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INCREASING THE SHOCK RESISTANCE OF THERMOELECTRIC ENERGY CONVERTERS

By combining the strength of materials methods with the Weibull approach, the influence of the nature of fastening thermoelectric legs in a thermoelectric energy converter on the probability of its failure-free operation depending on the magnitude of the shock acceleration was investigated. It was proven that this acceleration, for a given probability of failure-free operation, significantly increases 7 times when replacing the rigid fastening of thermoelectric legs to ceramic plates with an elastic one.

Key words: shock resistance, thermoelectric energy converter, mechanical stresses, strength of materials, Weibull approach, rigid fastening, elastic fastening.

Introduction

In real conditions of application, the shock resistance of thermoelectric energy converters becomes important. From the general approaches to the strength of materials [1] it follows that the destructive stresses in thermoelectric legs are significantly affected by the method of their attachment to ceramic plates. Therefore, the purpose of this article is to study the influence of this method on the probability of failure-free operation of a thermoelectric energy converter under shock loads on it. We will consider a thermoelectric energy converter with a purely series electrical connection of thermoelectric legs. It is known that during impact tests, shock loads are applied along three mutually perpendicular axes, two of which are perpendicular to the temperature gradient, are equal and are the most dangerous, since it is when shock loads are applied in these directions that bending stresses act in thermoelectric legs. Instead of considering the energy converter as a whole, we will consider only one of its legs. In this case, we will consider two model cases: absolutely rigid fastening of the leg at both ends and non-rigid (elastic) fastening of the legs at both ends.

In the first case, the thermoelectric leg will be considered as a beam, absolutely rigidly fastened at both ends. The corresponding physical models are shown in Fig. 1.

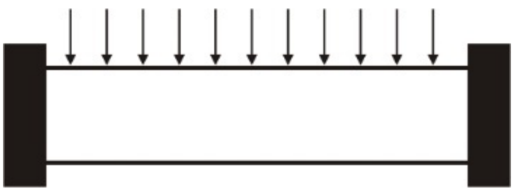


Fig. 1. Rigid fastening of the thermoelectric leg.

Shock acceleration $k_w g$ $\left(k_w = w/g\right)$ causes a shock load with intensity $q = \rho k_w g a^2$ uniformly distributed along the length of the beam. In each of the fastenings, two support reactions act: force and moment. This beam is doubly statically indeterminate, since there are 4 unknown reactions and only 2 equations for their determination. But our physical model has an axis of symmetry along which this beam can be cut and the problem made statically determinate. Then the distribution of bending stresses in half of the beam, which we consider to be uniaxial, is determined as follows:

$$\sigma(x) = \frac{3k_w g\rho}{a}\left(\frac{l^2}{4} + lx - x^2\right). \tag{1}$$

where x is the coordinate measured from the fixed end of the leg, l is its length a is the side of its square cross-section, ρ is the density of the thermoelectric material, k_w is the shock acceleration in units of g. Therefore, the probability of module failure in the event of a single shock load is determined as follows:

$$P\left(N_L\right) = \exp\left\{-2N_L a^2 \int_0^{l/2}\left[\frac{3k_w g\rho}{a\sigma_0}\left(\frac{l^2}{4} + lx - x^2\right)\right]^m dx\right\}. \tag{2}$$

Consider now the second case, when the leg is elastically fastened at both ends. Then it can be approximately considered to be fastened on two hinged-movable supports. The corresponding physical model is shown in Figs. 1, 2.

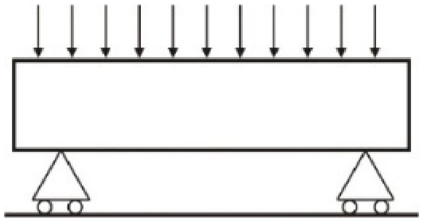


Fig. 2. Elastic fastening of the thermoelectric leg.

In this model, the support reactions are reduced only to forces directed vertically upwards. Therefore, the distribution of bending stresses in this model is defined as:

$$\sigma(x) = \frac{6k_w g\rho}{a}\left(lx - x^2\right). \tag{3}$$

Therefore, formula (2) takes the form:

$$P(N_L) = \exp\left\{-2N_L a^2 \int_0^{l/2}\left[\frac{6k_w g\rho}{a\sigma_0}(lx - x^2)\right]^m dx\right\}. \tag{4}$$

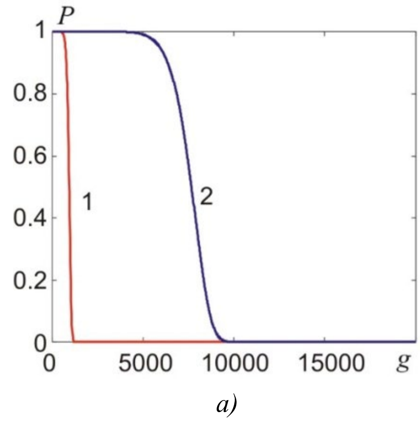
where m and σ_0 are the Weibull parameters of the thermoelectric material. Note that these parameters are determined purely experimentally and determine the probability of preserving the integrity of the leg. This is the essence of the Weibull approach1 [3 – 5].

However, we also take into consideration that in the contact area there is a shear force, which entails shear stress in the contact area. As a result, the required contact shear strength is determined by the ratio:

$$\sigma_{\mathrm{sh}} \geq 0.5\rho g n l, \tag{5}$$

therefore, at n = 5000 and the length of the bismuth telluride leg $l = 3$ mm, the required shear strength of the contact will be 0.57 MPa, which is significantly less than the true shear strength of the contacts. Thus, in terms of the stability of thermoelectric energy converters under shock loads, bending stresses in thermoelectric legs play a significantly greater role. $2N_L$ is total number of legs in the energy converter.

The results of calculations using formulae (1) – (4) are given in Fig. 3.



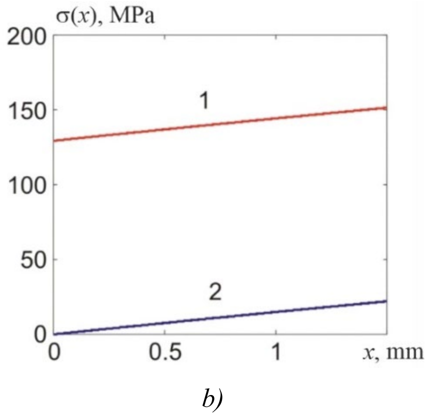


Fig. 3. Dependence of the probability of failure-free operation of the module after a single shock acceleration on the acceleration value (a) and the corresponding bending stress diagrams at a shock acceleration of 5000g (b) in the cases of rigid (1) and elastic (2) fastening of the legs.

The figure shows that in the case of rigid fastening of the legs, the module with an acceptable probability is able to withstand only a shock acceleration of less than 1000 g, in terms of crack resistance – about 2200 g, and in terms of the strength of the contact structure – only 730 g. But in the case of elastic fastening of thermoelectric legs, this acceleration increases to 5000 g., i.e. 7 times.

The reason for such a sharp difference lies in the fact that the diagrams of destructive stresses for the indicated methods of fastening thermoelectric legs differ sharply from each other. Their halves (since they are symmetrical) are shown in Fig. 3 *a*, *b*.

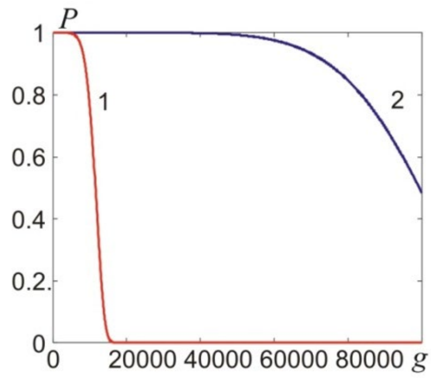


Fig. 4. Dependences of the probability of failure-free operation of the module after 1000 shocks with a given acceleration with rigid (1) and elastic (2) fastening of the legs.

Let us now determine the predicted shock resistance of the thermoelectric energy converter described in [2], taking into account that fatigue also occurs during shocks and, therefore, the result of each subsequent shock significantly depends on what happened as a result of the previous shocks. The results of the corresponding calculations are shown in Fig. 3 *b*, which shows the dependence of the probability of failure-free operation of the module after a single shock on the shock acceleration for both methods of fastening the legs.

The figure shows that in the case of non-rigid fastening of thermoelectric legs, the module will withstand an acceleration of 20.000 g with an acceptable probability, if the Weibull parameters of the thermoelectric material are those obtained during the analysis of the results of cyclic temperature tests. For this, however, the cracking strength of the material must be, as follows from Fig. 3 *b*, not less than 72 MPa. And this is quite achievable for special textured materials [6].

Conclusions and recommendations

By combining the strength of materials approach with the Weibull approach, it was found that in the case of rigid fastening of the legs, the module with an acceptable probability is able to withstand only a shock acceleration of less than 1000 g, in terms of crack resistance – about 2200 g, and in terms of the strength of the contact structure – only 730 g. But in the case of elastic fastening of thermoelectric legs, this acceleration increases to 5000 g. The reason for such a sharp difference lies in the fact that the diagrams and values of the destructive stresses with the specified methods of fastening thermoelectric legs differ sharply from each other.

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ПІДВИЩЕННЯ УДАРОСТІЙКОСТІ ТЕРМОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ ЕНЕРГІЇ

На основі поєднання методів опору матеріалів з підходом Вейбула, досліджено вплив характеру закріплення термоелектричних гілок, у термоелектричному перетворювачі енергії на залежність ймовірності його безвідмовної роботи від величини ударного прискорення і доведено, що це прискорення за заданої ймовірності безвідмовної роботи істотно зростає в 7 разів за заміни жорсткого кріплення термоелектричних гілок до керамічних пластин на еластичне.
Ключові слова: ударостійкість, термоелектричний перетворювач енергії, механічні напруження, опір матеріалів, підхід Вейбула, жорстке закріплення, еластичне закріплення.

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