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WAYS TO INCREASE THE RESISTANCE OF THERMOELECTRIC COOLING MODULES TO MECHANICAL IMPACTS

The possibility of a significant increase in the resistance of thermoelectric modules to mechanical impacts is shown. Bibl. 14, Figs. 7, Tabl. 2.
Key words: thermoelectric modules, reliability

Introduction

Thermoelectric modules are widely used in various industries, including telecommunications technology, aerospace, defense and special equipment, medical technology, automotive and household industries. In addition to performing cooling and heating functions in the above applications, thermoelectric modules are also used for direct energy conversion and recovery of low-grade waste heat into electrical energy. Among all applications, a significant number of modules are used in devices operating under significant mechanical loads - vibration, impacts. The resistance of thermoelectric modules to mechanical loads is especially important when used in military equipment, aerospace systems.

The purpose of this work is to highlight methods for increasing the resistance of thermoelectric modules used in military and aerospace products to mechanical impacts.

1. Design elements of modern cooling modules and their impact on reliability

Typical designs of modern cooling modules, mass-produced in different countries of the world [1, 2], contain series-connected thermocouple elements, which are mounted on flat ceramic plates. The plates perform the function of an electrically insulating heat spreader and simultaneously serve as design elements that provide rigidity and mechanical strength of the thermoelectric module. Thus, in the mentioned configuration of the module, the thermocouple half-elements (legs of *n*- and *p*-type conductivity) are connected in a series electrical circuit, and mechanically and with respect to the direction of the heat flow – in a parallel one.

Since thermoelectric modules are solid-state devices, the primary failure mechanism will be the destruction or degradation of the half-elements and soldered joints. Such failures occur due to mechanical stresses generated either by an external source (impacts, vibrations, lateral displacements, compressive or tensile loads) or by internal factors (thermomechanical stresses arising from a significant difference in the coefficients of thermal expansion of the materials that make up the structural elements of the modules: ceramics, copper, solder, nickel, thermoelectric material).

This paper considers mechanical stresses in a thermoelectric module, which are limited to the case when their occurrence is caused by the action of single mechanical impacts.

Mechanical impact is accompanied by a rapid release of energy leading to internal local elastic or plastic deformations in the thermoelectric module, generating waves of mechanical stresses and other effects that result in the loss of functionality or even complete destruction of the module structure. The impact load on the thermoelectric module also generates rapidly damped resonant oscillations in it. The values of overloads due to the impact, the nature and speed of distribution of mechanical stresses in the module structure are determined by the force and time of the impact, the nature of the change in acceleration. The impact acting on the thermoelectric module can lead to its destruction as an integral structure. A single impact can cause the destruction of a thermoelectric module due to the occurrence of powerful, albeit short-term overloads in the constituent elements of the structure. Multiple single impacts can lead to the accumulation of micro deformations, which can also lead to the destruction of the module. Due to the fact that the design of the thermoelectric module is an analogue of a spatial truss (which has resonant properties), even a single impact can cause an oscillatory process in the ensemble of thermoelectric half-elements, the ends of which are rigidly fixed between ceramic plates. This oscillatory process can also be accompanied by the appearance of microcracks in the thermoelectric material and in the contact zone of the thermoelectric material – anti-diffusion coating – connecting plate.

The resistance of the thermoelectric module to impacts will be determined by the elements of its design that are characterized by the lowest values of the tensile strength. Considering the design scheme of the thermoelement (Fig. 1), it can be assumed that the maximum strength of the thermoelement will be determined by the tensile strength of the thermoelectric material.

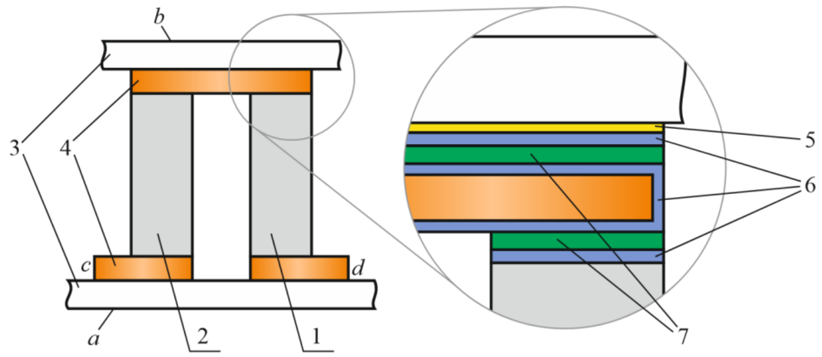

Fig. 1. Thermoelement design diagram: 1, 2 – half-elements of n- and p-type conductivity, 3 – ceramic plates, 4– copper connecting plates, 5 – ceramic plate metallization, 6 – nickel layers on the ceramic plate metallization, copper connecting plate and half-element contact surface, respectively, 7 –solder layers between the ceramic plate and connecting plate, as well as between the connecting plate and half-element. (a, b – the "hot" and "cold" sides, respectively; c, d – current leads).

This follows from the fact that the strength of the components of the thermoelement (ceramic plate, copper connecting plate, solder gaps in soldered joints) significantly exceeds its value for the bismuth telluride-based thermoelectric material. In addition, it is believed that the adhesion strength of the metallization to the ceramic and the nickel anti-diffusion coating to the thermoelectric material should exceed the cohesive strength of the corresponding materials. The presence of defects in the coatings leads to a decrease in their adhesion and, accordingly, to a decrease in the strength of the modules as a whole. This is especially true for anti-diffusion nickel layers located on the ends of the legs (half-elements). The main defects that lead to a decrease in the adhesion of nickel anti-diffusion coatings on the legs include: remnants of near-surface disturbed layers of thermoelectric material, microcracks, voids and cavities in the contact zone of the material, unremoved local contamination of the surface on which nickel layers are deposited, the presence of oxide films on the surface, wear and insufficient purity of electrolyte components, and other factors [3]. In addition, the deterioration of the adhesion of anti-diffusion coatings can be caused by defects that occur when cutting nickel-plated thermoelectric material blanks. During such cutting (even in the most gentle mode using diamond wires [4]), microcracks of the material under the coating and microdetachments of the coating from the material in the cutting zone can occur. Such defects are very difficult to detect when performing quality control of modules. They are potentially dangerous because they can develop over time and lead to failure of the thermoelectric module. Testing even a small sample from a batch of modules for resistance to single impacts allows us to identify the presence of dangerous defects and, if necessary, reject the batch. The point is that in the absence of defects in anti-diffusion coatings, their adhesion will exceed the cohesive strength of thermoelectric materials and the impact resistance of modules will fluctuate within the limits determined by the variation of cohesion at its average values. In the case of defects in coatings that have a tendency to develop, the impact resistance of modules will be determined by the combination of characteristics of the cohesive strength of thermoelectric materials and reduced adhesion In this case, the range of impact resistance of modules will be shifted towards lower accelerations. The spread of impact resistance values indicates the presence of dangerous similar defects and the need to reject a batch of modules manufactured in one technological cycle. The data obtained during impact testing of modules can be used to determine the reliability of a manufactured batch of modules by finding the Weibull material function [5].

2. Methodology and results of single impact testing of thermoelectric modules with standard type anti-diffusion coatings

The condition for using thermoelectric modules in the telecommunications sector is their compliance with general reliability requirements. Currently, the generally accepted regulations for the reliability of thermoelectric modules are the Telcordia GR-468-CORE document [6] and the MIL-STD-883F standards [7]. This paper describes a method for testing thermoelectric modules for resistance to single impacts, created in accordance with the specified documents. For testing, a random sample of 6 modules was taken from a batch of 30 units. The tests were carried out on an impact bench with a falling platform ЕБРИ.44043.001 developed at the Institute of Thermoelectricity. The bench allows testing thermoelectric modules in the range of peak impact loads of 500 – 3400 g with a half-sinusoidal acceleration pulse shape, 0.35 – 2.0 ms in duration. The modules were fixed with the lower ceramic plate to a thick metal plate connecting to the platform using epoxy adhesive and kept at room temperature for 24 hours. This was done to prevent the appearance of additional internal mechanical stresses in the module that could affect the test results. A metal plate weighing 30 g was attached to the upper ceramic plate using the above method (as a simulator of the mass of the object being cooled). The tests were performed under impacts with a half-sinusoidal acceleration pulse shape, 0.5 ms in duration, directed in the lateral directions (X; Y axes) and along the normals to the plane of the ceramic plates of the module (axis +Z – compressive loads and axis –Z – tensile loads). In principle, the impact test along the +Z axis (compressive stresses) could not be performed, since the compressive strength of the thermoelectric material is much higher than its tensile strength. However, even in this case, the probability of microcracks in the half-element body, which can subsequently develop to macrosize, makes it necessary to perform impact tests of the modules in the +Z direction as well. The number of impacts on each axis is 5, the initial level of peak accelerations is 1000 g. The criterion for module failure is an increase in internal AC resistance of more than 1% (at a constant module temperature). The test results of modules with a standard anti-diffusion coating are given in Table 1. The results show that there is a significant spread in the values of the resistance of modules with standard anti-diffusion coatings. If the maximum resistance of modules to impacts (1820 g, 1760 g, 1780 g) is characterized by violations of the integrity of the modules due to the rupture of the half-elements along the thermoelectric material, then the minimum resistance (1340 g, 1410 g, 1220 g) is associated with the detachment of the anti-diffusion coating from the surface of the thermoelectric material at the ends of the half-elements. This circumstance prompts the search for ways to increase the adhesion of the anti-diffusion coating to stable values that exceed the cohesive strength of the thermoelectric material.

Table 1

Impact resistance of modules with anti-diffusion nickel coating of classic type

Module №	$\Delta R/R$ –*change in module resistance*, %	Peak acceleration, *g*	Impact direction axis	Impact ordinal number	Ordinal number of impact at which the module was destroyed
1-K	Circle break	1820	*-Z*	1	1
2-K	+3.9	1330	*X*	4	5
3-K	+5.1	1410	*Y*	3	4
4-K	Circle break	1760	*-Z*	1	1
5-K	+4.3	1220	*X*	2	3
6-K	+5.1	1780	*-Z*	1	2

3. Design and optimization of anti-diffusion coatings with increased adhesion

The simplest (classic) version of the anti-diffusion coating is a thin uniform layer of an electrically neutral to thermoelectric metal material, located on the flat end surface of the thermoelectric half-element. In fact, the adhesion in this case will be lower than expected due to the presence of oxide films, various types of contamination, absorbed gas molecules, water, etc. on the surface of the thermoelectric material. The surface of the half-element after dimensional processing of the thermoelectric material has a deviation from the ideal plane, there are microcracks and scratches on its surface, and a near-surface damaged layer of the thermoelectric material also appears. Therefore, as a result of cutting the plate of thermoelectric material with an anti-diffusion coating into half-elements, micro-tears of the anti-diffusion layer from the surface of the thermoelectric material may occur. To increase the adhesion of the anti-diffusion coating, the surface of the ends of the half-elements can be embossed, or even in the form of a bandage, when the anti-diffusion coating is located not only on the end plane of the half-element, but also on part of its side surface [8].

An analytical calculation of the influence of the metal coating of thermoelectric legs on the efficiency of the thermoelement was made in [9]. However, as is typical for analytical methods, such a calculation was possible only due to a certain number of approximations and assumptions.

To determine the influence of connecting anti-diffusion coatings of various geometric configurations on the efficiency of thermoelements, it is necessary to take into account the topology of the contact region. It is also necessary to take into account the temperature dependences of the kinetic coefficients of the thermoelectric material, thermal and electrical connecting resistances, the geometric configuration of the half-elements and anti-diffusion coatings. Therefore, for the precise determination of the influence of thermoelectric effects in the near-contact region of the half-element, it is necessary to use numerical methods. In this case, the problem can be considered using the most generalized approaches, where the thermoelectric converter is part of the thermoelectric medium in which

$$\left.\begin{aligned}\alpha &= \alpha(x,y,z,T),\\ \sigma &= \sigma(x,y,z,T),\\ \kappa &= \kappa(x,y,z,T).\end{aligned}\right\}. \tag{1}$$

where α is thermoelectric coefficient; σ is electric conductivity; κ – is thermal conductivity; T is temperature; x, y, z are spatial coordinates.

Based on the general laws of conservation of energy in a thermoelectric medium, one can obtain equations for finding the distribution of temperature $T(x, y, z)$ and electric potential $U(x, y, z)$ in the medium (for the stationary case) [10].

$$-\nabla\left(\kappa\nabla T\right) = \sigma\nabla\left(\alpha T + U\right)\left(\nabla U + \alpha\nabla T\right), \tag{2}$$

The boundary conditions for the system of equations (2), (3) will have the following form:

- For the “hot” face

$$T(x, y, z) = T_h = \text{const}; \tag{4}$$

- For current leads

$$U_0 = 0 \text{ (“earth”)}, \tag{5}$$

$$U_I = \text{const (supply voltage)}; \tag{6}$$

- for all other boundaries

$$\vec{n}(-\kappa\nabla T) = 0 \text{ (thermal insulation)},$$

$$\vec{n}\left(-\sigma\alpha\nabla T - \sigma\nabla U\right) = 0 \text{ (electric insulation)}, \tag{7}$$

where $\vec{n}$ is the normal vector to the boundary.

The presented approach allows one to arbitrarily select the coefficients (1) and accordingly change the configuration of the working volume of the half-element and anti-diffusion coatings.

In this work, the system of second-order partial differential equations (2), (3) with variable coefficients (1) and boundary conditions (4) – (5) was solved on the COMSOL Multiphysics platform [11].

Using this approach, the influence of the bandage anti-diffusion coating on the parameters of the thermoelement was calculated.

The simulation used the values of kinetic coefficients obtained on the equipment developed at the Institute of Thermoelectricity [12–13]. They are shown in Figs. 2–5 for materials of n- and p-type conductivity. Fig. 5 shows the thermoelectric figure of merit Z of a thermocouple made of such materials. The contact electrical resistance was measured using the method [14] and in this model it was considered to be $5 \cdot 10^{-6}$ Ohm•cm^2, the temperature of the “hot” face T_h = 300 K.

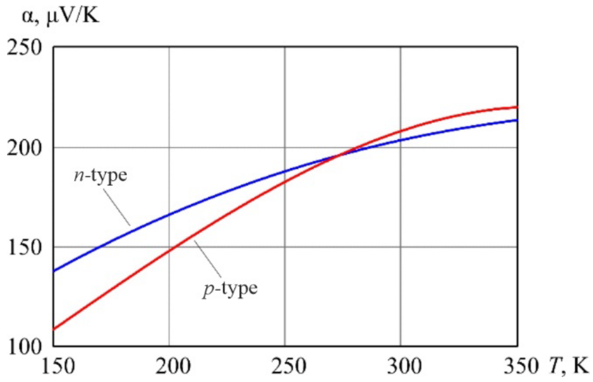

Fig. 2. Temperature dependence of thermoelectric coefficients.

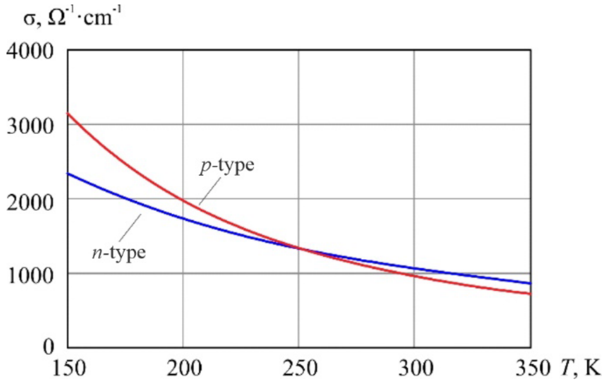

Fig. 3. Temperature dependence of electric conductivity coefficients.

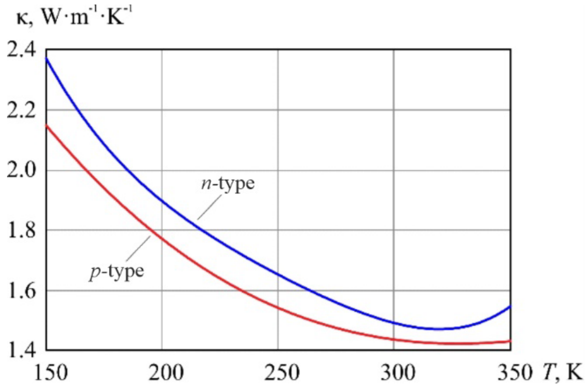

Fig. 4. Temperature dependence of thermal conductivity coefficients.

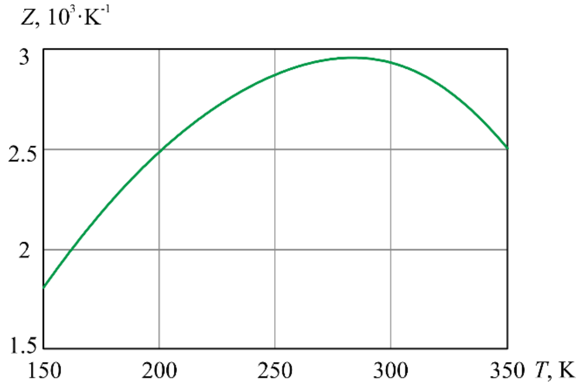

Fig. 5. Temperature dependence of thermoelectric figure of merit.

Fig. 6 shows the results of computer simulation of the effect of the bandage anti-diffusion coating on the maximum temperature difference of the thermoelement.

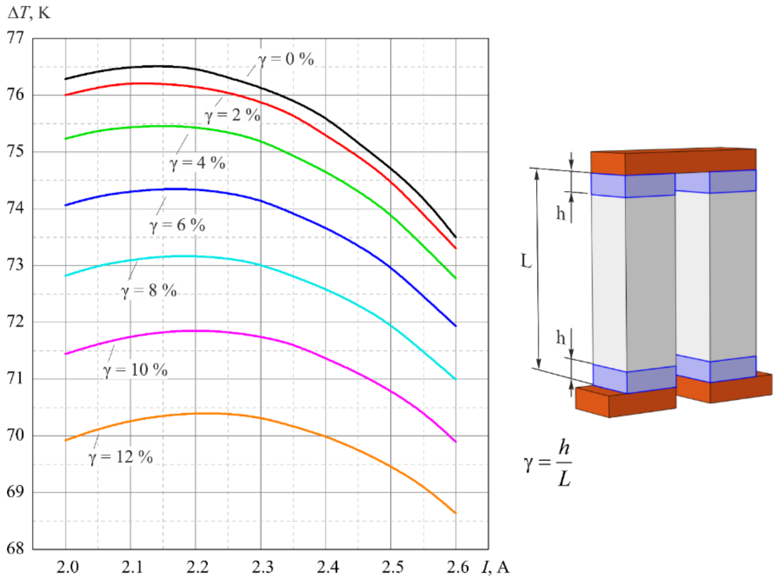

Fig. 6. Dependence of the temperature difference ΔT of the thermoelement on the value of the supply current I and the relative height of the bandage coating $\gamma = h / L$ (h – the height of the bandage, L – the total height of the half-element).

At relatively small relative heights of the bandage (up to 4% of the total height of the half-element) the reduction of the maximum temperature difference is only 1.3% (about 1ºC). Even when the bandage height is increased to 12% of the total height of the half-element, the drop in the temperature difference does not exceed 6% of its maximum value. The obtained results indicate a slight decrease in the energy characteristics of half-elements at relative heights of the bandage coating up to 10% of the total height of the half-element. This allows creating highly efficient thermoelectric modules using a bandage type of anti-diffusion coating.

4. Results of tests on the resistance of modules with a bandage anti-diffusion coating of half-elements to the action of single impacts

To conduct impact resistance tests, a batch of 30 modules with a bandage anti-diffusion coating was manufactured, completely similar in geometry and the thermoelectric material used to modules with a classic anti-diffusion coating.

The procedure for preparing modules with a bandage anti-diffusion coating for testing and the tests themselves were similar to the methodology used for modules with a conventional anti-diffusion coating.

The results of tests on the resistance of modules with anti-diffusion bandage coating of half-elements to the action of single impacts are presented in Table 2.

All the modules during the tests were destroyed due to the rupture of the half-elements directly in the thermoelectric material. That is, the adhesion of the bandage anti-diffusion coating exceeds the cohesion of the thermoelectric material. Therefore, the impact resistance of modules with bandage anti-diffusion coating will be approximately at the same level.

Table 2

Shock resistance of modules with anti-diffusion nickel coating of the bandage type

Module number	$\Delta R/R$ – change in module resistance, %	Peak acceleration, *g*	Impact direction axis	Impact ordinal number	The ordinal number of the impact at which the module was destroyed
1-B	6.2	1900	- Z	2	3
2-B	16.7	2020	- Z	1	2
3-B	Circle break	2000	- Z	1	1
4-B	Circle break кола	2180	- Z	1	1
5-B	9.1	1880	- Z	2	3
6-B	1.4	2030	X	1	4

The spread of the values of resistance of modules with a bandage coating to shocks is in the range determined by the variation of the cohesion of the thermoelectric material, in contrast to the resistance of modules with a conventional anti-diffusion coating, in which the adhesion of the coatings does not always reach the level of the material cohesion. Fig. 7 shows histograms constructed in accordance with the values of resistance of modules to impacts specified in Tables 1 and 2.

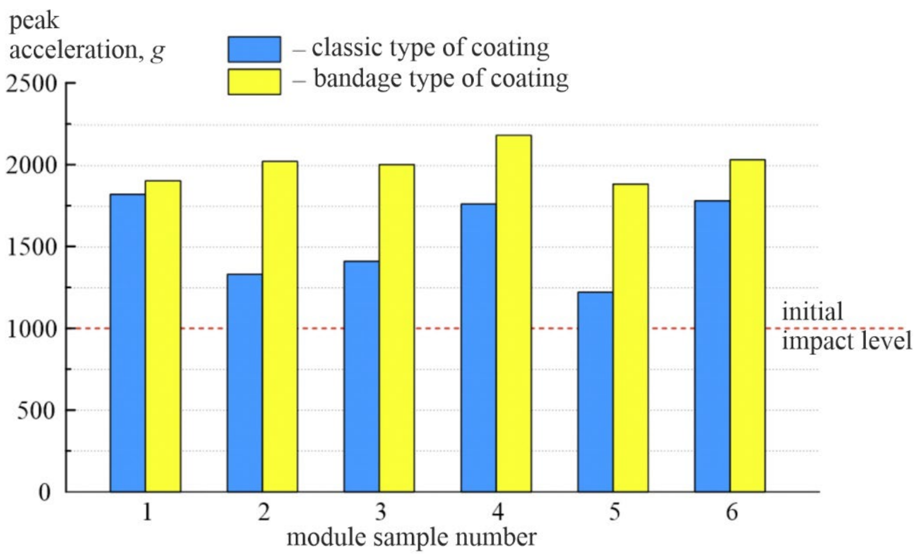

Fig. 7. Impact resistance of thermoelectric modules with anti-diffusion nickel coatings of classic and bandage types.

It can be seen that the impact resistance of modules with a conventional type of anti-diffusion coating is unstable and is characterized by a significant spread of its values, while modules with a bandage-type anti-diffusion coating, identical in geometry and thermoelectric material, are characterized by high and stable impact resistance.

Conclusions

1. The influence of the bandage anti-diffusion coating on the energy parameters of thermoelements has been determined.
2. It has been shown that the use of thermoelements with an anti-diffusion bandage-type coating significantly increases the resistance of thermoelectric modules to mechanical impacts.

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ШЛЯХИ ПІДВИЩЕННЯ СТІЙКОСТІ ТЕРМОЕЛЕКТРИЧНИХ МОДУЛІВ ОХОЛОДЖЕННЯ ДО ДІЇ МЕХАНІЧНИХ УДАРІВ

Показано можливість суттєвого підвищення стійкості термоелектричних модулів до дії механічних ударів. Бібл. 14, рис. 7, табл. 2.
Ключові слова: термоелектричні модулі, надійність.

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