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Mathematical model of bending two-layer film aluminium-polyimide structure due to temperature changes

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Mathematical model of bending two-layer film aluminium-polyimide structures due temperature changes during making by adhesiveless method printing and thermo treatment for imidization of insulation is obtained. Different linear expansion coefficients of layers lead to distortion flatness of structure. Model connects temperature changes with mechanical bending moment, qualities of materials, dimensions layers and permits to calculate all parameters stress-strain state: curvature, situation of neutral surface concerning adhesion surface, distribution stresses and forces in materials. Model uses common hypotheses of theory bending about existence neutral layer in curving structure, that all normals to neutral surface of curving structure don't become distorted, remain normal to deformed surface and adjoin layers don't press one on another. Results of work can be used for selection of materials and constructive elements of flexible connecting cables and boards for detector systems in high-energy physics experiments.
Keywords: flexible cable, printed board, adhesiveless structures.

Разработана математическая модель изгиба двухслойных пленочных алюминий — полиимидных структур, вызванного изменением температуры в процессе изготовления безадгезивным методом печати и термообработки для имидизации изоляции. Различные коэффициенты линейного расширения слоев приводят к нарушению плоскостности структуры. Установлена связь изменения температуры с механическим изгибающим моментом, с конструктивными размерами слоев и свойствами материалов. Это позволяет рассчитать все параметры напряженно-деформированного состояния структуры: радиус кривизны, положение нейтральной поверхности относительно поверхности адгезии слоев, распределение напряжений и сил, действующих в материалах. Модель использует общие гипотезы теории изгиба о существовании нейтрального слоя изогнутой структуры, что все нормали к нейтральной поверхности изогнутой структуры не искривляются, остаются нормальными и к деформированным поверхностям материалов, отсутствует давление соседних слоев друг на друга. Результаты работы могут использоваться при выборе материалов и конструктивных элементов гибких соединительных кабелей, шлейфов в физических высокоэнергетических экспериментах.

Математична модель згинання двошарових плівкових алюміній-поліімідних структур при змінах температури. *І.Ш.Невлюдов, В.М.Борщов, В.А.Палагін, Є.А.Разумов-Фризюк, І.Т.Тимчук, В.В.Невлюдова, А.Ю.Петрова.*

Розроблено математичну модель згинання, яке викликано зміною температури у процесі виготовлення двошарових плівкових алюміній-поліімідних структур безадгезивним методом друку та термічної обробки для імідізації ізоляції. Різні коефіцієнти лінійного розширення шарів призводять до втрати компланарності структури. Встановлено зв'язок згинання алюміній-поліімідної структури з параметрами матеріалів, розмірами шарів та змінами температури. Модель використовує загальні гіпотези теорії згинання про існування нейтрального шару зігнутої структури, перпендикулярності усіх нормалей до деформованої нейтральної поверхні та відсутності тиску сусідніх шарів один на одного, тобто плоскої деформації. Результати роботи можуть використовуватися при виборі матеріалів і конструктивних елементів гнучких з'єднувальних кабелів та плат для детекторних систем в експериментах фізики високих енергій.

1. Introduction

Manufacturing aluminium-polyimide materials is performing many tens of years. Flexible cables and printed boards on their basis are using for creating electronic devices for different purposes, including interconnection elements in detector systems of physics experiments what allows decrease material budget in detecting volume.

Presently limited number of adhesiveless aluminium-polyimide materials are available on the market with thicknesses of aluminium foil 10–30 μm and polyimide 10–20 μm. But for realization of new products materials with wider range of thicknesses of aluminium foil are needed. Production technology of such materials is based on applying liquid polyimide on aluminium foil with further heat treatment [1, 2]. Significant deformation (bending) of materials appears after heat treatment operation (imidization of the polyimide layer) in manufacturing of raw aluminium-polyimide with thickness of 50–100 μm. Bending of the material depends on thickness of dielectric and conductive layers. Presence of material bending leads to the complications of manufacturing process of flexible cables and boards, reducing yield of products and can lead to the impossibility of further assembling products on their base.

Adhesiveless lacquer foil materials obtained by applying liquid lacquer on foil are producing in Russian Federation by the Research Institute of Electronic Materials and Public Corporation Kron. At present, they mainly produce dielectrics FDI-A50 and FDI-220 on polyimide base with reduced level of imidization. For those materials thickness of aluminium foil is 30 μm and polyimide film is 20 μm. However, these materials are unstable, have limited warranty period of storage (no more than 6 months) and lead to significant value of shrinkage at manufacturing processes of products after etching-off the foil, and during thermal treatment operations. Wider nomenclature of foiled materials is presented by Scientific Production Enterprise Polikom Ltd (Russian Federation) [3]. In addition to abovementioned materials with low level of imidization, this enterprise also organized the serial production of foiled materials with high level of imidization and thicknesses of aluminium foil 14, 20, 25 and 30 μm, as well as nickel foil 7 μm and copper foil 20 μm. At the same time, materials with aluminium foil thicker 30 μm and information about their creating is absent.

It's need to study process bending structures with adhesiveless leacquer foil materials for interconnections on base aluminium-polyimide in flexible connecting cables for detector systems in high-energy physics experiments.

Manufacture technology of aluminium-polyimide materials typically includes two main steps, namely: applying liquid polyimide on chemically cleaned aluminium foil and further curing at 300–400°C for imidization of the polyimide layer.

Mathematical model is need for calculation optimal ratio of thicknesses aluminium and polyimide and decreasing bending. Task of research is actual and will allow to determine initial data for production of two-layer adhesiveless dielectrics. Model will used and for other compositions of materials like nickel-polyimide, copper-polyimide, etc.

2. Investigation method

Three general hypotheses theory of bending [4, 5] have been used for working out mathematical model of bending two-layer structures caused by temperature changes during cooling from the imidization temperature of polyimide to normal working and difference of temperature coefficients of linear expansion of the layers.

The first hypothesis supposes that there is neutral layer in the curving structure, length of which is not changing at deformation. Material of layers from one side of neutral layer are compressed, from another side layers are stretched.

The second hypothesis demands that all normals to neutral surface of curving structure don't become distored, remain normal to deformed surface. It guarantees realization Hook's law and simple calculation stresses in layers depending on distance from neutral surface.

The third hypothesis considers that adjoin layers don't press one on another, i.e. deformation is flat, there are only normal stresses in cross sections.

Beside it, materials of layers are homogeneous, isotropic and submitted to Hook's law.

These three hypotheses at deformation of structure under influence of temperature changes lead to cylindrical bending, because change of lengths of all the elementary longitudinal segments Δl_i of the structure is caused by the same effect of Δt (except for differences acting on the edges of material with length of 5–6 thicknesses of structure) (see Fig. 1).

Cylindrical curving is important case of curving in which neutral surface is modified in cylindrical surface. Its peculiarity that is no difference at considering small and large deformations. At cylindrical curving cross deformations are straitened over interaction adjoining longitudinal fibers and distance between such fibers is constant.

Denote longitudinal axis — x, cross axis — y. Set of directions z is perpendicular to dx elements in cross section y_i = const. These normals converge at point that is the center of curvature. Cross section plane y_i = const with neutral cylindrical surface is circle. Its length is constant, i.e. circle is neutral axis of bending.

Relative lengthening ε_x and ε_y in arbitrary layer depends from its distance z to neutral surface and definite by flat stretched state:

$$\varepsilon_x = \frac{z}{\rho_x} = \frac{\sigma_x}{E} - \mu\frac{\sigma_y}{E}, \quad (1)$$

$$\varepsilon_y = 0 = \frac{\sigma_y}{E} - \mu\frac{\sigma_x}{E}. \quad (2)$$

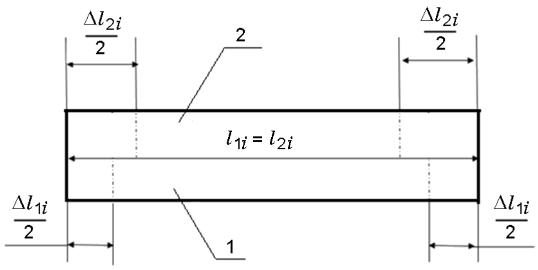

Fig. 1. Layers shortening in case temperature decrease and absence of layers adhesion. 1 — aluminium layer, 2 — polyimide layer. Solid lines-circuit of layers before cooling, dotted lines-after cooling.

Then normal stresses σ_x and σ_y are equal:

$$\sigma_y = \mu\sigma_x, \quad (3)$$

$$\sigma_x = \frac{Ez}{\rho_x(1-\mu^2)}\}, \quad (4)$$

where z — distance from neutral surface to arbitrary layer;

ρ_x — radius cylindrical curving of surface;

E — Young's modulus of elasticity;

μ — Puasson's coefficient.

Condition continuity gives once more equation, which denotes structure state. It of demands equality relative deformations of layers on line adhesive surface ($\varepsilon_{1ad} = \varepsilon_{2ad}$)

$$\frac{\sigma_{1ad}E_2}{\sigma_{2ad}E_1} = \frac{\alpha_1}{\alpha_2}. \quad (5)$$

It will be marked in two-layer aluminium-polyimide structure values, which concern to aluminium, with index 1, to polyimide — with 2. Then temperature coefficient of linear expansion, Young's modulus of elasticity, height and area cross section aluminium layer will α_1, E_1, h_1, S_1; polyimide layer — α_2, E_2, h_2, S_2, width $b_1 = b_2 = b$. In calculation let $b = 1$.

At manufacturing two-level structure is very important cooling from temperature of imidization $t = 300°C$ to normal temperature $t = 20°C$. Stresses appear in layers due to temperature change and different values α_1 and α_2. Each element of the length of structure is subjected to the same force. Therefore, the deformation is a cylindrical curvature and flat.

It is necessary to note, that according to hypothesis about saving perpendicularity and absence of curvature of all normals to neutral surface, forces in the cross sections are normal, tangent forces can be neglected. Only normal stresses σ_1 and σ_2 act in layers of structure. Distributions of these normal stresses denote by Hooke's law:

— in aluminium:

$$\sigma_{1z} = E_1\varepsilon_z = \frac{zE_1}{\rho_x}, \quad (6)$$

— in polyimide:

$$\sigma_{2z} = E_2\varepsilon_z = \frac{zE_2}{\rho_x}, \quad (7)$$

where coordinate z counts from neutral layer, positive direction z — down. Neutral layer position a from adhesion layer is determined in condition equality to zero force F_n, that calculates as sum of integrals σ_x on thickness upper and lower layers in according with Figure 2 and taking into account $b = 1$.

$$F_n = \int_{h_1-a}^{-a}\sigma_{1z}dz + \int_{-a}^{-a-h_2}\sigma_{2z}dz = 0, \quad (8)$$

we get using (6, 7):

$$F_n = \int_{h_1-a}^{-a}\frac{E_1}{\rho_x}zdz + \int_{a}^{-a-h_2}\frac{E_2}{\rho_x}zdz = \quad (9)$$

$$= \frac{E_1}{2\rho_x}[a^2 - (h_1^2 - 2h_1a + a^2)] -$$

$$- \frac{E_2}{2\rho_x}[a^2 + 2ah_2 + h_2^2) - a^2] = 0.$$

Whence

$$a = \frac{E_1h_1^2 - E_2h_2^2}{2(E_1h_1 + E_2h_2)}. \quad (10)$$

Algebraic expression for bending moment M_x is sum of integrals normal forces on thickness upper and lower layers and on distance z to neutral layer (so as areas $S_1 = h_1 \cdot b$; $S_2 = h_2 \cdot b$ and $b = 1$)

$$M_x = \frac{E_1}{\rho_1}\int_{-a}^{h_1-a} z^2 d\delta - \frac{E_2}{\rho_x}\int_{-a}^{-h_2-a} z^2 d\delta = \quad (11)$$

$$= \frac{E_1}{\rho_x}\left[\frac{(h_1 - a)^3 + a^3}{3}\right] + \frac{E_2}{\rho_x}\left[\frac{(h_2 + a)^3 - a^3}{3}\right].$$

Curvature

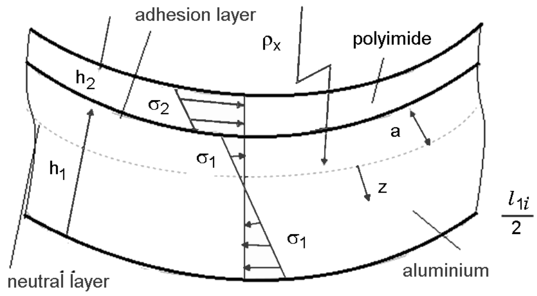

Fig. 2. Cross section small element l_{ij} of structure with stresses σ_i forms typical neutral and adhesion surfaces.

$$\frac{1}{\rho_x} = \frac{M_x}{E_1I_1 + E_2I_2}, \quad (12)$$

where I_1 and I_2 — moments of inertia of cross sections of aluminium and polyimide layers relatively neutral axis:

$$I_1 = \frac{(h_1 - a)^3 + a^3}{3}, \quad (13)$$

$$I_2 = \frac{(h_2 + a)^3 - a^3}{3}. \quad (14)$$

4. Discussion

Previous equations estimate dependences between α_i, E_i, thickness h_i and stresses σ_i, curvature, bending moment M_x, relative deformations ε_i, but no give possibility to calculate absolute values one of them and connection with temperature change Δt is absent. Curvature of bending can be measured experimentally. But it is not convenient for using different layers' thickness and low measurements accuracy.

Development of model

Consider combined action of temperature and mechanical force. Due to change temperature aluminium-polyimide structure will bended. Mechanical force opposite direction will straighten it and possible make structure flat (then $1/\rho_x = 0$). Relative linear deformation of all layers ε_1^{t+M} and ε_2^{t+M} will be the same.

Index t concerns thermal action, M — action of mechanical force.

For aluminium layer:

$$\varepsilon_1^{t+M} = \frac{\sigma_1}{E_1} + \alpha_1 \cdot \Delta t. \quad (15)$$

For polyimide layer:

$$\varepsilon_2^{t+M} = \frac{\sigma_2}{E_2} + \alpha_2 \cdot \Delta t. \quad (16)$$

Furthermore, normal forces in structure are equal zero:

$$F = \sigma_1^{(t+M)} \cdot h_1 + \sigma_2^{(t+M)} \cdot h_2 = 0. \quad (17)$$

Solving of system equations (15, 16) gives:

$$\sigma_1^{(t+M)} = -\frac{(\alpha_1 - \alpha_2) \cdot \Delta t}{h_1 \cdot \left(\frac{1}{E_1 \cdot h_1} + \frac{1}{E_2 \cdot h_2}\right)}. \quad (18)$$

$$\sigma_2^{(t+M)} = -\frac{(\alpha_1 - \alpha_2) \cdot \Delta t}{h_2 \cdot \left(\frac{1}{E_1 \cdot h_1} + \frac{1}{E_2 \cdot h_2}\right)}. \quad (19)$$

Summing of stresses $\sigma_1^{(t+M)}$ and $\sigma_2^{(t+M)}$ through thickness h_1 and h_2 gives couple of forces with arm $(h_1 + h_2)/2$.

Moment of couple of forces:

$$M_x^{(t+M)} = -\frac{(\alpha_1 - \alpha_2) \cdot \Delta t}{h_1 \cdot \left(\frac{1}{E_1 \cdot h_1} + \frac{1}{E_2 \cdot h_2}\right)} \cdot \frac{h_1 + h_2}{2}. \quad (20)$$

Now action temperature bending moment can be picked out:

$$M_x^{(t)} = M_x^{(t+M)} - M_x^{(M)}. \quad (21)$$

Values of stresses due to temperature changes can be calculated as difference $\sigma_i^{(t+M)}$ (18, 19) and $\sigma_i M$ (6, 7):

$$\sigma_1^{(t)} = -\frac{(\alpha_1 - \alpha_2) \cdot \Delta t}{h_1 \cdot \left(\frac{1}{E_1 \cdot h_1} + \frac{1}{E_2 \cdot h_2}\right)} \cdot \left[\frac{1}{h_1} - \frac{(h_1 + h_2) \cdot E_1 \cdot z}{2 \cdot (E_1 I_1 + E_2 \cdot I_2)}\right], \quad (22)$$

$$\sigma_2^{(t)} = -\frac{(\alpha_1 - \alpha_2) \cdot \Delta t}{h_1 \cdot \left(\frac{1}{E_1 \cdot h_1} + \frac{1}{E_2 \cdot h_2}\right)} \cdot \left[\frac{1}{h_2} - \frac{(h_1 + h_2) \cdot E_2 \cdot z}{2 \cdot (E_1 I_1 + E_2 \cdot I_2)}\right], \quad (23)$$

Curvature of aluminium-polyimide structure in process cooling from temperature imidization to normal Δt is defining by equation:

$$\frac{1^{(t)}}{\rho_x} = \frac{(\alpha_1 - \alpha_2) \cdot \Delta t \cdot (h_1 + h_2)}{2 \cdot \left(\frac{1}{E_1 \cdot h_1} + \frac{1}{E_2 \cdot h_2}\right) \cdot (E_1 \cdot I_1 + E_2 I_2)}. \quad (24)$$

Equations (21–24) estimate stress-deformed state two-layer structure only with using well-known parameters of materials, construction and conditions of temperature its layers. This is mathematical model of bending due temperature changes of two-layer film structures.

This mathematical model of bending is suitable for calculating deformation caused by temperature changes for two-layer structures: metal-polymer compositions, various polymers.

5. Conclusions

Developed mathematical model of two-layer aluminium-polyimide structures connects temperature change with mechanical bending moment, qualities of materials, dimensions layers and permit to calculate all parameters of the stress-strain state of laminate: radius of curvature, position of the neutral surface relative to the adhesive surface of layers, distribution of stresses and forces in materials.

Model can be used for calculating bending of other two-layer structures, as well as for choice of materials to ensure the necessary properties of structures which work in wanted temperature range.

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