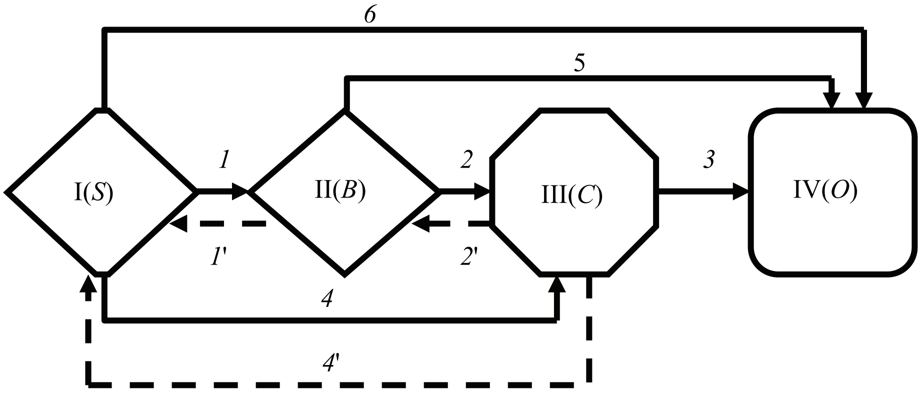

Fig. 1. Diagram of logical connections reflecting the processes of additive production of products

represent logical operations: the translation of information, flows of matter and energy, the start and stop of the automatic cycle.

The graph edges reflect the state changes (*1–6* and *1′*, *2′*, *4′*) of the process medium, and the routes provide various combinations of changes, depending on the choice of the initial process and the order of the subsequent processes.

Thus, different options of technological routes have the form of sequences when they are selected as the initial process (see Fig. 1):

I) Solid Freeform Fabrication: $1 \rightarrow 2 \rightarrow 3$; $4 \rightarrow 3$; $1 \rightarrow 5$; $4 \rightarrow 2' \rightarrow 5$; 6;

II) Laminate Synthesis: $1' \rightarrow 4 \rightarrow 3$; $2 \rightarrow 3$; $1' \rightarrow 6$; $2 \rightarrow 4' \rightarrow 6$; 5;

III) Rapid Prototyping: $2' \rightarrow 1' \rightarrow 6$; $4' \rightarrow 6$; $2' \rightarrow 5$; $4' \rightarrow 1 \rightarrow 5$; 3.

Considering the replacement in the model of the self-reproduction of processes (direct access to the flows of matter and energy, the self-tuning of the program of reproduction, the translation of the information flow, the self-organization of the structure of the automaton) by the providing elements of the technological system (part, tool, adaptation, machine), we conclude that it is impossible to use form-building tooling to create a finite state machine, since for the production of a part there must be equipment, which cannot be manufactured without certain tools, etc. [13, 14].

Thus, algorithms [14, 15], proposed according to the von Neumann self-reproduction model [4], allow describing additive technologies for the creation of products without form-building tools, and their reverse sequences are the technologies that cannot be used as a finite state machine.

In accordance with the existing terms of the processes of additive production algorithms, description of the proposed diagram of logical relationships provides an opportunity to analyze existing methods of solid freeform fabrication of products and develop new ones.

Additive synergistic technologies for laminate synthesis of products

In addition to new hardware and software, advanced technologies are based on laminate synthesis of product surfaces and self-organization of structures of composite materials [15, 17]. Thus, in determining the foundation of knowledge-intensive nanotechnologies, Zh. I. Alferov, in addition to probe microscopy, distinguished *epitaxial growth of films on the surfaces* and material *heterostructures self-assembly* [18].

In addition, the *synergetic concept* involves the limitation of the number of states and rules for their transition in the technological system [19]. Determination of the dominant processes of structure formation under intensive influences is expediently carried out using the concept of mode in distributions of the continuous random variable of the controlled parameter [16]. A mode is understood as a parameter value at which the density of its distribution has a maximum.

According to the synergetic concept, stable modes are adjusted to dominant unstable modes and as a result can be excluded. This leads to a sharp reduction in the number of controlled parameters, and the remaining unstable modes can serve as order parameters that determine the processes of structure formation [15].

Therefore, an approach that considers additive methods as *synergistic technologies* that ensure the self-organization of surface phenomena in the layer-by-layer formation of the surface layer structures from various materials and control of their properties under various physical influences is particularly promising [9, 10].

The self-organization of surface phenomena ensures the stable formation of a layer of a certain thickness with significant changes in the distance from the energy source or the feed material to the surface being formed, and also, as a result of interpenetration, allows the successive layers to be fused [19].

The distance to the surface formed is a particularly sensitive factor in the “direct deposition of the layer” according to DD-technologies, and the change in distance is especially important for stabilizing the thickness in the “preliminary layering” of the material according to BD-technologies, implying the existence of a platform on which the material is layer-by-layer product.

As a result, the choice of the energy source or the feed material in the additive technology determines not only the process medium represented as discrete or continuous, but also the surface phenomena that ensure the processes of self-organization in synergistic technologies [19].

Direct "fabrication" of products by laminate synthesis of the material is possible in various aggregate states – solid, liquid, gaseous, and also in a variety of high-energy processes [15] with a set of distributed, localized and single focused absorption zones [19, 20], depending on the flux density energy (Table 2).

In the process of induction heating with powder coating [21], as well as surfacing by dipping a part in a molten metal, a number of localized or distributed energy absorption zones are located on the entire build-up surface [22]. The thickness of the layer being formed is determined by the adhesion between the melt and the surface of the product. It is described by the speed of the workpiece, the surface tension and the coefficient of internal friction. The maximum thickness of the layer when flowing through the melt of the surface is limited by the conditions of the potential flow and is calculated as the thickness of the boundary layer beyond which the flow is broken down.

In plasma cutting, sputtering and surfacing of metallic powders in the solid state, a distributed energy absorption zone is formed in plasma processes [23]. The thickness of the layer being formed is determined by the combined effect of the kinetic and thermodynamic factors described by the velocity of the powder particles and the thermodynamic potential of the plasma flow; and the formation of the layer is characterized by the ratio between the kinetic and Joule energy of the flow.

In the processes of electroerosive treatment of the surface and electromagnetic surfacing of the powder, many localized energy absorption zones are formed. Electromagnetic surfacing allows for coatings of a certain thickness, after which the layer being formed loses stability, and peaks are formed on the surface, which turn into craters in subsequent discharges [24]. The electromagnetic fluxes allow controlling the surfacing process. Thus, the movement and fixation of the particles of the ferro-powder are determined by the induction of the magnetic field; the intense heat release at the points of contact with the surface formed and the melting of the powder are determined by the strength of the electric field. As a result of the growing resistance of the ferro-powder medium and the electrical conductivity of the applied coating, the thickness of the applied layer is stabilized [19].

Table 2

High-energy processes of layered synthesis of products

Processes of separation and formation of layers	Aggregate state of the applied material	Absorption zones and energy flux density, W/cm^2	Thickness of the layer to be separated and formed, mm
Induction heating with powder sintering and dipping in molten metal	Solid (powder), liquid (melt)	A set of localized, 10^2–10^4; distributed, 10^2–10^4	0.3–3.0 [21, 22]
Plasma cutting, sputtering and surfacing of metallic powders	Solid (powder)	Distributed, $5\cdot10^2$–10^5	0.1–10.0 [23]
Electroerosive treatment and electromagnetic surfacing of powder	Solid (powder)	A set of localized, 10^3–10^5	0.05–0.50 [24]
Laser cutting, surface melting and alloying	Liquid (melt)	Single focused, $5\cdot10^3$–10^7	1–10 (for thermoelectric convection 0.01–1.0) [25]
Electron beam cutting, surface melting and modifying	Liquid (melt)	Single focused, 10^3–10^6	
Ion implantation and deposition	Gaseous	A set of localized, 10^3–10^5	0.002–0.200 [26]

The process of electromagnetic surfacing is determined by electromagnetic and inertial forces and is described by the magnetic interaction of particles and the electric field strength in the working zone.

In laser cutting, surface melting and alloying of the surface layer, it is advisable to consider a single focused energy absorption zone scanned across the entire surface being formed [19]. In radiation treatment as a result of convective instability in a narrow surface layer of a melt of a certain thickness, the dissipative structures consisting of vortices are formed. With sufficiently rapid cooling in such a state, a cellular structure is formed along the crystallization front. The thickness of the altered layer is described by the relationship between the properties of the metal, its surface tension and volume expansion coefficients, and the density in the molten state [25].

In the processes of electron beam cutting, melting and modifying of the surface layer, it is advisable to consider a single focused energy absorption zone. During the crystallization of the material, a cellular structure is also formed in the melt bath [19]. The process of formation of dissipative structures in the melt is determined by the manifestation of thermocapillary phenomena and is associated with the buoyancy lift and the dissipation force in the melt [25, 26].

In the ion implantation and coating deposition from the gaseous state, the ion flux, without focusing, is distributed over the surface of the part, forming a number of localized energy absorption zones. The thickness of the applied coating is determined mainly by the thickness of the layer in which the potential applied to the part effectively affects the ions [24]. This layer is described by the ratio of the electric field potential and the density of plasma ions taking into account their charge and mass. Ions, as a result of the combined effect of their potential energy in the electric field and the thermal energy of the plasma flow, are distributed exponentially, thereby setting the thickness of the deposited coating [26].

The considered high-energy processes allow for layer-by-layer application of materials with special properties on the surface of products of a geometrically complex shape. This allows changing the physical and mechanical properties of the surface material, depending on the requirements for the use of parts in the machine [19, 26].

Formation of the surface layer of a complex shape

High-energy processes of additive technologies are considered from system positions as sequences of transformations of energy, matter and entropy in material and information subsystems aimed at changing the accuracy and topography of surfaces and the physical and mechanical properties of the material [27].

To analyze the ways of formation of structures and phases of surface layers of parts in the processing system, unstable variables (temperature, pressure, current strength, magnetic induction, etc.), which control the development, evolution of parameters stable in this process are distinguished, are used. This approach allows considering any structure as a self-stabilizing energy-conditioning complex [19, 27]. In its evolution, the alternation of system transitions from a stable state to an unstable one is accompanied by a change in the scale level of the energy absorption process and the formation of dissipative structures [19, 26].

The interfaces of the structures and the gradients of the properties of the layers in the additive synergistic technologies that form the composite material of the product are determined by technological barriers making it possible to establish the boundary conditions for laminate synthesis [28].

The conditions for creating a layer in high-intensity processes can be reasonably related to the design features of the product shells formed. Computer surface and solid modeling makes it possible to see the configuration of the boundaries; at the same time, the problems of modeling of layered shells are not reduced to simple scaling, but take into account the design features and specific technology conditions associated with process stability, interpenetration of layers and other surface phenomena [6, 15].

When induction surfacing by dipping into melt is used, the internal cavities are filled, but the pore filling depends on the wetting conditions of the melt [22]. In the processes of plasma spraying and surfacing, the edge rounding occurs [23]. In electromagnetic surfacing, the thickness of the deposited layer is reduced on the most prominent areas [32]. The thickness of the altered layer during laser or electron-beam fusion is inhomogeneous and depends on the degree of presence of alloying elements due to the concentration stratification of the melt in the resulting vortices [25]. In the case of ion deposition of coatings on protrusions with a small radius at the apex, owing to the increase in the potential, the layer grows most intensively [26].

As a result, the conditions for creating a layer in high-energy processes should be related to the design features of the products being formed. To create layers of stabilized thickness in physical fields, it is necessary to ensure the stability of the process system for induction, plasma, electromagnetic, laser, electron-beam, and ion surface treatments.

Self-organization of surface phenomena in a process medium

Particular attention should be given to the process medium, which is created by the effects of concentrated energy flows in the processes of applying flat layers (BD-technologies) and the formation of shells (DD-technologies).

Due to the roughness relief on the surface of the workpiece, the velocity of the flow of the *continuous process medium* varies. Therefore, there is a boundary layer between the potential flow and the surface of the part. This boundary layer, called the Prandtl layer, is not free-vortex since it has friction due to the flow resistance in the laminar flow caused by the viscosity of the medium [29]. As a result, the uneven thickness of the coating formed in the melt is determined by the Prandtl boundary layer.

If the Reynolds number exceeds the critical value for laminar flow, part of the boundary layer breaks off. This leads to the fact that part of the flow becomes turbulent and the flow resistance increases significantly.

In the technological system, the ion-plasma, electronic, and radiation effects of a *discrete process medium* are not completely absorbed by the surface layers formed. In this case, the scattering of fluxes is not always associated with the formation of dissipative structures in the surface layers, and is often due to reflection, refraction, or other phenomena of the removal of matter and energy from the working zone [19].

In ion-vacuum processes, most of the plasma ions bombard the cathode, which leads to evaporation from its surface of neutral and excited atoms, which in turn ionize in a vacuum arc and return to the cathode in the form of ions. The so-called plasma self-generation process [26] is carried out. The main thing in this process is that the vacuum arc plasma is an effective source of ions of the cathode material.

If there are protrusions and cavities of various shapes on the surface of the base, this leads to a curvature of the trajectory of ion motion and, accordingly, to the fact that the number of ions falling on the substrate per unit time is not the same in different places. As a consequence, the thickness of the applied coating will be different and with increasing potential the ion density in the plasma will increase. The region of arising in homogeneities is limited mainly by the thickness of the Debye layer adjoining it, that is, the layer in which the potential applied to the base effectively affects the ions [19, 26].

Consequently, it can be concluded that the formation of ion flows to the substrate occurs mainly in the Debye layer, the thickness of which depends on the ion density, their charges, masses and energy. The developed surface of the base and the presence of unevenness on it cause the thickness of the applied coating, the formation of various structures in it [19, 24]. To reduce the thickness of the coatings, it is necessary to strive to reduce the thickness of the Debye layer, which is achieved by decreasing the potential applied to the substrate or by increasing the ion density.

Synthesis of composite materials in additive technologies

To study the spatiotemporal results of technological effects in the additive synthesis of a composite material, the material should be considered as a distributed system from the standpoint of the general theory of systems [30]. This approach assumes that the properties of the system are determined by the properties of the elements from which it is constructed and by the organization of the interaction of these elements. Owing to the approach, it becomes possible to study the role of local properties of elements and optimize their relationships in determining the global properties of the system.

To describe the properties of composite materials, the distributed system of interacting elements in the structural phase scale of the process medium is considered [30, 31]. The state and acts of changing the material state can be modeled on a discrete, homogeneous environment of logical functions related to the class of "continuous environment" models with discrete modifications, since they satisfy the following basic principle: only neighboring cells that are functionally connected when changing properties are denoted by the points [31].

To distinguish the models of tissue with local point-to-cell interactions, the term "point-like tissue" is used, since the excitation transfer here is carried out according to the "point-to-point" principle. Point-like tissue is a set of locally interacting points and cells. As a model of a continuous excitable environment, point-like tissue is a kinematic model convenient for studying the global properties of propagation of "excitation" waves without taking into account the dynamic effects inherent in real process mediums.

Discrete tissue models are defined on network graphs. The definition of graph G means the assignment of possible functional connections in the set of vertex cells X. A further transition from this structural scheme $G(X)$ to a certain model of the tissue $T(X)$ is connected with the choice of the form of the functional equipment of the structural elements of the graph. With a formal approach, some properties of cells are assigned to the vertices, and the edges are the properties of the transmission of certain influences that affect the properties of the vertex-cells [31].

Diagram of logical connections in the additive technology is a state machine. By adopting different ways of layer building for the functional states of the technological system, we construct the kinetic scheme of the finite state machine with: I) direct fabrication of parts; II) laminate synthesis; III) rapid prototyping; IV) formation of three-dimensional objects (Fig. 2).

Using block diagrams for a set of modes for each functional state, algorithmic schemes of the states of the process medium is obtained. After combining the algorithmic state diagrams, we construct a cell machine of the process medium during the fabrication of products (Fig. 3), in which the element IV has no outputs and does not perform logical transformations. Considering the interconnections of states of a finite machine, the graph of the cell state of the process medium is obtained (Fig. 4); element IV is the final one and has no feedbacks.

The configurations of cell machines, reflecting their excitation instruction cycle (Fig. 5), represented by the graphs of the states of the cell automata of the process medium (Fig. 4), describe the behavior of the elements of the mosaic structure (Fig. 3) in the "fabrication" of products.

The configurations considered for the "mosaic space" of states (Fig. 5) include:

I – Solid Freeform Fabrication will mainly be represented by regimes with a breakdown of the state of rest (Fig. 5*c*);

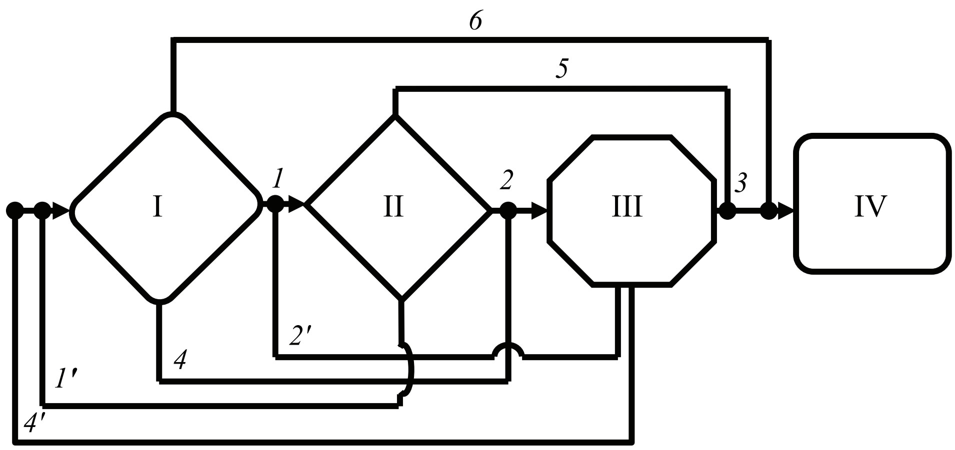

Fig. 2. Kinetic scheme of functional states of the technological system

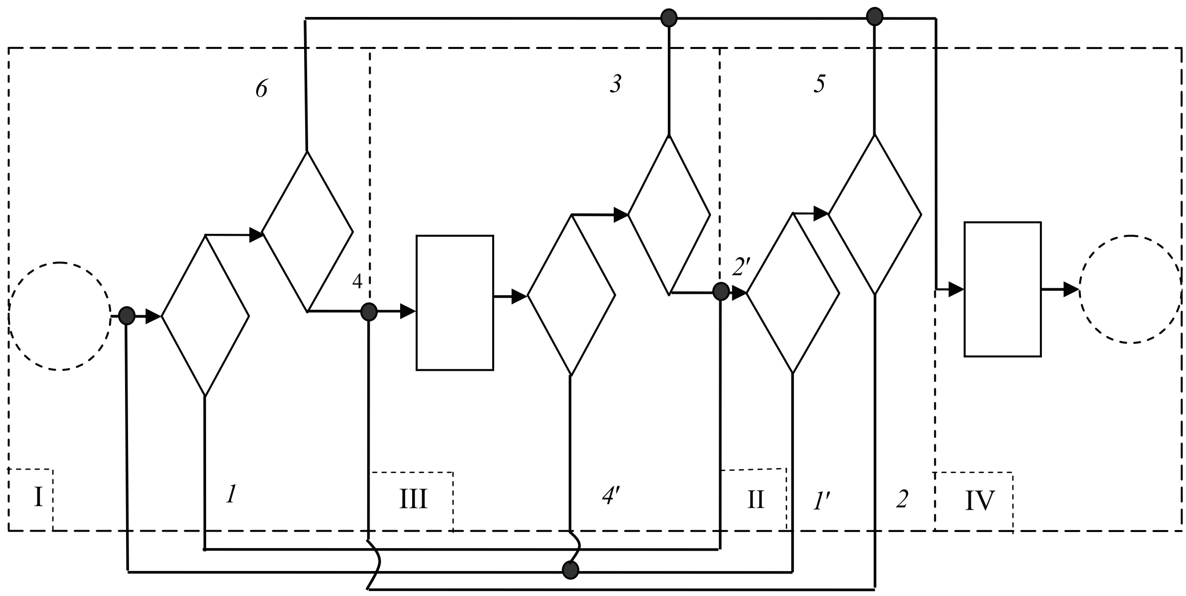

Fig. 3. Cell machine for process medium

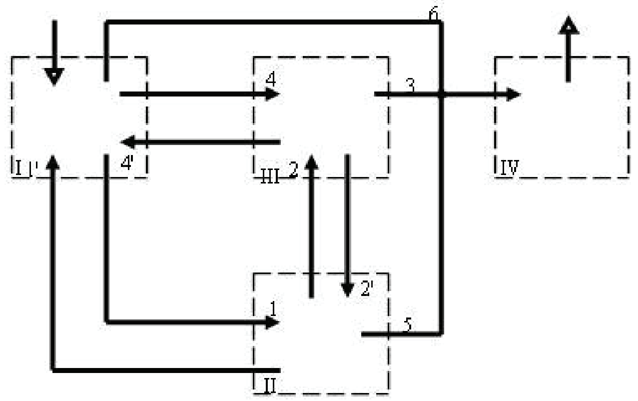

Fig. 4. Graph of the cell machine state of the process medium

II – Laminate Synthesis will mainly be described by splitting the states of refractivity and excitation (Fig. 5*b*);

III – rapid prototyping in the first approximation will be characterized by a general simplified scheme (Fig. 5*a*);

IV – completion of the transmission of matter and energy flows will describe the formation of voids, channels or cavities in which structures of other materials can be created.

As a result, the state graph of the finite state machine (Fig. 4) can be effectively used to describe the functional states of elementary cells of the technological environment [36].

Transformation by cellular automata of material structures

In the general case, "mosaic" discrete models have the structure of simple networks N_s^n, while continuous models are defined on continuous manifolds of the type of a real space using topological connections of this space [32]. The properties of each cell – vortex $x \in X$ of the "mosaic structure"can be described by a certain set of states $Z = \{z_1, \ldots, z_m\}$ with the indication of the transition graph $P(Z)$ in this set of states; properties of transitions in P for different effects on the cell x through internal or external links; links with the current state of the cell x, states of edge-bonds emerging from x.

The mathematical content of these formal relationships can vary widely. In order to describe the process of migration of a single act of changing cell states, one can use their representation as finite automata [28].

The process of excitation of the cell is based on the concepts of stimulus and threshold with the isolation of states (Fig. 5): z_0 of rest, z_+ of excitation; z_- of refractivity [32]. is stable in the absence of external input stimuli j_+ relative to the given cell. To make the transition into an excited state $z_0 \to z_+$, it is necessary that condition $j_+ \geq \aleph$ is satisfied, i.e., the stimulus must exceed a certain threshold level $\aleph$, which will be first assumed to be equal to unity, $\aleph = 1$.

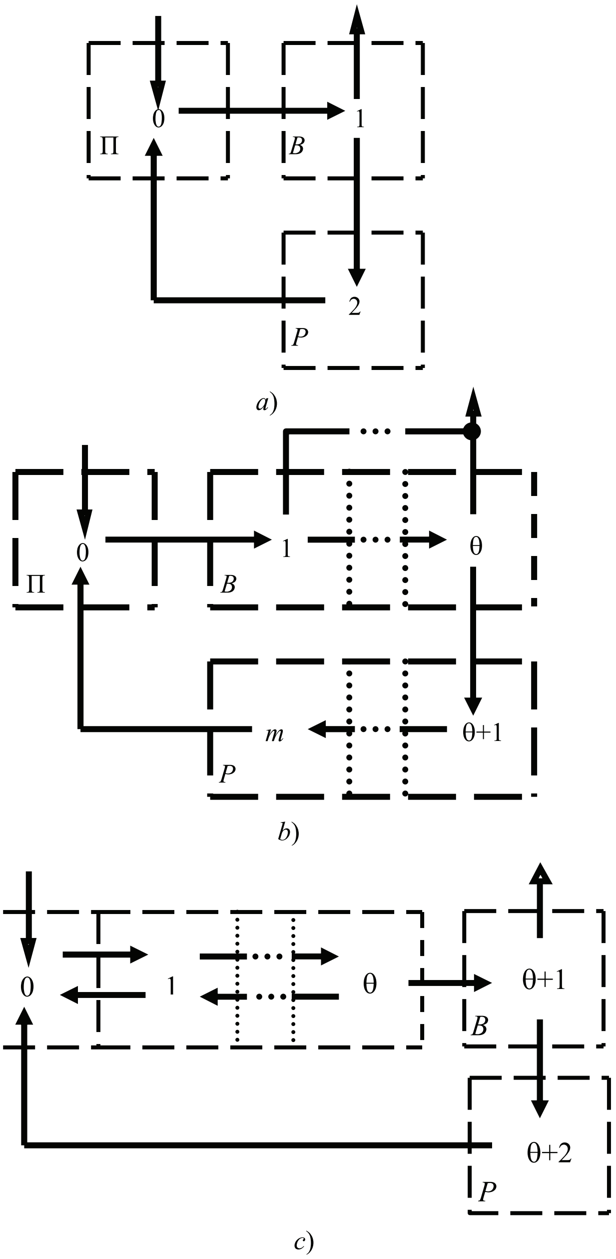

Fig. 5. Configurations of cell machines that reflect states of rest (П), excitation (B), refractivity (P) excitable automata cells: with a simplified scheme (*a*), splitting the states of excitation {1, …, θ} and refractivity {θ+1, …, *m*} into clock sub-states (*b*) and partitioning the state of rest {1, …, θ} into clock sub-states (*c*)

Excitation or transition $z_0 \to z_+$ if $j_+ \geq 1$ occurs instantaneously, but then in a state z_+ the cell stays for a finite time θ_+, after which the transition to the refractive state occurs automatically $z_+ \to z_-$. If θ_- is cell lifetime in refractory state z_-, which is the state of nonexcitability of the cell, then the complete single excitation cycle $z_0 \to z_+ \to z_- \to z_0$ last time $m = \theta_+ + \theta_-$. This cycle of the cell always passes through an autonomous program, and external stimulation can only be regulated by the moment the excitation cycle starts. In the limit, when the cell is under the constant action of an overthreshold stimulus, at the end of the cycle, instead of the transition $z_- \to z_0$ the transition $z_+ \to z_+$ is immediately performed, i.e. new excitation.

The state of excitation z_+ differs from others mainly in that the cell in it is itself a source of stimulating action, which is called output and is denoted as j_-. This scheme can be shown as a graph $P(Z)$, where $Z = \{z_0, z_+, z_-\}$ (Fig. 5*a*).

In the discrete representation of time τ it is convenient to take as an integral durations θ_+ and θ_-, and in graph $P(Z)$, replace states z_+ and z_- with chains of states $z_+ = (z_1, ..., z_i)$, $z_- = (z_{i+1}, ..., z_m)$, where $i = \theta_+$, $m = 1 + \theta_+ + \theta_-$ (Fig. 5*b*).

Modification of the graph P(Z) when divided into clock substates of the state $z_0 = (z_1, ..., z_i)$, where $i = \theta_0$, gives the life cycle of a cell $m = \theta_0 + 2$ (Fig. 5*c*). The state of a cell at an arbitrary moment τ can be characterized by a vector $\mathbf{z} = \mathbf{z}(\tau)$ of the order $m + 1$. If at the moment τ the cell is in the state k, then $\mathbf{z}(\tau) = \mathrm{e}_k$, i.e., at this moment only the k-th component of the vector $\mathbf{z}$ is equal to 1, and the remaining components are equal to zero.

The change of states in a single cycle is described by a linear equation

$$\mathbf{z}(\tau+1) = \mathbf{P}\mathbf{z}(\tau)$$

with a transition matrix $\mathbf{P} = \mathbf{P}(\tau)$, which is a function of time, which is inherent in the properties of its variable elements p and q. These elements are expressed by the function of a single jump, the argument in which is the difference between the stimulus and the threshold: $p = \varepsilon(j_+ - 1)$, $q = 1 - \varepsilon(j_+ - 1)$, , i.e., if $j_+ \geq 1$, then $p = 1$, $q = 0$, and if $j_+ < 1$, then $p = 0$, $q = 1$.

To describe intercellular interactions, it is necessary to determine the behavior in time of the cell's output stimulus $j_-(\tau)$, which can be expressed as a scalar product of the state vector $\mathbf{z}(\tau)$ with a vector $\mathbf{a}_+ = \mathbf{e}_1 + ... + \mathbf{e}_{\theta+}$, which is an "indicator" of excitation states:

$$j_-(\tau) = \mathbf{a}_+ \cdot \mathbf{z}(\tau).$$

A full description of intercellular interactions within the framework of this formalism requires the attraction of a matrix of cell connections, that is, the definition of a structural model of space [32].

Using the described automatic circuit of cell excitation, it is possible to determine stochastic modifications of the excitation model in which the vector $\mathbf{z}$ describes the probability distribution of the cell in each of the states of the set Z, and the elements of the matrix $\mathbf{P}$ represent the probabilities of transitions between states. Then p is probability to go into an excited state under the action of a stimulus j_+, $p = \alpha\varepsilon(j_+ - 1)$, where $\alpha < 1$; and $q = 1 - p$.

The most general is the model in which all transitions between the states are random and the duration of the excitation and refractivity states θ_+ and θ_- are random variables. However, a model with deterministic durations θ_+ and θ_- is sufficiently substantive, when only the transition is determined in a probabilistic way. The absence of a transition, that is, the excitation of z_0 also describes the formation of a channel, cavities or their filling during prototyping.

The motion of the transfer front of properties in the mosaic space

The structure of the point-like tissue $T(X)$ of the mosaic space on the set of vertex cells X is given by a constraint matrix whose order is equal to $|X|$. Selecting the subsets X_0, X_+, X_-, corresponding to different states of the vertices $X = X_0 \cup X_+ \cup X_-$, $X_0 \cap X_+ \cap X_- = 0$, we introduce the indicator vectors of these subsets: $\mathbf{u}_0$, $\mathbf{u}_+$, $\mathbf{u}_-$, respectively. The order of each of these vectors is $|X|$; the elements different from zero and equal to 1 are, for example, those of the vector $\mathbf{u}_0$, which correspond to the vertices $x \in X_0$, etc. In the general case, both the subsets X_0, X_+, X_-, and their indicators are functions of the time τ, which is considered discrete. The vertex x is in the excited state the source of excitation for all those vertices into which the links go from it.

The propagation path of the excitation is represented by the union of the sets $\Phi(x, \tau)$ for all instants of time τ of excitation existence in $T(X)$. Suppose that up to the instant $\tau = 0$, there is no excitation in $T(X)$, and at the initial time, the points of the set $X_+(0)$ are excited by an external action. Step by step it is possible to describe the subsequent migration of excitation for arbitrary initial sets $X_+(0)$. In this case, the states z_0 for the cells of the process medium should be considered as the front boundary of the excitation wave.

Excitation wave $\mathbf{u}_{+}(\tau) = \boldsymbol{\varphi}(\tau)$ for $\tau \geq 0$ is called fundamental if $X_{+}(0) = \{x_0\}$, single point $x_0 \in X$ and $\mathbf{u}_{+}(\tau) \equiv 0$ for $\tau < 0$ [32]. Fundamental wave $\boldsymbol{\varphi}(\tau)$ represents the "response" of the medium to a local disturbance, which for point-like tissue is an act of excitation of a single point. The concept of a fundamental wave is related to the notion of an "ordinal set" of vertices of a tissue graph. If the threshold of rest $\aleph \leq 1$, then in each clock cycle, the front of the fundamental wave "occupies" vertices of the same order in the tissue graph $T(X)$ with respect to the initially excited vertex x_0, i.e., the fundamental set $\Phi(x, \tau)$ is the set of vertices of order τ.

For example, in homogeneous two-dimensional networks N_s^2 for s = 3, 4, 6. 8 (Fig. 6) vertices of successive fundamental fronts $\Phi(x, \tau)$ are arranged in accordance with the perimeter values of the elementary circuits.

In the discrete models under consideration, in contrast to the continuum models, the effects of summation of the impacts that can be studied when estimating the possibility of propagation of excitation in simple networks are reproduced at different values of the threshold of rest $\aleph$ [28, 32].

The path $\chi(\tau)$ is said to be finite if there exists such finite time moment τ_0 that $\chi(\tau) = 0$ for $\tau > \tau_0$ and if $\chi(\tau) \neq 0$ for $\tau \leq \tau_0$. The path has a duration τ_0 if it is initiated at the time $\tau = 0$ and $\tau_0 > 0$. The propagation of the excitation is said to be degenerate for a finite path and non-degenerate, otherwise [32].

If $\aleph \leq 1$, then for the excitation of any stationary point in $T(X)$ it is sufficient that only one of its neighboring points is excited. If the graph of the tissue does not contain absorbing vertices, that is, there are no outgoing edges, then the fundamental extension from any vertex $T(X)$ exists and is non-degenerate for an unbounded set X.

If $\aleph > 1$, there is a need for changes in determining the fundamental distribution. Indeed, let the threshold $\aleph = 2$, that is, an arbitrary resting point x is excited at the moment $\tau + 1$, if at the previous moment τ, at least two of its neighboring points are excited. Obviously, in this case the excitation of a single point of tissue is not sufficient to create a propagating excitation wave. Therefore, in the general case $\aleph > 1$ the propagation is called fundamental, if it is initiated by the initial excitation of some minimal set of points $\Phi(x, 0)$, where $|\Phi(x, 0)| > 1$ [32].

In the network N_3^2 one can select two point so that in the next cycle if $\aleph = 2$ they could trigger (excite) another point. However, here no larger initial set $\Phi(x, 0)$ is capable of creating a path of more than one clock cycle (Fig. 6*a*).

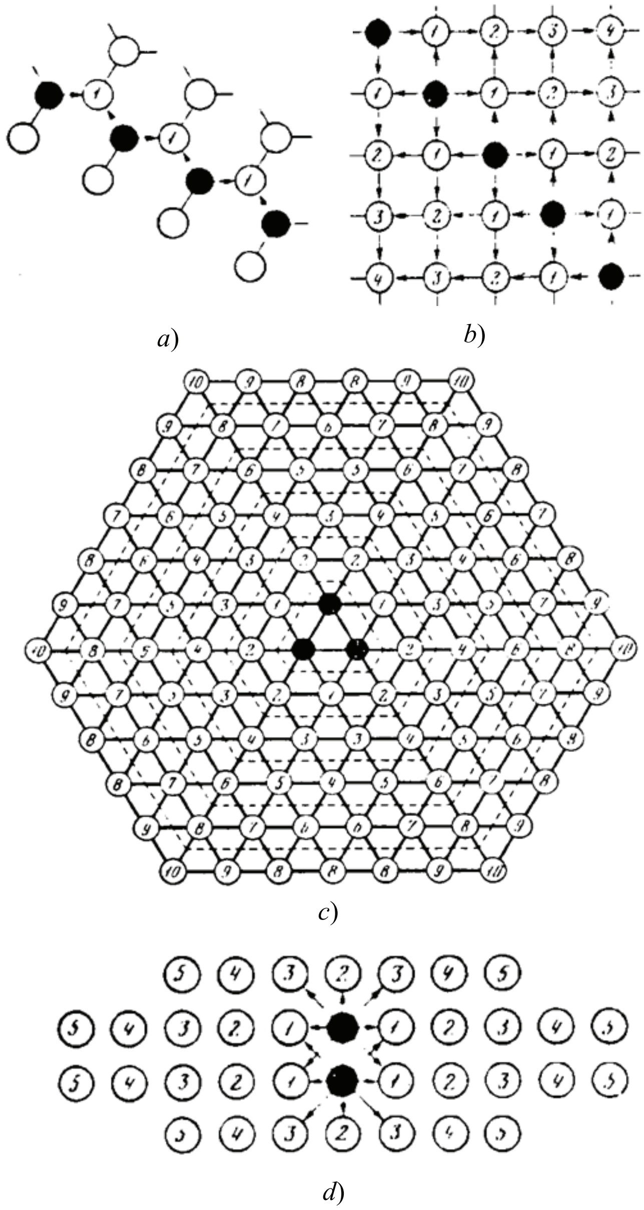

Fig. 6. Forms of propagation of excitation at the threshold $\aleph = 2$: excitation degeneracy in N_3^2 (*a*), N_4^2 (*b*); nondegenerate wave in N_6^2 at θ = 2 (*c*), in N_8^2 at θ = 1 (*d*)

In the network N_4^2 if $\aleph = 2$ the initial excitation of a pair of diagonal points also leads to propagation only by one step, but the excitation of k diagonal points belonging to the same straight line causes a degenerate propagation with a duration $\tau = k - 1$ (Fig. 6*b*). It is impossible to increase the path length in N_3^2 and N_4^2 by increasing the excitation duration θ of each point.

Network N_6^2 in this respect is significantly different from previous ones. If $\theta = 1$ the propagation pattern in N_6^2 is similar to that in N_4^2. However, if $\theta = 2$, then from a pair of neighboring points, the excitation propagates two cycles, and with the initial excitation of three points of one triangle (Fig. 6*c*), the subsequent excitation wave does not degenerate. Thus, in a network N_6^2 combining the effects of spatial and temporal summation of impacts, one can create a nondegenerate propagation of excitation if $\aleph = 2$, however, the network loses this property if $\aleph = 3$ [32].

Network N_8^2 if $\aleph = 2$ and $\theta = 1$ makes it possible to create a nondegenerate propagation without the use of time summation by the initial excitation of two neighboring points. With the initial conditions chosen, the diagonal pair of points does not possess this property, and a simple pair of neighboring points has. In the latter case and if $\aleph = 2$ the front has a stable shape: it consists of two fronts containing four points (Fig. 6*d*). This case is typical for the creation of an anisotropic form of excitation propagation in a homogeneous isotropic medium [32].

Thus, in order to understand the functional organization of process media modeled by discrete point-like tissues in the "mosaic space", it is required to determine the necessary and sufficient conditions for the nondegenerate propagation initiated by the initial excitation of cells-points, with their connection topology, followed by the configuration of the front of the excitation wave [28, 32]. The initial conditions of the excitation process in additive technologies are determined by the power, flow and distribution in space and time of the energy flows and the material flow [15].

Conclusion

The analysis of the current state and prospects for the development of additive technologies in computerized production makes it possible to talk about a new paradigm in its evolution, which indicates the transition to the self-reproduction of machines, including parts of organisms or organisms themselves. As a result, the concept of a "digital factory" is formed and detailed, in which additive technologies are the defining link of the system, including developed subsystems: 3D-design and production and consumption management, from modeling the product, its materials and components in accordance with new technological capabilities and ending with reception and operation of a functionally oriented product.

A unified diagram of logical connections in the processes of additive technologies is presented. It is a finite state machine and it is shown that it can be used both for a 3D-printer that provides preform "fabrication" of a product of complex shape and structure, and for the additive synthesis of its composite material. In this case, the structural elements of the "mosaic space" – the cellular machines built on the basis of von Neumann's self-reproduction model can be used to describe processes in structural materials and in functional biological tissues.

Additive processes of direct creation of products by laminate synthesis in accordance with the features of the construction of the layers formed (BD-technologies) and shells (DD-technologies) reveal new perspectives in resource design of machine parts. The use of self-organization of surface phenomena allows forming layers of a certain adjustable thickness across the complex shape of the working surface and controlling the provision of material properties with energy flows.

The continuum model of the point-like tissue of the "mosaic space" is considered, in which each point does not differ in properties from the cells of the discrete model and is in one of three states: rest, excitation and refractivity. It is shown that the propagation of impacts in the process midium can be described using classical wave principles for modeling the changes and transfer of states, structures and properties of the material.

References

1. Kurant R. et al. (eds) *Matematika v sovremennom mire* [Mathematics in the Modern World]. predisl. V.A. Uspenskogo. M.: Mir, 1967, 208 p. (Rus)

2. Viner N. *Kibernetika ili upravlenie i svjaz' v zhivom i mashine* [Cybernetics or control and communication in a living and a machine]. M.: Sovet. radio, 1958, 296 p. (Rus)

3. Kuzin L. N. *Osnovy kibernetiki: v 2 t. T. 2: Osnovy kiberneticheskih modelej* [Fundamentals of cybernetics. Vol. 2. Fundamentals of cybernetic models]. M.: Jenergija, 1979, 584 p. (Rus)

4. Neumann von John (edited by Burks Arthur W) *Theory of Self-Reproducing Automata*. (Scanned book online), University of Illinois Press, (1966), Accessed 2017-04-30

5. Vityaz P.A. Kheifetz M.L., Chizhik S.A. "Industrija 4.0": *ot informacionno-kommunikacionnyh i additivnyh tehnologij k samovosproizvedeniju mashin i organizmov* [Industry 4.0: From information and communication and additive technologies to the self-reproduction of machines and organisms]. *Izvestija NAN Belarusi. Ser.fiz.-tehn. nauk*. 2017, Vol. 2, pp.54-72. (Rus)

6. Golubev O.P., Kuchta S.V., Mrochek Zh.A., Svirsky D.N., Soukhinenko B.N., Kheifetz M.L. *Perspektivnye tehnologii mashinostroitel'nogo proizvodstva* [Advanced technologies of engineering production] ed. by Zh. A. Mrochek, M. L. Kheifetz. Novopolock: Polock. gos. un-t, 2007, 204 p. (Rus)

7. Gibson I. Rosen D., Stuker B. *Additive Manufacturing Technologies: 3D Printing, Raid*

Prototyping, and Direct Digital Manufacturing. N.Y.: Springer, 2015, 498 p.

8. Zlenko M.A, Popovich A.A, Mutylina I.N. *Additivnye tehnologii v mashinostroenii* [Additive technologies in mechanical engineering]. SPb.: Izd-vo Politehn. un-ta, 2013, 222 p. (Rus)

9. Kheifetz M.L. *Additivnye sinergotehnologii poslojnogo sinteza izdelij iz kompozicionnyh materialov pri vozdejstvii potokami jenergii* [Additive sinergotechnologies of layered synthesis of articles made of composite materials when exposed to energy flows]. *Naukoemkie tehnologii v mashinostroenii*, 2016, Vol.4(58), pp. 3-9. (Rus)

10. Viyaz P.A., Kheifetz M.L., Chizhik S.A. *Sostojanie i perspektivy razvitija tehnologicheskih kompleksov additivnogo proizvodstva izdelij iz kompozicionnyh materialov* [State and prospects of development of additive technologies for products from composite materials]. *Naukoemkie tehnologii v mashinostroenii*. 2017, Vol. 7(73), pp. 42-48. (Rus)

11. Vityaz P.A., Ilyushchenko A.F., Kheifetz M.L. *Operativnoe maketirovanie i proizvodstvo izdelij slozhnoj formy iz kompozicionnyh materialov* [Rapid prototyping and manufacture of articles with complex shapes made of composite materials]. *Naukoemkie tehnologii v mashinostroenii*, 2011, Issue 2, pp. 3-8. (Rus)

12. Chizhik S.A., Kheifetz M.L., Filatov S.A. *Perspektivy razvitija tehnologicheskih kompleksov additiv-nogo sinteza kompozicionnyh materialov i formoobrazo-vanija izdelij* [Prospects for development of technological systems for additive synthesis of composite materials and products shaping]. *Mechanika mashin, mechanizmov i materialov*, 2014, Vol.4 (29), pp. 68-74. (Rus).

13. Kheifetz M.L. *Ot additivnogo proizvodstva k samovosproizvedeniju mashin, ih uzlov i detalej* [From additive production to self-reproduction of machines, their units and parts] Naukoemkie tehnologii v mashinostroenii, 2017, Vol. 4 (70), pp. 37-48. (Rus)

14. Kheifetz M.L. *Modeli i algoritmy proizvodstva izdelij bez ispol'zovanija formoobrazujushhej osnastki* [Models and algorithms for the production of articles without the use of form-building equipment]. *Vestsi Natsyyanal'nai akademii navuk Belarusi. Seryya fizika-technichnych navuk*, 2001, Issue 2, pp. 59-62. (Rus)

15. Kheifetz M.L. *Formirovanie svojstv materialov pri poslojnom sinteze detalej* [Formation of materials properties at the synthesis of layered components]. Novopolotsk, Polotsk State University, 2001. 156 p. (Rus)

16. Akulovich L. M., et al. *Intellektual'noe proizvodstvo: sostojanie i perspektivy razvitija* [Intellectual production: state and prospects]. Ed. by M.L. Kheifetz and B.P.Chemisov. Novopolotsk, Polotsk State University, 2002. 268 p. (Rus)

17. Ruseckij A.M., et al. *Teoreticheskie osnovy proektirovanija tehnologicheskih kompleksov* [Theoretical bases of technological systems designing]. Ed. A.M. Rusetsky. Minsk, Belaruskaya Navuka Publ., 2012, 239 p. (Rus)

18. Alferov Zh.I. *Istorija i budushhee poluprovod-nikovyh geterostruktur* [The history and future of semiconductor heterostructures]. *Fizika i tehnika poluprovodnikov*, 1998, vol. 32, Issue 3, pp. 2-7. (Rus)

19. Kheifetz M.L. *Proektirovanie processov kombini-rovannoj obrabotki* [Design process of combined processing]. Moskow, Mashinostroenie Publ., 2005, 272 p. (Rus)

20. Kheifetz M.L. *Analiz algoritmov proizvodstva izdelij po modeljam samovosproizvedenija fon Nejmana* [The analysis of algorithms of products manufacturing according to models of von Neumann's self-reproduction]. *Doklady Natsional'noi akademii nauk Belarusi*, 2001, Vol.45, Issue 5, pp. 119-122. (Rus)

21. Dorozhkin N.N., Mironov V.V., Vereshchagin V.A., Kot A.A. *Jelektrofizicheskie metody poluchenija pokrytij iz metallicheskih poroshkov* [Electrophysical Methods for Obtaining Coatings from Metal Powders]. Riga, Zinatne Publ., 1985, 131 p. (Rus)

22. Tkachev V.N., Fishteyn B.M., Kozintsev N.V. *Indukcionnaja naplavka tverdyh splavov* [Induction surfacing of hard alloys]. Moskow, Mashinostroenie Publ., 1970, 184 p. (Rus)

23. Vityaz P.A., Ivashko V.S., Manoilo E.D. *Teorija i praktika gazoplamennogo napylenija* [The Theory and Practice of Flame Spraying]. Minsk, Nauka i technika Publ., 1993, 296 p. (Rus).

24. Kheifetz M.L., Akulovich L.M., Mrochek Zh.A., Zeveleva E.Z. *Jelektrofizicheskie i jelektrohimicheskie metody obrabotki materialov* [Electrophysical and Electrochemical Methods of Materials Processing]. Novopolotsk, Polotsk State University, 2012, 292 p. (Rus)

25. Eidelman E.D. *Vozbuzhdenie jelektricheskoj neustojchivosti nagrevaniem* [Excitation of electric instability by heating]. *Uspechi phiziczeskich nauk*. 1995, Vol. 165, Issue 11, pp. 1279-1294. (Rus)

26. Kheifetz M.L., Kozhuro L.M, Mrochek Zh.A. *Processy samoorganizacii pri formirovanii poverhnostej* [Self-organization processes in the formation of surfaces]. Gomel, V.A. Belyi Metal-Polymer Research Institute of the National Academy of Sciences of Belarus, 1999, 276 p. (Rus)

27. IvanovaV.S., Balankin A.C., Bunin I.Zh., Oksogoev A.A. *Sinergetika i fraktaly v materialovedenii* [Synergetics and fractals in material science]. Moscow, Nauka Publ., 1994, 383 p. (Rus)

28. Chizhik S.A., Kheifetz M.L., Filatov S.A. *Tehnologicheskie bar'ery pri vysokointensivnyh vozdejstvijah v processah poslojnogo sinteza i obrabotki materialov* [Technological barriers at high-exposure impacts related to the layering synthesis and processing of materials]. *Vestsi Natsyyanal'nai akademii navuk Belarusi. Seryya fizika-technichnych navuk*, 2015, Issue 3, pp. 107-113. (Rus)

29. Loitsiansky L.G. *Mehanika zhidkosti i gaza* [Fluid Mechanics]. Moscow, Nauka Publ., 1987, 840 p. (Rus).

30. Druzhinin V.V., Cantorov D.S. *Problemy sistemologii* [Problems of Systemology]. Moscow, Soviet Radio Publ., 1976, 296 p. (Rus)

31. Tsetlin M.L. *Issledovanija po teorii avtomatov i modelirovaniju biologicheskih sistem* [Investigations in the Theory of Automata and Modeling of Biological Systems]. Moscow, Nauka Publ., 1969, 368 p. (Rus)

32. Smolyaninov V.V. *Matematicheskie modeli biologicheskih tkanej* [Mathematical Models of Biological Tissues]. Moscow, Nauka Publ., 1980, 368 p. (Rus)