INFORMATION SYSTEMS AND INNOVATIVE TECHNOLOGIES IN PROJECT AND PROGRAM MANAGEMENT

Collective monograph edited by
I. Linde, I. Chumachenko, V. Timofeyev

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The monograph presents the achievements of Ukrainian scientists on enterprise management, the use of economic and mathematical modeling, information technologies, management technologies and technical means in the field of enterprise functioning and development and project management at enterprises.

The publication is recommended for professionals in the fields of economics, information technology, project and program management - for undergraduate and graduate students, as well as academics and teachers of higher education.

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CONTENT

21. MODELING OF DESTRUCTION PROCESSES OF THE INSTALLATION CONNECTION OF ELECTRONIC EQUIPMENT

Nevliudov I., Demska N., Starodubcev N., Nevliudova V.

Modern technologies move away from the traditional design of hard electronics into the form factors of flexible switching structures, which are often operated in a dynamic mode and can be subjected to such actions as alternating loads, bending and twisting, stretching, vibration, the presence of a chemically aggressive environment, etc. Despite a large number of existing studies using an arsenal of achievements in the field of materials science, means of classical and quantum physics, the theory of chemical reactions, statistical physics, fracture mechanics, up to date, some essential phenomena occurring at the atomic-molecular level during the implementation of the manufacturing process and design of flexible structures have not been fully disclosed. In this paper, we consider the processes of the appearance in the materials and structures of connectors of products of physicochemical reactions associated with the presence of two sources of medium formation, which are interpreted as the formation in a certain place, over a certain period of time, of a substance with new properties, the appearance of which can cause degradation processes. As a result, the obtained dependences, together with the statistical processing of the obtained information, can provide a sufficient description of the process for its optimal control, even under conditions of incomplete certainty about the subtle mechanisms of atomic-molecular interaction between the materials involved in the process.

At the moment, production trends are based on the introduction of new solutions and technologies Industry 4.0, IoT, cloud services, etc. [1-2], the most important role in the performance of which is played by modern automation equipment (sensors, actuators, regulators, etc.), which are designed to provide the necessary level of accuracy, performance parameters, small overall mass characteristics, high functionality, low power consumption and cost [1].

The main problem of integrating modern technical means for introducing Industry 4.0 technology remains that now, all finished parts are based on traditional electronic components of rigid (flexible-rigid) printed circuit boards, which are significant in thickness and limited in flexibility, and also cannot be fully adapted hardware solution for each specific size and shape of the automation object [3]. Therefore, modern technology is moving away from the traditional design of hard electronics in the future of flexible form factors that can offer new features that were not previously possible, especially in markets such as medicine, IoT, sensors and smart textiles [4].

The scope of application of flexible electronics is quite wide and covers both household appliances and components of military, aviation, space, medical and industrial equipment. Their widespread use in these areas is due to several advantages: compactness, even with a large number of contacts; simple and quick replacement of damaged cable; organization of conductors, eliminating entanglement; connection of modules and actuators, remote from each other, within one unit or product; "Mobility" of the connection [5].

Most flexible circuits are just passive connectors that are used to connect electronic components such as integrated circuits, resistors, capacitors. However, some of them can be used to create mutual communication between other electronic units either directly or through connectors.

More than 50% of the failures of the electronic equipment (EE) are connected to the connectors. Their possible causes may be: corrosion, loose connection, loss or deformation of the cable due to vibration [6].

Molecular-kinetic models, using an arsenal of classical and quantum physics, the theory of chemical reactions, statistical physics, fracture mechanics [7], etc., give an idea of atomic-molecular interaction, revealing the subtle mechanism of physicochemical processes in production and operation of EE.

The use of these models is a prerequisite for the creation of EE with new operational and technical properties and the corresponding technological processes. The success of these models is associated with the processing of a large amount of information, often obtained using unique tools and mathematical methods.

The basis for modeling the destruction processes of the EE mounting joint can be the theory of the destruction of solids, the basic principles of which are to consider the destruction process as the action of creep phenomena and brittle fracture arising under the action of an external force load, while conditions arise for exceeding the allowable tensile strength. It seems important to ensure such a fracture mechanism [8] when there is no significant rearrangement of the internal structure of the material, i.e. creep effect reduction [9].

Many properties of materials and, in particular, mechanical and dielectric properties exhibit peculiar features due to the partially delayed reaction of the material to external influences. Any deformation of the material under the action of an external force is not accompanied by an instantaneous restructuring of the internal structure to an equilibrium state that meets new conditions. This requires a certain period of time until all particles in accordance with these conditions come to equilibrium. So, if you quickly deform the material and maintain the degree of deformation constant, then the stress required for this gradually decreases (stress relaxation). If, having quickly deformed the material, to maintain a constant voltage, then for some time the strain (strain relaxation) will increase. The physical mechanism of this process is currently presented as follows.

Atoms of a solid make thermal fluctuations with period $t_{p0} \approx 10^{-12} \div 10^{-13} c$. Under the influence of thermal fluctuations from time to time, there is a rupture of chemical bonds. The probability of this event, equal $\exp(-U_a / kT)$, depends on the height of the activation barrier U_a and temperature T, decreasing with increasing U_a and decreasing T. In the absence of external voltage (at $\sigma = 0$), the energy required to break the bond is equal $U_0 = Q_{subl}$ for metals and $U_0 = Q_{destr}$ for polymers. The stress σ created in the body reduces the activation energy of the destruction process from U_0 to $U_0 - \gamma\sigma$ and thereby increases the probability of bond breaking, and, consequently, the number of broken bonds in a unit volume.

The formation of submicroscopic regions with broken bonds and their fusion with each other leads to the fact that the body is destroyed by the applied voltage. The higher is a so the stronger the activation energy decreases, the faster and in a larger number of broken bonds, therefore, the less time is required for the development of the destruction process.

Thus, to ensure the fracture mode in the absence of noticeable creep, only a short-term insignificant increase in stress over the tensile strength is necessary.

The theoretical strength of solids σ_0, calculated according to one atomic model or another, is many times greater than the real strength σ_r. At present, it is generally accepted that such a difference between σ_r and σ_0 is explained by the presence of various kinds of defects in real solids, in particular, microcracks, which reduce their strength [10]. The appearance of a crack of length l leads to a stress concentration at its edges if a tensile force F_{out} is applied to the specimen (Fig. 1).

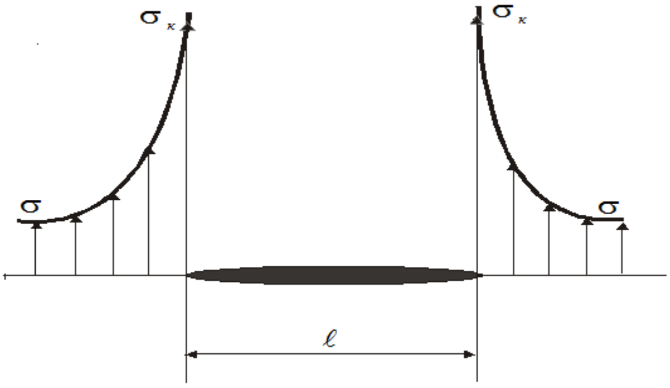

Fig.1. The stress concentration at the edges of the crack

The process of destruction proceeds more or less gradually and takes a certain time t_p to complete. This time required for the development of the process of destruction from the moment of loading the body to the moment of its rupture is called the temporary strength or durability of the material [11-12].

The durability of the material being destroyed t_p, tensile stress σ and absolute temperature T are related by the following relation:

$$t_p = t_{p0} \exp[(U_0 - \gamma\sigma)/kT], \tag{1}$$

where t_{p0}, U_0 and γ – constants, depending on the nature and structure of the material.

Logarithm (1), we obtain

$$\ln t_{p0} = \ln t_{p0} + (U_0 - \gamma\sigma)/kT = \ln t_{p0} + U_a/kT, \tag{2}$$

where $U_a = U_0 - \gamma\sigma$ – fracture activation energy.

These formulas were tested on a large number of various materials (metals, glasses, polymers, crystals, etc.) with a change t_p of 8–10 orders of magnitude and change of T in a wide spread. This means that t_{p0} for all materials is approximately the same. As experiments have shown, t_{p0} for all materials is approximately the same and approximately equal $10^{-12} \div 10^{-13} s$, that is, close to the period of atomic vibrations near the equilibrium positions. Building dependence $\lg t_p$ on $1/T$, for a given σ, U_a can be experimentally determined. It has been established that for metals U_a it coincides well with the energy of sublimation, for polymers - with the energy of thermal destruction, i.e. with energy breaking chemical bonds.

The magnitude of the stress at the edge of an acute crack having a radius of curvature *a* is determined by the following relation:

$$\sigma_{edg} = \sigma(1 + 2\sqrt{l/\mathrm{a}}), \tag{3}$$

where σ_{edg} – stress at the crack edge;

σ – cross-section average stress.

The destruction of the sample occurs at a value $\sigma = \sigma_r$ at which the stress σ_{edg} reaches the theoretical strength of the material σ_0:

$$\sigma_{edg} = \sigma_r(1 + 2\sqrt{l/a}) = \sigma_0. \tag{4}$$

From here you can determine the real strength of the material σ_r:

$$\sigma_r = \frac{\sigma_0}{1+2\sqrt{l/a}} \approx \frac{\sigma_0}{2\sqrt{l/a}}. \qquad (5)$$

From relation (5) it can be seen that the real strength of the body is the lower, the longer the crack that appears in it and the smaller the radius of curvature of its edge. In order σ_r for it to be 0.01 σ_0, it is sufficient that cracks in the body of $l \approx 1$ microns in size with a radius of rounding off of the edges are equal to the lattice parameter.

Thus, the fracture mechanism of a compound is based on the nucleation and development of cracks and microcracks in a medium formed during the formation of a compound containing defects in the microstructure. A significant stress concentration at the edges of the crack leads to conditions when the fracture time of the material becomes much less than the relaxation time, i.e. to ensure the minimum impact of the fracture process on the restructuring of the material structure adjacent to the fracture surface. In practice, such conditions can be realized in such a test mode of joint strength, when significant deformations are achieved in a few seconds, which leads to short-term creep, and the process is characterized by brittle fracture.

When installing EE, sufficient conditions are created for the implementation of such a destruction mechanism. One can make an assumption about the presence of two sources of the formation of the medium containing structural defects: firstly, particles of foreign substances; secondly, the products of physic-chemical reactions on the surface and in the volume of the material forming the compound (MFC). These sources are very intense at the stage of MFC activation during installation, especially in the absence of a protective environment.

Removing foreign substances from the surface is fundamentally impossible in real installation conditions since even with perfect cleaning of the surface from mineral and organic contaminants, the metal surface is so active that it is almost instantly covered by environmental molecules that form adsorbed films on it. First of all, oxide films are formed on metals and semiconductors, the thickness of which can vary from a monomolecular layer to tens to hundreds of nanometers. In addition to oxide films, the surface can capture fairly thick layers of water, fat and other substances from the environment. The strength of fixing adsorbed layers, especially oxide films, is very high, and their removal from the surface is very difficult.

A feature of the surfaces of polymeric materials [13] is their high hydrophobicity. The process of adsorption and penetration of moisture through the surface consists of sorption (absorption) of its surface diffusion into the surface layer and possible desorption (separation) at the interface between the surface and the environment. With a weak interaction of moisture with the surface, the speed of its passage through the surface is determined by the law of diffusion

$$Q = DStdc / dx, \tag{6}$$

where Q – amount of diffused moisture;

dc/dx – its concentration gradient in the surface layer;

S – surface area;

t – diffusion time.

With a weak interaction of moisture and the polymer, Henry's law is usually fulfilled, according to which the concentration of moisture in the polymer is proportional to the vapour pressure above the polymer p :

$$c = \alpha p, \tag{7}$$

where α – sorption coefficient.

Substituting (7) into (6), we find

$$Q = AStdp / dx, \tag{8}$$

where $A = D\alpha$ – permeability coefficient, numerically equal to the amount of steam passing through a unit area of the polymer surface per unit time with a pressure gradient equal to one.

For an example Tab. 1 shows the time of formation of a monolayer of moisture calculated by (8) for a number of polymers widely used in EE. The data of the Table1 shows that the time of occurrence of the monolayer can be significantly less than the time of the interoperation gap during the installation of EE.

Table 1 - The time of formation of a monolayer of moisture for a number of polymers

Material	The time of formation a monolayer of moisture, s
Ftoroplast -4	2400-600
Epoxy resin	35
Polyethylene	45-22
Polystyrene	10-5
Silicon-Organic Rubber	5-1

Water permeability substantially depends on the physical state of polymers, the flexibility of their chains, the packing density of molecules, and other factors. Amorphous polymers with flexible chains that are in a highly elastic state (rubbers, rubbers) have the highest permeability, polymers with rigid chains in the glassy state have the lowest permeability. In the same state, the permeability of the polymer decreases with increasing packing density of its molecules and reaches its maximum value in the crystalline or partially crystalline state (fluoroplastic-4).

These patterns are easy to understand by considering the mechanism of diffusion of vapours and gases in polymers. As in the case of liquids, the diffusion of gas molecules in polymers occurs along with voids, which are continuously formed due to the thermal motion of individual sections of the molecules. With the increasing flexibility of chains, their mobility increases, and, consequently, the probability of the formation of voids along which vapour molecules can diffuse, which leads to an increase in the permeability of polymers in a highly elastic state. In glassy polymers with rigid chains, the permeability increases with increasing friability of the molecular packing, leading to the appearance of a large number of micropores.

Thus, it can be assumed that the surfaces prepared for joining are a rather powerful source of foreign particles, which weaken the strength of the material and determine the mechanism of the onset of the fracture process as the occurrence and development of cracks. A significant increase in stress at the ends of a developing crack causes a weakening of the creep processes and towards brittle fracture. The development of microcracks occurs in a layer of material, the structure and properties of which can be determined by the nature of the physicochemical interaction in which the materials to be joined are involved, with the participation of external factors that contribute significantly to the imperfection of the structure and composition of the MFC layer.

Depending on the initial physicochemical properties of the materials being joined, as well as the mounting conditions, the MFC in the composition of the compound may have a different structure and composition.

Polymeric materials are characterized by the manifestation of the basic properties associated with thermosetting and the influence of activators such as solvents, thickeners, and other components, which lead to a significant change in the properties of polymeric MFCs after the formation of the compound. A targeted effect on the course of the process of the compound formation using polymeric materials takes into account the regularities of the influence of solvents and other additional components on the structure of the material, its rheological properties, diffusion and adsorption to joined surfaces.

The main interest is the laws of mass transfer, leading to diffuse phenomena that lag behind in speed from the processes of adsorption and swelling of the initial surfaces. The general idea of the diffusion mechanism during the interaction of polymeric materials is given by the theory of stochastic processes, which relates the value of the diffusion coefficient to the frequency of the molecule jump and its mean free path [13]. This allows us to consider the transition of a diffusing molecule from one position to another as overcoming the energy barrier between two equilibrium states, to characterize the total energy expenditures for the transfer of a substance in the structure of a polymer material, and on this basis to analyze the mass transfer processes during the formation of an assembly joint. The absolute values of the diffusion activation energy for materials of various nature and installation conditions vary widely. A common technique for changing the activation energy is the introduction of an organic solvent, which leads to its decrease, which manifests itself in an increase in the diffusion coefficient and corresponding acceleration of the whole process.

A large role in the installation process using polymeric materials can play the porosity of the connected surfaces. When considering the laws of transport [13] in a system of static micropores whose radius is much larger than the size of diffusing particles, the diffusion coefficient depends on the porosity of the polymer; tortuosity of pores; a change in chemical potential during the transition of a material from a dissolved to an adsorbed state; concentration of adsorption centers.

A simpler version of the interpretation of the diffusion mechanism in polymers is to use the results of the theory of the free volume of the polymer V resulting from the thermal motion of segments of the polymer chain. Since any condensed medium has a free volume, in the presence of solvents, plasticizers, and other components, the total free volume in a first approximation is determined by the sum of the free volumes of the system components, and the free volume of each component increases linearly with increasing temperature. Therefore, the value V can be expressed by the relation

$$V = V_{c1} + \alpha_1 (T - T_{c1}) \upsilon_1 + V_{c2} + \alpha_2 (T - T_{c2}) \upsilon_2 + \ldots = \sum_{i=1} [V_{ci} + \alpha_i (T - T_{ci}) \upsilon_i], \tag{9}$$

where V_{ci} – fraction of the free volume of the *i*-th component at its glass transition temperature T_{ci}; υ_i – volume fraction of the *i*-th component in the system; T – temperature exceeding T_{c1}; α_i – a jump in the temperature coefficient of expansion at a temperature above T_{ci} and below it. It is accepted here that polymer characteristics have an index $i = 1$.

In the case when a practically pure polymer $(\upsilon_1 \approx 1)$ is considered in the presence of a very small amount of a diffusing substance ($\upsilon_2 \approx 0, \upsilon_3 \approx 0$ etc.), the free volume of the polymer

$$V = V_{c1} + \alpha_1 (T - T_{c1}). \tag{10}$$

An increase in the free volume of the polymer leads to an increase in the diffusion mobility of the low molecular weight substance. At the same time, the free volume of the polymer according to formula (9) increases with increasing temperature and the concentration of the solvent or plasticizer. Moreover, the presence of a solvent contributes to a sharper increase in the free volume compared to the initial polymer with increasing temperature, the free volume theory suggests that the diffusing molecule moves without energy consumption and depends only on the probability of the appearance of a required microcavity near the molecule. The temperature dependence of the diffusion coefficient in the form of relation (9) taking into account (10) allows one to reveal the effects of plasticizing substances that lower the glass transition temperature of the polymer.

Conclusions

At present, some essential phenomena occurring at the atomic-molecular level during the implementation of the process are not fully disclosed. In addition, the adequacy of models largely depends on random, unforeseen factors, which can significantly reduce the efficiency of using models in real conditions of production and operation of EE.

In this study, an MFC fracture mechanism is proposed that uses the basic principles of the theory of fracture of solids, which suggest that the fracture process be considered as the action of creep and brittle fracture, provided that the allowable tensile strength is exceeded due to stresses arising from external forces. These conditions are provided when testing the mounting connections for strength and lead to the formation of PR.

The basis of the accepted destruction mechanism is the presence of defects, the source of which is the introduction of foreign atoms and molecules into the MFC. When installing EE, sufficient conditions are created for the implementation of such a destruction mechanism. Under conditions of short-term creep, the process is characterized by brittle fracture, the fracture mechanism is based on the nucleation and development of cracks and microcracks in the medium of the test material.

As a result, the obtained results, together with the statistical processing of the obtained information, can provide a sufficient description of the process for its optimal control even in conditions of incomplete certainty about the subtle mechanisms of atomic-molecular interaction between the materials involved in the process.

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