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Smart Materials in Materials Science

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The basic categories of materials which form the row in order of complication of their performance such as simple–multifunctional–adaptive–active–smart are considered. Energy aspects of external effects upon materials, and behavior of materials response to the stimuli of physical, chemical and biological nature, are examined. A model of smart material is proposed as the atom-molecular structure provided with a feedback system which corrects the primary reaction of material upon effect of surroundings via optimal usage of its energy.

Keywords: smart material, surroundings, external stimuli, feedback system, model.

Smart materials are materials organized in a special way. They differ from common materials in that the elements of its structure have properties of cybernetic system thus allowing the material to adapt efficiently to varying operating conditions. A model of smart material is proposed as an atomic-molecular structure provided with a feedback system that optimally corrects a primary reaction of the material to external stimuli. The experimental results that support the advisability of smart material model realization in materials and engineering systems are reported.

Introduction

The *smart material* (SM) and *intelligent material* terms were proposed in the 1960s when a demand arose for materials that interacted with strong electromagnetic fields of electronic information systems. Now these problems are solved via designing tiny electronic systems, which became possible owing to advances in nanotechnology that operates with structural elements 0.1÷100 nm in size. *Nano* and *smart* materials are key words in materials science of the 21st century.

Up to now, a great amount of disembodied data concerning SM has been accumulated in the scientific literature and on the Internet. A demand arose for the systematization of the data most of which serves to some extent to provide sensation and advertisement. This task is still critical despite the fact that the problems of SM development and operation are considered in more than a hundred of books some of which are mentioned in our references [1–5].

The aim of the work is to substantiate the methodology of SM development based on the criteria of the nature of energy effects upon the material, its response, and feedback mechanisms.

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1. Retrospection

The history of improvement of materials is dialectically associated with the history of society development. Aspiration to discovery of new materials was in all ages due to the people's wish to improve their own life.

The names of the historical stages (stone, copper, bronze, and iron ages) imply the significance of materials in ancient history of mankind. The next generation of materials launched its life cycle in the second millennium AC, when fast development of metallurgy changed abruptly the level of engineering and technology of materials. First industrial plastic mass products appeared at the turn to the 20s century. A new era of ceramic materials which were used by people even in the neolith epoch, started in the 1930s owing to the advances in powder metallurgy. In such a manner, main types of materials being at the disposal of humanity were introduced in production. Scientific engineering revolution that took place late in the 1940s resulted in the creation of principally new materials, i.e., superconductors, semiconductors, synthetic diamonds, and so forth.

At that time the specialists in the materials science believed that natural resources of traditional engineering materials were exhausted. The designers of the equipment that operates under extreme conditions such as high temperatures (engines), deep vacuum (space apparatuses), super-high speed friction (arms), etc. were among the first to comprehend this fact. In the second half of the 20th century the development of composite materials that combine dissimilar components became the main trend in the materials science. The up-to-date tendency in material improvement is in the creation of SM with involvement of nanotechnologies [5].

The history of SM commenced in 1834 when French physician and mathematician A. Ampere proposed a "cybernetics" term. This Greek word was used to call the science about the methods of society management using the term that in ancient times denoted the science about ship navigation (*kybernëtes*, governor, pilot).

Cybernetics in its modern understanding as the science about general regularities of information reception, storage and processing was born in the USA. Professor Norbert Wiener, Massachusetts Technological University, was the first to use this term [6]. Electron computing facilities formed the basis of management systems that realized cybernetic methods. N. Wiener and J. Von Newmann, the creator of digital computer, connected I. Pavlov's and I. Sechenov's ideas about the self-regulation of biological systems with the principles of operation of facilities that realize artificial intelligence [7].

The SM research findings have being discussed in scientific journals. *Smart Materials Bulletin* has been released for more than 20 years. Permanent headings devoted to SM are available in numerous journals including *Advanced Composite Bulletin*, *Progress in Materials Science*, *Computational Materials Science*, etc. This proves the fact that the development of smart engineering systems has become a leading tendency in the materials science of the 21st century.

2. Main Concepts

The classes of materials form the following raw in increasing complexity of their performance: simple – multifunctional – adaptive – active – smart.

Simple materials perform just one main operating function in engineering item. The *main* word is used here because almost always a complex of physical, chemical, mechanical, and other natural properties of the material is realized in the article in an uncontrollable manner and imparts an additional operating property to it.

Multifunctional materials perform both main and additional functions in an article. This can be exemplified by bronze (engineering and tribotechnical material), engineering plastics (protection of metallic parts from corrosion and creation of electric isolation), ceramic materials (high hardness, dielectric properties, thermal and chemical resistance).

Adaptive materials change pointedly their structure under the action of operation factors when their intensity reached a threshold value [8]. Principally, the structure of any material alters naturally under external stimuli. *Pointedly* implies that the structural alteration of an adaptive material is useful in terms of the efficiency of the article that is made of this material.

A grease can serve as an example of the adaptive material. It is a greasy lubricating material obtained by the introduction of a solid thickener (soap, paraffin, black, etc.) into a liquid oil. Under loads lower than the yield strength of the spatial frame formed by the thickener, the grease has properties of solid. Under heavy loads, it transforms into an abnormally viscous lubricating fluid. After unloading, the frame structure is recovered and the lubricant is again similar to solid [3].

The memory effect is the recovery of the original article shape damaged by plastic deformation, during heating. The recovery of the shape of steel articles results from martensitic transformation or reversible twinning in the steel structure [9]. Irreversible alteration of the alloy structure with *shape mem*ory is used in self-opening antennas of space ships, undetachable (free of welding, soldering, and gluing) pipe connections, and in orthopedics in fixation of hard-accessible bone parts.

Active materials, while performing the functions that are intrinsic of engineering materials, have beneficial physical, chemical, or biological influence on the mated parts and environment [10].

Magnetic fluid (MF) that seals the connection of the spinning shaft and housing of the machine can be exemplified as an active material. When exposed to the governing magnetic field, the MF ductility is lowered down and the MF layer in the connection gap resists actively to the pressure of the sealing medium. With increasing pressure and squeezing the interlayer from the gap, its adhesion to the magnet poles increases. Thus the stability of the interlayer position in the gap and impermeability of the connection are provided [11].

A chemically active filtering material consists of carbon tissue impregnated with complexons, namely, amino polycarbonic acids and their derivatives. The complexons are remarkable by that they react with metal cations and form stable coordination compounds. The filtering material mechanically catches hard impurity particles in the fluid under filtering and exhibits its activity via bonding chemically the ions of hard metals solvated in it [12].

A carrier of microorganisms in biological filters is a biologically active material. The agglomerates of microorganisms in the carrier vapors give rise to a biological film. The water passing through the filter clears itself from solid impurities and the microorganisms immobilized on the film decompose the organic components of flows [12].

A smart material performs functions compatible with its natural properties and when the energy of external effects reaches a threshold it, first, transforms this energy into the alteration of its own structure to provide a higher level of performance and, second, controls and automatically regulates this level with a feedback system (FS) via comparison of the external effect and the degree of property alteration. When external effects are ceased the SM regenerates, i.e. recovers its original characteristics. However, due to the energy losses spent on structure reconstruction (release of Joule heat, hysteresis, friction, incompleteness of phase transitions, etc.) absolute SM regeneration never occurs. The efficiency of SM structure reconstructions $\eta = W_a / W < 1$, where W and W_a are the specific energy of external effect and the activation energy of structure reconstruction, respectively.

3. Energy Aspects of the External Effects on Materials

In operation of engineering articles, materials are exposed to the impacts of the mated parts and surroundings. Any external effects execute a work on the material changing its structure and internal energy; the latest depends on the thermodynamic parameters of the material (volume, temperature, concentration, an so forth). The regularities of material responses to external effects determine the feedback mechanisms that occur in SM.

Physical effects include mechanical stresses, temperature, and physical fields such as nuclear, gravitational, and electromagnetic fields.

Mechanical stresses initiate collisions and interaction of gaseous particles, homogenization or breaks in fluid continuity, as well as elastic or plastic deformation of solids. Deformation is responsible for the reconstruction of the solid structure, occurrence of anisotropy in it, which is ultimately displayed in the break of the solid continuity. It is initiated as crack formation and finished as specimen damage. Mechanical stresses complicated by friction induce the material fatigue that implies a local increase in dislocation and vacancy density. Tribochemical reactions occur on the friction surface thus inducing the wear of tribopairs. Therefore, the energy of mechanical effect initiates the primary reconstruction of material structure that serves in SM as a signal to activate FS.

The FS energy is governed by the variation in the internal energy of the material that causes the structure transformation. According to the first law of thermodynamics, the transition of an adiabatically isolated material from state 1 into state 2 yields the variation in the internal energy U equaling work PdV that is done within the material by an external mechanical force in an infinitely slow quasi-static process: $U_2 - U_1 = \int_1^2 PdV$, where P is external pressure and V is material volume. In a general case, according to the second law of thermodynamics $dU = TdS - PdV$, where T is temperature and S is material entropy. Minimum U at constant entropy, volume, and mass of the material determines its stable equilibrium. Any deviations from minimum are potential sources of the feedback energy in SM.

Temperature is one of the basic thermodynamic parameters of the state that characterizes the heat equilibrium of material. The processes that run at nonequilibrium temperature (phase transitions, diffusion, viscosity fluctuations, thermoelectric phenomena, etc.) are accompanied by variations in the internal energy of the material and govern the feedback mechanism in SM.

Physical fields are responsible for the interaction of the material element structure. The nuclear forces that act between nucleons and govern the structure and properties of the nuclei of chemical elements are of significance when *smart* nuclear reactions run. The gravitational field is universal interaction between any matters. The effect of this indispensable companion of all processes that occur on the earth should be taken into account particularly in evaluating the state of colloid systems in liquid and gaseous phases. The electromagnetic field induces the interaction of electrically charged particles or those having a magnetic moment. External electromagnetic field interacts with the charged particles of the material creating the induced currents that are responsible for energy losses and damping of electromagnetic oscillations, electric polarization, and magnetization of materials by varying their dielectric and magnetic permeability. Polarized and magnetized materials are the sources of electric and magnetic fields whose energy is beneficial for functioning FS in SM.

Surroundings have a ***chemical effect*** on materials**.** Chemically resistant materials do not enter into chemical reactions with the surroundings, but absorb their active molecules that are concentrated in the surface layer of condensed materials. This phenomenon – adsorption – alters the composition of the sample surface layer and its surface energy thus governing the mechanisms of feedback formation in SM.

Chemical reactions can be accompanied by the release of heat and light, variations in the aggregate state, and other energy transformations that are advisable to use for activating FS. An energy barrier between the initial and transitional states of the reacting material, or activation energy, is governed by variations in Gibbs energy ΔG in the material. A decrease in the Gibbs energy during reaction ($\Delta G \rightarrow 0$) is a necessary condition for spontaneous (without energy supply from outside) reactions. The set of energy sources of reaction activation in materials (plasmochemical, radiation-chemical, thermal, photothermal, electrochemical) provides a variety of energy methods for FS stimulation.

Biological effects on materials are mainly attributed to microorganisms (bacteria, microscopic fungi, and sometimes protozoa and viruses) organized in biological systems. Biological damage of materials is due the necessity of energy supply of microorganisms on account of external sources that are presented by materials. The energy interaction between biosystem and material is based on atomic-molecular processes where the biological catalyzer of energy exchange or enzymes play a major role. The internal energy of materials is converted into, e.g., the energy of creation of electrochemical potentials that arise from concentration gradient of ions H^+ or Na^+ at different sides of the biological membrane of microorganisms [13]. The reduction of internal energy is responsible for the biological damage of materials.

4. A Model of Smart Material

Primary reconstruction of material structure is an inevitable consequence of its interaction with the surroundings. This response of the material to external stimuli results from physical, chemical, and biological processes that occur in the material.

Smart materials differ from simple ones in FS availability (Fig. 1) which corrects the primary reaction of the material to environmental effects via secondary reconstruction of its structure. Let us exemplify this fact in the following manner.

The feedback systems are often presented as a circuit [14] in which a signal from the amplifier output comes to its input (Fig. 2). A *converter* block is a device that converts the input signal z into the output signal Z from which in the next block its part (signal x) branches off. The $x \rightarrow X$ transformation occurs in the feedback circuit following a special algorithm. The feedback system is characterized by the coefficient β of signal transmission along its channel $X = \beta Z$. In the systems with negative feedback $U_{out} < U_{in}$, consequently, $x < X < 0$ and $\beta = X/Z < 0$.

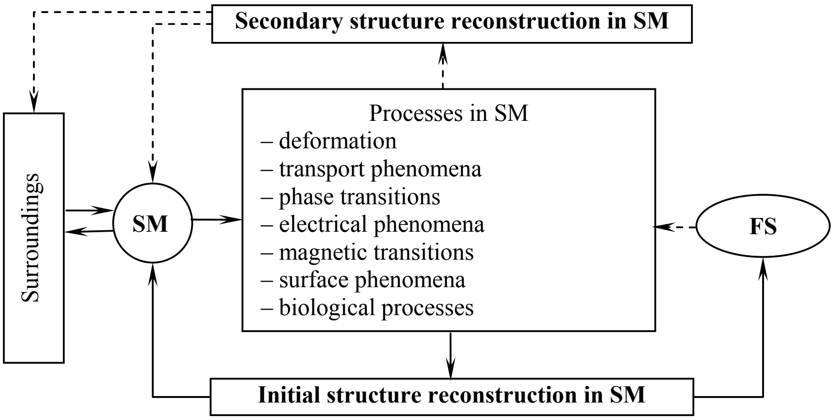

Fig. 1. Diagram of bonds via which the structure of smart material (SM) and surroundings interact with assistance of feedback system (FS). The continuous lines correspond to the primary reconstruction and the dashed lines correspond to secondary reconstruction of SM structure

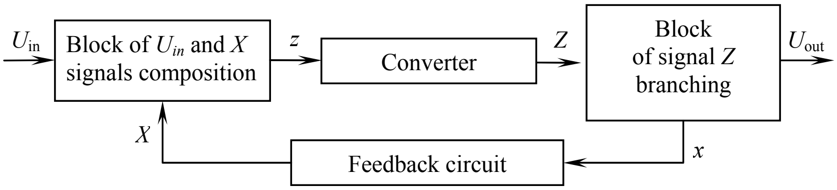

Fig. 2. Block diagram of feedback system [14]

A final SM reaction to external effects results from *smart* correction of its susceptibility to external effects. The correction occurs most often (as shown in Fig. 1) by the same mechanisms as the primary structure reconstruction. The SM structure is repeatedly transformed under the action of FS signals owing to the energy of external effects. Firstly, this leads to the economy of the internal material energy and prolongs its service life. Secondly, this allows the efficiency parameters of the material to be optimized by the criterion of minimum energy losses. The SM structure under external effects varies with time by the *necessary and sufficient* principle.

It can be seen in Fig. 1 that the cycle of the secondary reconstruction of the material is closed in *a black box* presented by the SM structure. External effects are transmitted to it as a rule by means of FS. At the output from the black box, we have the SM properties that are optimized by the criterion of energy conservation. Therefore, the SM model can be presented in a simplified form as shown in Fig. 3. We can comment it as follows. The environmental effects (or operating conditions) cause the primary reconstruction of SM structure. The FS sums up the data about the degree of this reconstruction and intensity of external effects and then initiates (on account of external energy) the secondary reconstruction of SM structure that governs its operating properties. The mechanism of information transfer from environment to FS as well as energy, physicochemical, and biological mechanisms of secondary reconstruction are understandable principally but not fully elucidated. On this basis, the SM structure presented in Fig. 3 as a picked out rectangle can be likened to *a black box* in which the processes run to transform a common material in a smart one.

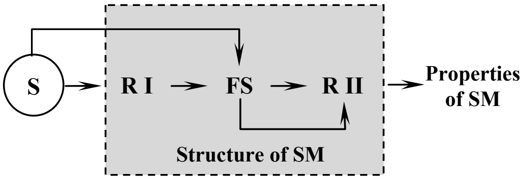

Fig. 3. Simplified model of *smart* material. S – surroundings, RI и RII – primary and secondary reconstruction of the materials, FS – feedback system

5. Experimental Results

The modern materials science has at its disposal a sufficiently wide nomenclature of SM for machine building (tribological, anticorrosion, sealing, and some other designations), medicinal equipment (materials for endoprostheses, applicators, physiotherapeutic articles, and so forth), tare and packing manufacture (baro-, thermo-, and photochrome materials that signalize leakages and worsening quality of the packed products), biotechnologies, filtration systems, radiation protection, etc. [1-5]. Below are given the experimental results that confirm the advisability of SM model realization (with different degrees of completeness) in adaptive, active, and smart materials and engineering systems.

A polymer anticorrosive film designed for packing metallic parts is a typical example of SM [15]. In its surface layer, it contains a complex of contact and volatile corrosion inhibitors (CI). A part packed in the cover of such film is protected from corrosion at the initial stage of storage owing to the transfer of contact inhibitor from the film to the part surface. With evaporation of the volatile inhibitor, a partial pressure of vapors of the second inhibitor is additionally created in the cover, its adsorption on the surface protects the parts from corrosion for a long time (for years). The evaporation is ceased in the sealed cover once a critical pressure is achieved. If the sealing is failed, the evaporation continues producing a protective environment in the cover until the inhibitor is present in the film.

Figure 4, *a* shows the microstructure of the polyethylene film made by sleeve molding and thermodiffusive saturation (while the sleeve is blown up) of the polymeric basis with volatile CI G-2 in the oil solution of the contact CI MSDA [16]. The micropores are seen through which contact CI is delivered to the film surface and volatile CI is evaporated. At the initial stage, kinetic curves of G-2 evaporation from the films (Fig. 4, *b*) are parabolic dependencies $m/m_0 = a\tau^{0,5}$, where m and m_0 are CI amounts desorbed for time τ , and $\tau_0 \rightarrow \infty$, a is a coefficient. This indicates that the rate of evaporation is limited by CI diffusion in the film pores. The kinetics of evaporation of initial G-2 is linear. The evaporation of volatile CI depends on its concentration in the film, production method, and is accelerated with temperature elevation.

In this *smart* system, the evaporation of volatile inhibitor functions as FS. It is limited by partial pressures of its vapors in the hermetically sealed cover. A second FS can operate in smart film that is based on the color chemical reaction of the volatile inhibitor with filler particles in the film that are, e.g., green in color. When the inhibitor is exhausted, the filler changes its color from green to red. This is a signal for repacking the part in a new cover made of a fresh film [15].

It is rather difficult to obtain FS in the structure of one material. It is a far easier to create it in an engineering system (electric, tribological, etc.) where a material displays the features of artificial intelligence owing to the fact that FS functions are spread between the system elements. A friction unit

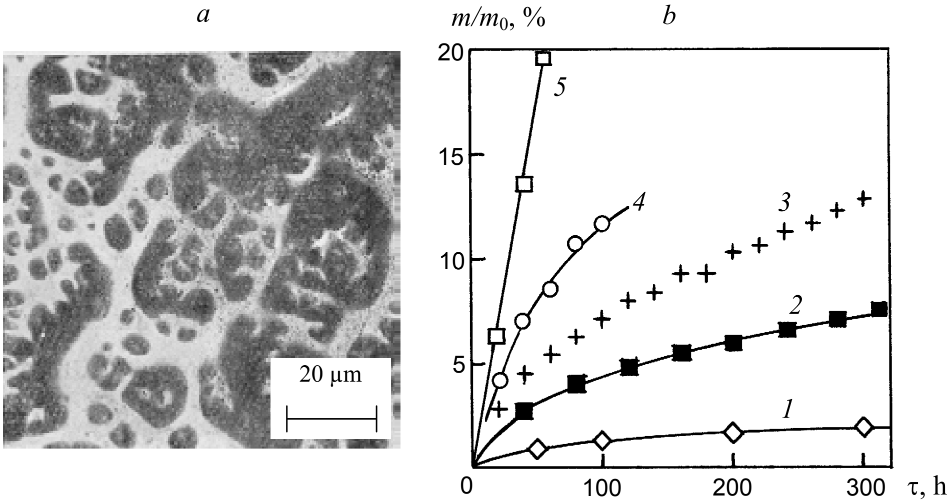

Fig. 4. Microstructure (*a*) of the film surface and kinetic curves (*b*) and evaporation of volatile CI G-2 from the film: CI concentration: 1÷3 – 0.09 wt %; 4 – 1.4 wt %; 5 – G-2 in its original state. Temperature 25 °C (1, 4, 5), 50 °C (2), and 60 °C (3)

in which ***the effect of selective transfer*** is realized can serve as a classical example of *smart* system. It was discovered in the 1960s by Russian tribologists D. N. Garkunov and I. V. Kragelsky in copper alloy friction against steel under boundary lubrication with alcohol-glycerin mixture which excludes copper oxidation. At sliding velocities of up to 6 m/s, pressures from 30 to 40 MPa and temperatures from 40 to 70 °C a servovit copper film about 1 μm thick is forming on the friction surface of the steel part under steady state friction. The lattice in this film has numerous vacancies: more than 10 % of lattice nodes are not occupied with atoms. The wear of such pair is reduced to the transfer of the servovit film from one surface to another. Owing to this, the coefficient of friction in the pair declines down to the values that bare characteristic of liquid lubrication, which provide the effect of wearlessness [17].

The *smart* system of selective transfer is controlled by FS whose function is performed by the electric field of the *steel–alcohol mixture–copper* galvanic pair. The servovit film consists of colloid copper particles that result from the anode reaction in this pair and forms via the electrophoresis mechanism in its field [18].

The human joint that operates under significant loads for decades and is characterized by extremely low coefficient of friction (0.02 ÷ 0.05) and cartilage wear compensation, is a *smart* friction assembly. The sympatic nervous center that regulates the permeability of blood capillaries, production of lubricating synovial fluid, its circulation in the cartilage friction zone, etc. plays the role of FS [19]. ***Joint endoprostheses*** (implants of movable bone junctions) differ from natural joints primarily in the absence of cartilages, antifrictional microporous bodies filled with synovial fluid (SF). When a healthy joint is loaded, the SF is released from the micropores on the friction surface sites that undergo the highest load and lubricates them. The creation of an artificial cartilage is the first step in approximating implants to a *smart* system. It is a microporous layer (Fig. 5, *a*) that forms on endoprosthesis parts made of ultrahigh-molecular-weight polyethylene (UHMWPE). The material has operated reliably in endoprosthetics friction pairs since the 1960s. The micropores of artificial cartilage can be filled with drugs to accelerate the healing of the operative wound [20].

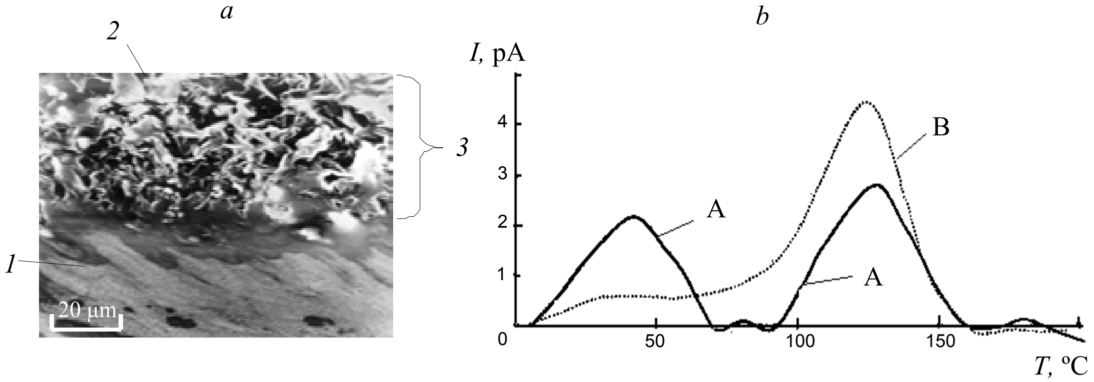

Fig. 5. Cross section (*a*) and TSC spectra (*b*) of UHMWPE cartilage: 1 – initial UHMWPE structure; 2 – friction surface; 3 – microporous layer. A – initial sample; B – after friction in synovia (p = 2 MPa, v = 0. 1 m/s)

Operation on the joint is not just the removal of pathologically modified tissues but also a procedure that destroys natural distribution of the biophysical field of the joint. The defects of the biofiled can be compensated by electric polarization of the artificial cartilage. The polarization charge formed in the dielectric part of endoprosthesis is maintained for a long time at friction. It enhances the adsorption of SF and products of its tribodestruction on the surface of artificial cartilage. A peak that corresponds to the polymer melting temperature (135 °C) is enhanced on the spectra of thermally stimulated currents (TSC) of the UHMWPE electret samples subjected to friction in SF (Fig. 5, *b*). This indicates that the electret field-induced adsorption of tribodestruction products of the synovia has occurred on the friction surface [21]. The adsorption layer is capable of self-recovery, provides boundary lubrication and protects the polymer part from fatigue wear in the form of subsurface cracks [20].

Unipolar joint endoprostheses operate in the friction pairs with a natural cartilage. The spherical head of the endoprosthesis traumatizes and damages the cartilage with time. In order to prolong the life of the reconstructed joint, an artificial cartilage is formed on the UHMWPE head and its micropores are filled with drugs, namely, chondroprotectors that accelerate the physiological regeneration of the cartilage [22]. The chondroprotector is released from the micropores in those parts of the natural cartilage that contact the head and are deformed by it. This serves as a signal for activating a natural joint FS to initiate the regeneration of the cartilage tissue. Presently *smart* endoprostheses with artificial cartilage are clinically tested at behest of the Ministry of Health of Belarus.

The *smart* sealing system (Fig. 6) is provided by a liner in the form of a T-shaped porous polymer ring whose communicating pores contain up to 30 wt % of liquid metal [23].

As the set of electromagnets is switched on, a magnetic flow arises in the liner that induces annular currents in the liquid-metal filler. When exposed to the compressing electromagnetic force, the filler occupies the position in the liner volume that is symmetrical relative to magnetic poles. At pressure difference Δp occurring in the liner the liquid metal moves from this position to one of the magnets. Its interlinkage, induction annular current, and, respectively, electromagnetic force to hold the filler in the pores increase. Therefore, depending on the pressure difference, the electromagnetic force directed inversely to the vector Δp varies automatically. The experiments show that these *smart* liners reliably seal media under excessive (2 to 3 MPa) and vacuum pressure (up to 10^{-4} mmHg). Here,

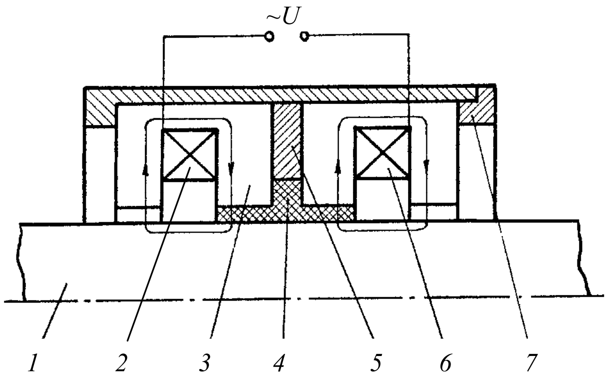

Fig. 6. Induction liquid-metal liner: 1 – ferromagnetic shaft; 2, 6 – energizing coils of electromagnets; 3 – magnetic circuit; 4 – T-shaped porous ring with liquid-metal filler; 5 – diamagnetic dividing bushing; 7 – seal unit case

the electromagnetic interaction between the liquid-metal filler and magnetic system field performs the FS functions.

An electret biodestructable polyolefin-based film [24] was developed in connection with the following problems. Utilization of packing wastes became a global challenge long time ago; therefore, accelerated biodestruction in soil is a necessary demand for packing films throughout the world [25]. This is achieved by filling a polymer binder with substances that serve as energy sources for microorganisms, i.e. by biopolymers, primarily, starch, some inorganic salts, etc. [26]. Nowadays, chemical technological reserves of film biodestruction acceleration with the use of these methods are exhausted. However, the barrier can be overcome when forming a polarization charge of optimal density in the film [27]. When employing the film, the charge increases the storage terms of certain food products without preservatives [28] and improves the deformation strength characteristics of packing [12] and storage conditions of packed fur and textile products [24]. When recycling the films in soil an electret charge (with the surface density 4 to 8 nC/cm^2) causes an accelerated biological proliferation of the films (up to 40 %) with the colonies of soil microorganisms [29]. As a result, the electret film starts losing strength almost immediately on being appeared on a trash dump and is destroyed faster than the non-electret one (Fig. 7) degrading totally within 2 years. The electret charge field is an ecologically safe factor and disappears in the course of film biodestruction.

The electret biodegradable film is a typical active material that organizes in a particular manner the surroundings soil microbiota. The film does not belong to SM since it does not have FS to regulate the activity of microorganisms in the course of film biodestruction that is degraded into fine (of mm-order) ecological harmless fragments. To convert a biodestructable film into biodegradable one (final products are water and CO$_2$), one should create a control system of energy exchange between microorganisms and polymer electret that can optimally concentrate the energy on the hard-degradable film parts.

Conclusions

Modern materials science possesses an ever-increasing variety of smart materials. It has become critical to move the process of smart materials and smart engineering systems creation from heuristic

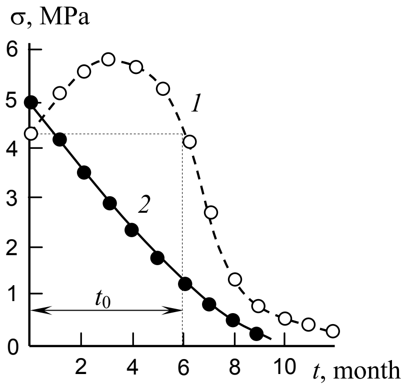

Fig. 7. Ultimate tensile strength of starch-filled (20 wt %) polyethylene films vs. exposure time in soil: 1 и 2 – non-electret and electret films; t_0 – biodestruction incubation period of non-electret film

insights to the professional "handicraft" methodical basis that allows specialists to develop SM in their routine work. The following prerequisites exist for such change.

External (operating) effects on materials are a primary chain and energy source for a SM cybernetic system. They implement their function via altering the internal energy and structure of the material. The regularities of material responses to chemical, physical, and biological effects are responsible for the realization of the set of feedback mechanisms. The latter, depending on the degree of primary structure transformation, spends a part of the energy of external effects on its secondary reconstruction. This process determines the economy of the material's internal energy in response to external effects thus prolonging its service life. Under the action of FM, the SM structure varies with minimal energy losses following the *necessary and sufficient* principle.

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Умные материалы в материаловедении

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Умный материал – это особым образом организованный материал, отличающийся от обычного тем, что элементы его структуры имеют свойства кибернетической системы, рационально приспосабливая материал к изменяющимся условиям эксплуатации. Предложена модель умного материала как атомно-молекулярной структуры, снабженной системой обратной связи, которая оптимально корректирует первичную реакцию материала на воздействие окружающей среды. Приведены результаты экспериментов, подтверждающие целесообразность реализации модели умного материала в материалах и технических системах.

Ключевые слова: умный материал, окружающая среда, внешние воздействия, система обратной связи, модель.