Transient of Thermal Stresses in Printed Circuit Boards

Oldrich Suba, Libuse Sykorova

Abstract**—** Results of FEM modelling of thermal stress analysis in printed circuit boards are given in the article. It is shown that thermal stress alone is not solely caused by differences in coefficients of thermal expansion of individual layers. The emergence of thermal stress is subject to both the layered structure of the wall and given boundary conditions, as well as the existence of a temperature gradient in the direction normal to the surface of the wall. A practical application focuses on the issue of recycling of PCB with the effort to achieve separation of layers due to thermal stress. Role modelling of thermal stress in this area lies in predicting the possibility of separation, depending on the type of thermal stress and material parameters.

Keywords**—** Thermal stress, Printed circuit boards, Layered walls.

I. INTRODUCTION

LAYERED, i.e. non-homogenous walls of boards and shells respectively, unlike homogenous (one-layer) walls, are characterized by the emergence of thermal stress at any change of temperature towards the base - referential state which we consider to be stress-free. Usually it is considered that the formation of thermal stress in layered walls is subject to different values of thermal expansion of individual layers [1]. In fact, apart from the difference in thermal expansion coefficients an instant value of the gradient of generally transient temperature field takes part in the formation of thermal stress. The resulting stress is also influenced by the given boundary conditions to which the wall is exposed during the thermal load [2,3] . Usually, deformation of the membrane type is not prevented, i.e. in the central plane of the wall. In many cases, the bending-torsional deformation of the wall is prevented, whether because of gripping the edges or due to the influence of the thin-walled element geometry. In case of completely free planar wall – board, the general bending deformations and the respective stress components are formed there (except for cases in which the symmetry structure of the wall to the middle plane occurs).

A practical application focuses on the issue of recycling of printed circuit boards (PCB) with the effort to achieve separation of layers due to thermal stress. Role modelling of thermal stress in this area lies in predicting the possibility of separation, depending on the type of thermal stress and material parameters.

The electronic waste is the fastest growing kind of waste at present. Worldwide it forms up to 5% of weight of solid domestic waste now, almost as plastic packages. In the countries of European Union, where families annually product about 8 millions of tons of electronic waste, its dimension grows in the rate of 3 till 5% per year, fast three times faster than total waste dimension. It is estimated that European Union will have to face up to almost 11 millions of tons of electronic waste in keeping of electronic sale. Ten years later will the annual production rise almost up to 14 millions tons. It is needful to add next 3 millions of tons of electronic waste coming from organizations and firms.

II. THERMAL STRESS DUE TO DIFFERENCES IN THERMAL EXPANSION OF LAYERS

Share of different thermal expansion coefficients of individual layers on thermal stress of the given layered structure can be identified only when the layered board is exposed to a temperature change of the heating type. Influence of the temperature gradient is thus excluded. Let the double-layered wall be exposed to the temperature change from the output (reference) state T_m, which is assumed to be stress-free. If both layers were mutually separated, the relative length change of each of them would be the same in all directions, assuming isotropy of the properties of both layers:

$$\varepsilon_k^T = \alpha_k \Delta T \quad , \quad k = 1,2 \quad , \quad \Delta T = T - T_m \quad ,$$

where:

α_k ... thermal expansion coeficient of k-th layer,
k ... number of the layer (1- Cu, 2- polymer composite),
T_m ... temperature of reference state,
T ... temperature of the wall.

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O. Suba is with the Tomas Bata University in Zlin, nam. T. G. Masaryka 5555, 76001 Zlin, Czech Republic (corresponding author to provide phone: 00420-57603-5168; fax: 00420-57603-5176; (e-mail: suba@ft.utb.cz).
L.Sykorova is with the Tomas Bata University in Zlin, nam. T. G. Masaryka 5555, 76001 Zlin, Czech Republic (e-mail: sykorova@ft.utb.cz).

As shown in Figure 1, the difference of thermal expansion of layers is balanced out by their elastic deformation. During heating or cooling respectively of ΔT, the wall shows outwards (membrane deformations are not prevented) some macroscopic membrane deformation ε^T. Let's imagine (without limiting the generality of the task) that ΔT is positive, i.e. it is heating, and $\alpha_2 > \alpha_1$. The layer 2 (polymer composite) is then compressed, the layer 1 (Cu-conductive path) is expanded – see Fig.1. Membrane deformations of the board are free, so that membrane forces in the wall sections are zero. It applies to the following relationship:

$$\sum_{k=1}^{2} s_k \sigma_{ki}^T = 0 \quad , \quad i = x, z. \tag{1}$$

where:
s_k ... thickness of k-th layer,
σ^T_{ki} ... thermal stress component in direction i.

Stress in each layer is equibiaxial, assuming isotropy of the layers, so the index and the axis of the coordinate system x,z in the plane of the wall can be omitted. Deformations in both layers are equal to ε^T and are given by the algebraic sum of thermal expansion and elastic deformation as follows:

$$\varepsilon^T = \varepsilon_k + \varepsilon_k^T. \tag{2}$$

where :
ε^T ... equibiaxial effective expansion of the wall,
ε_k ... equibiaxial elastic deformation of k- layer.

Equation of elasticity for the k-th layer can be written in the following form

$$\varepsilon_k = \frac{1}{E_k}\left(\sigma_k^T - \nu_k \sigma_k^T\right) = \frac{\sigma_k^T}{E_k^*}. \tag{3}$$

where:
E_k ... Young´s modulus of k-th layer,
n_k ... Poisson ratio of k-th layer,
and $E^* = E / (1 - \nu)$.

Substituting (3) to (2) results in

$$\varepsilon^T = \frac{\sigma_k^T}{E_k^*} + \alpha_k \Delta T.$$

If we derive σ^T_k and then substitute it into equilibrium equation (1), we get the following relation for the effective expansion of the wall

$$\varepsilon^T = \frac{\sum_{k=1}^{2} E_k^* s_k \alpha_k}{\sum_{k=1}^{2} E_k^* s_k} \Delta T = \alpha_c \, \Delta T,$$

where:
α_c ... effective thermal expansion coefficient of the layered wall.
The values of thermal stress are then

$$\sigma_k^T = E_k^* \Delta T \left(\alpha_c - \alpha_k\right) \quad , \quad k = 1,2. \tag{4}$$

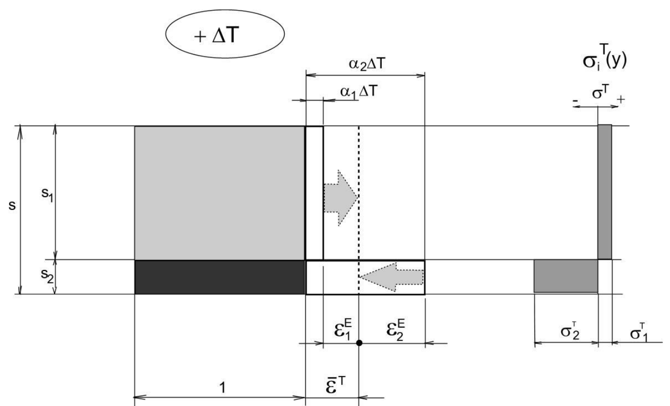

Fig.1 Thermomechanical behaviour of the two-layer board at tempering change of temperature

Relation (4) does not apply in areas of free edges of the double-layer wall. Here, it is necessary to solve the relevant boundary task.

Stress (4) is sustained in the sense of linear elasticity if a change of temperature condition still exists. In fact, it is subject to relaxation due to viscoelastic behaviour of the polymer layer.

III. Stress due to the temperature gradient

Now consider generally layered wall, i.e. a wall with generally varying properties along its thickness, exposed to thermal effects with random thermal profile ΔT(y) corresponding to a certain moment of transient heat transfer through the wall – Fig.2.

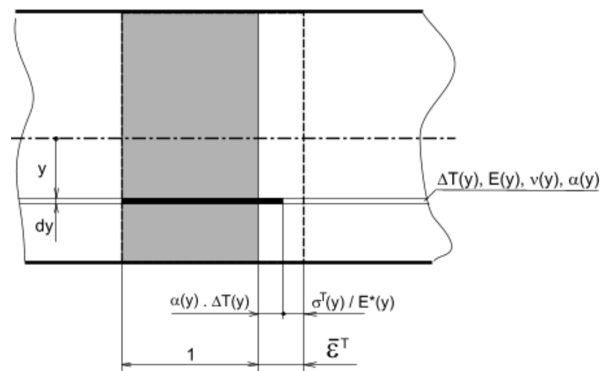

Fig. 2 Generally layered wall

Not only the elastic constants but also the coefficient of linear thermal expansion generally changes both discontinuously at the layer interface and continuously within

each layer due to possible dependences of constants on temperature.

This task can be seen as a wall imaginary composed of an infinite number of layers of elementary thickness dy; each layer has its own values of elastic constants and thermal expansion coefficient. The value ΔT(y) expresses the difference between the real temperature at place y and the reference temperature of the wall, i.e. temperature at which zero stress of the wall is assumed.

Let the wall be gripped again in a way which prevents its warpage but allows membrane deformations, i.e. deformations in the directions of the reference surface are possible. The resulting membrane forces in the wall sections then equal to zero, so that

$$\int_{(s)} \sigma^T(y)\, dy = 0 \ , \qquad (5)$$

where:
σ^T ... distribution function of transient thermal stress,
y ... coordinate in normal direction .

Unless there is warpage of the wall, the sum of thermal expansion and elastic deformation, which is in each imaginary layer dy constant, equals to effective expansion of the wall ε^T. Considering that this is an equibiaxial stress, so that

$$\varepsilon^T = \frac{\sigma^T(y)}{E^*(y)} + \alpha(y)\ \Delta T(y)$$

where:
E*(y) = E(y) / (1 - ν),
α(y) ... distribution function of thermal expansion coeficient,
ΔT(y) ... transient temperature state of the wall.

When using (5), the final uniaxial wall effective deformation can be expressed by the following relation

$$\varepsilon^T = \frac{\int_{(s)} E^*(y)\,\alpha(y)\,\Delta T(y)\,dy}{\int_{(s)} E^*(y)\,dy}.$$

Thus equibiaxial thermal stress in the area of coordinate y will be

$$\sigma^T(y) = E^*(y)\left[\varepsilon^T - \alpha(y)\,\Delta T(y)\right] \qquad (6)$$

Like the relation (4) the expression (6) does not apply in areas of free edges of the double-layer wall, where the boundary stress-tops form, especially those of shear stress components at the layers interface. Unlike (4), stress given by the relation (6) is transient (time dependent) in cases of time-variable temperature field. After disappearance of the temperature gradient, thermal stress also disappears.

IV. FEM MODELLING OF THE THERMAL STRESS OF PCB LAYERS

In recent years the development of consumer electronics has brought the necessity of electrical waste recycling due to falling prices of electronics, and thus its massive consumption, and also a decrease of its lifetime.Although the formation of thermal stress can be generally regarded as a negative phenomenon in terms of utility properties of plastic and composite products, in practice there are cases in which thermal stress is formed deliberately. This is the case of printed circuit boards recycling; the aim is to break the interface and thus separate individual layers with the use of thermal stress [2]. The role of thermal stress modelling in this area lies in predicting the possibility of separation in dependence on the type of thermal stress and material parameters of the layers.

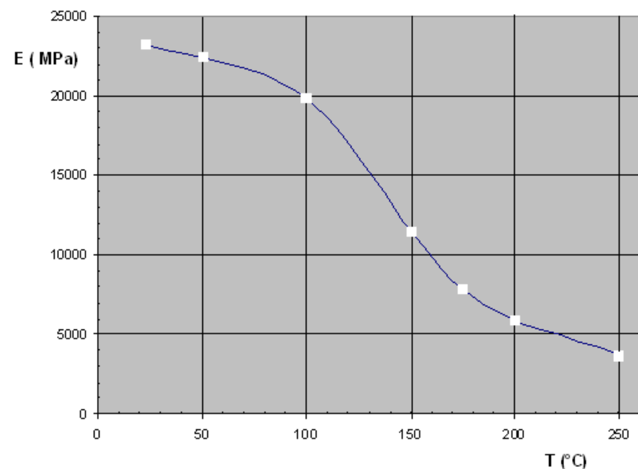

Fig.3 Temperature dependence of Young´s modulus of polymer composite used in stress modelling

FEM modelling of transient thermal stress states runs in two stages. Firstly, the appropriate thermal boundary conditions of the board are set and the instantaneous profiles of the temperature field are calculated in the chosen time steps[4,5]. Time-variable thermal boundary conditions are entered via so-called time-curves. Secondly, the appropriate mechanical boundary conditions are set and the instantaneous values of transient thermal stress components are calculated for the chosen time frames of the course of the temperature in the board. Whereas the mechanical and thermal parameters of the material layer 1 (Cu) can be considered to be temperature-independent in calculation, the layer of polymer composite 2 shows strong temperature dependences of physical properties

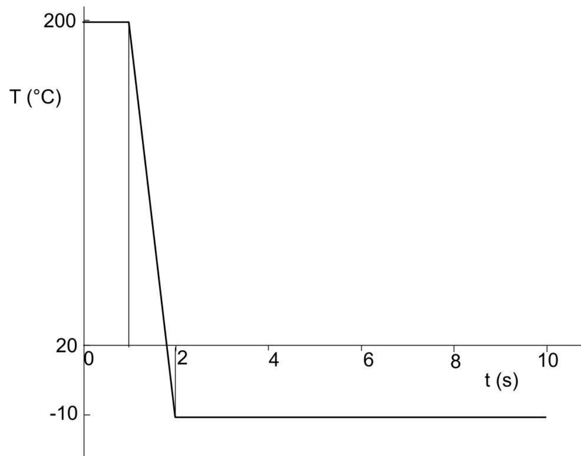

Fig. 4 Time curve of the temperature on the PCB surface for modelling of rapid, i.e. non-homogenous, cooling.

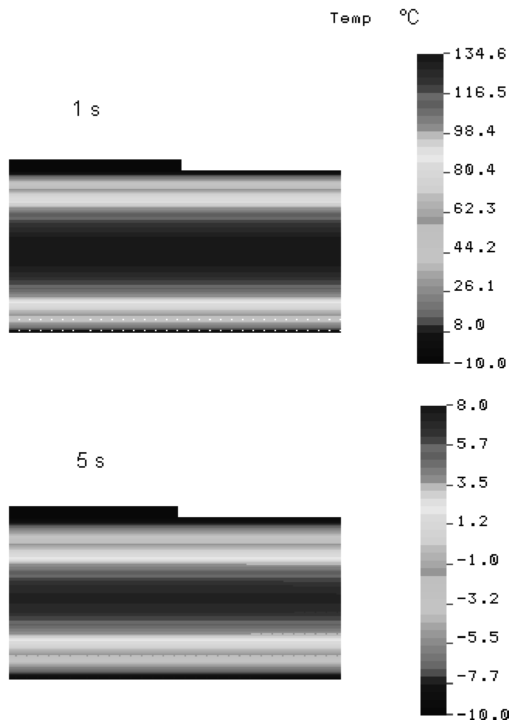

Fig. 5 Calculated temperature states 1 and 5 s after the immersion into brine of the temperature of - 10 °C.

on temperature, especially that of the modulus of elasticity. Therefore these dependencies were generalized by appropriate temperature curves in calculation. Thus the composite layer becomes quasi-layered during pull of the temperature gradient

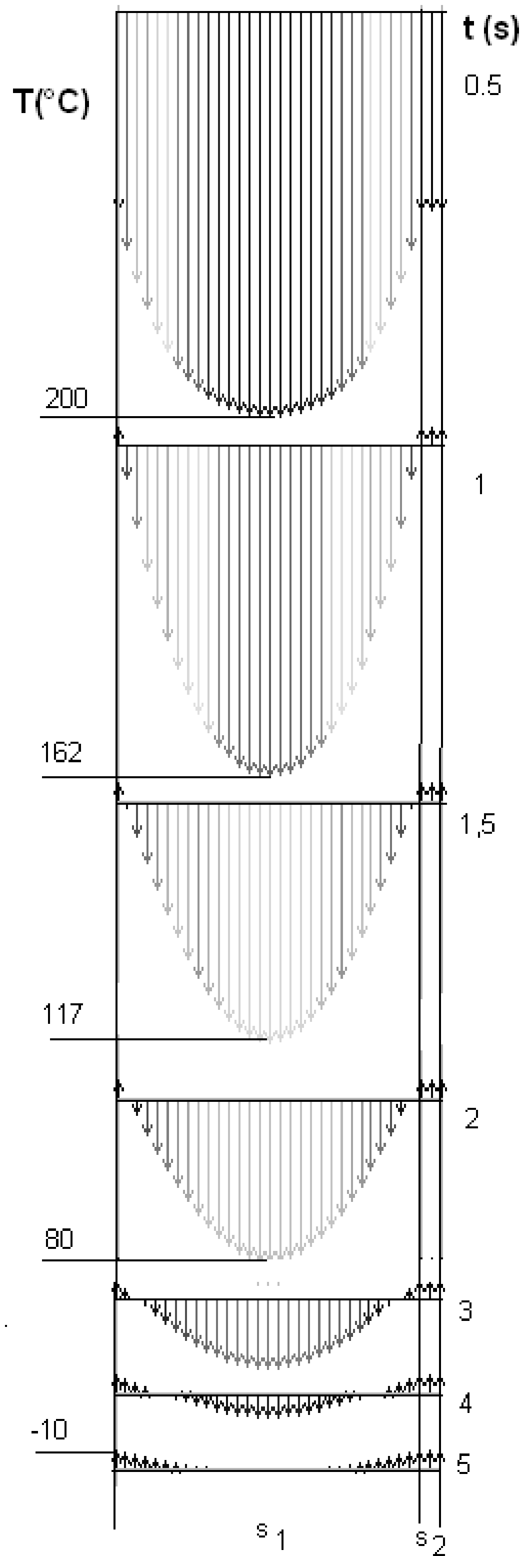

Fig. 6 Time dependent temperature profils in PCB wall

on its thickness; it means that the individual equidistant planes, respectively imaginary layers of elementary thickness, show different values of thermoelastic properties at the given instant of time. Measured temperature dependence of Young´s modulus of the composite layer is shown in Fig. 3.

Time curve of the chosen model of thermal process is shown in Fig.4. The PCB board is heated to the temperature of 200°C. By the immersion into brine of the temperature of -10°C the surface is rapidly cooled to this temperature in the time interval of 1 – 2 seconds. Then the board remains in the bath until the disappearance of the thermal gradient, i.e. until the temperature fully reaches the value of -10°C. Resultant temperature time dependent profiles of the PCB wall is shown in Fig. 5, 6.

After the analysis of the time-variable temperature field the results of chosen time moments are used for the analysis of thermal stress. Geometry of selected rotationally symetric model of PCB structure is shown in Fig. 7. Selectet thickness of Cu – layer (1) is 0,1 mm, composite thickness (2) is 1,5 mm. Computional values of linear thermal expansion coefficients are: $\alpha_1 = 1{,}67.\ 10^{-5}\ K^{-1}$, $\alpha_2 = 4.\ 10^{-5}\ K^{-1}$.

Fig.7 Geometry of rotationally symetric model of PCB .

Results of modelling of thermal stress states are shown in following diagrams. The reference temperature (temperature of the wall, at which no thermal strains exist in the structure) was defined by value of 20 °C. In this case consequent stress state is superposition of stress due to differences in thermal expansion of layers and stress due to the temperature gradient. In Fig. 8 is shown distribution of shear stress near the edge of the layer 1 in time 1s, when the PCB wall is still heated to the temperature of 200°C. Distribution of shear stress after the immersion into brine of the temperature of -10°C is shown in Fig. 9. Distribution of interlaminar normal stress is shown in Fig. 10,11.

However. in fact, stress in case of remain in the temperature of 200°C is subject to relaxation due to viscoelastic behaviour of the polymer layer. In oder to exclude this type of thermal stress, caused by diferent thermal expansion let us consider the case, when coefficients of thermal expansion layers 1 and 2 are identical. Results of modelling of thermal stress states are shown in following diagrams. Shear stresses in dependence of time is shown in Fig. 12-16.

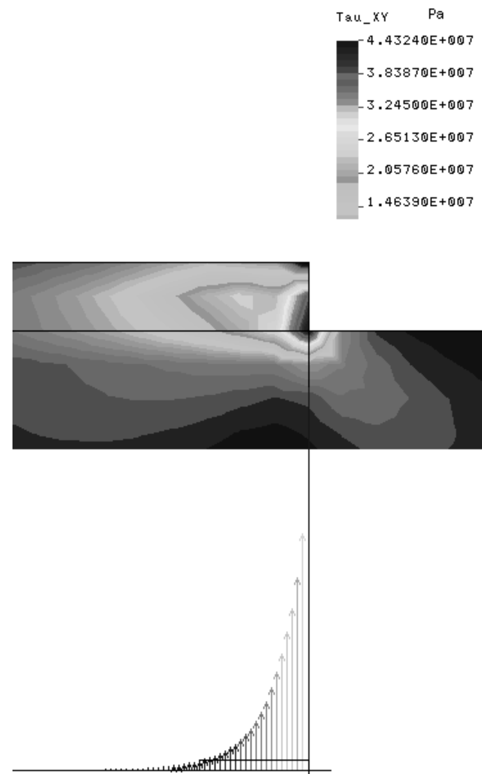

Fig. 8 Distribution of shear stress near the edge of the layer 1 – time 1s

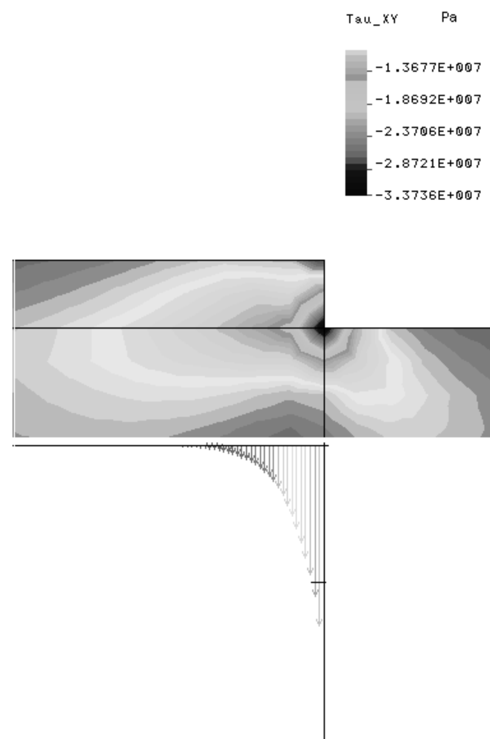

Fig. 9 Distribution of shear stress near the edge of the layer 1 – time 2s

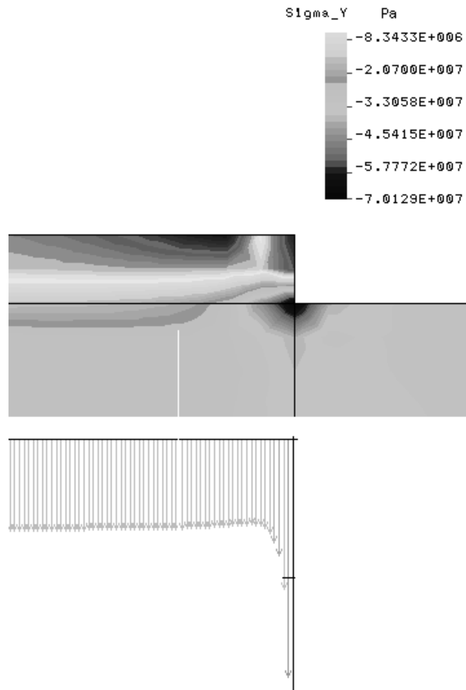

Fig. 10 Distribution of interlaminar normal stress component – time 1s

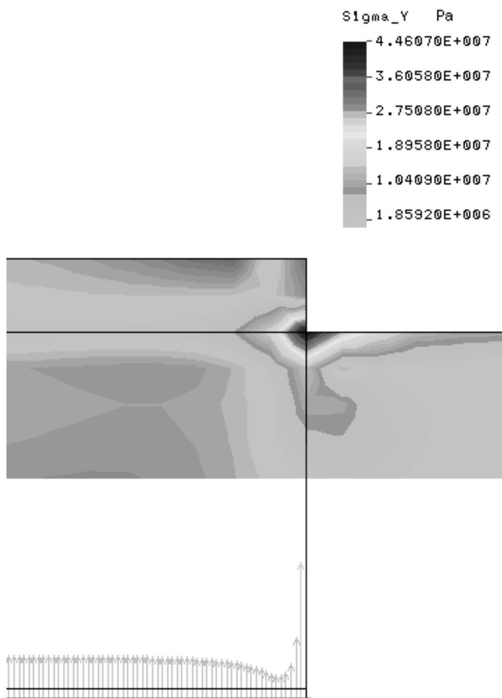

Fig. 11 Distribution of interlaminar normal stress component – time 2 s

Values of biaxial normal stress in individual layers according to (4) or (6) respectively do not themselves affect the separation of the layers. It depends on the existence of peaks of shear and interlaminar normal stress components on the edges of layers at their interface directly proportional to normal thermal stress.

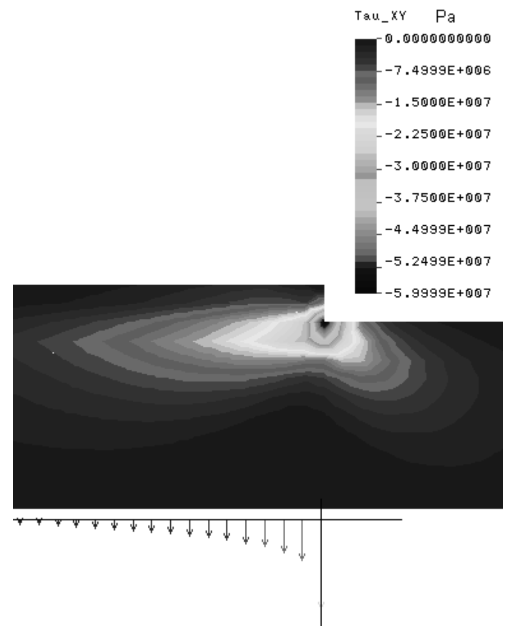

Fig.12 Distribution of shear stress near the edge of the layer 1 – time 1,5 s

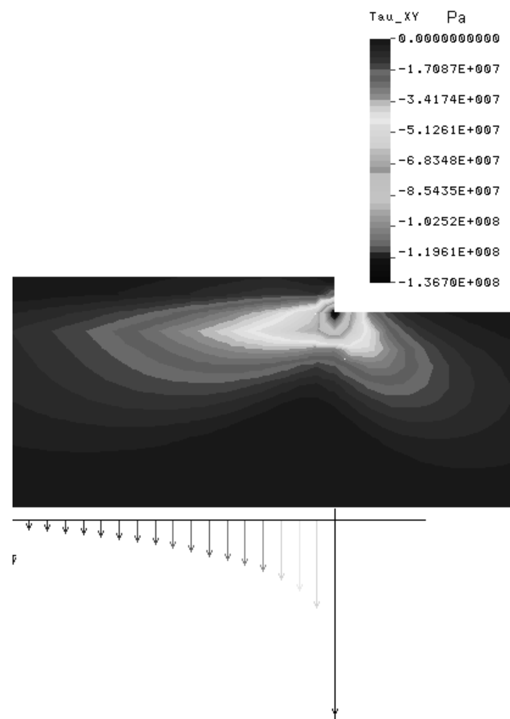

Fig.13 Distribution of shear stress near the edge of the layer 1 – time 2s

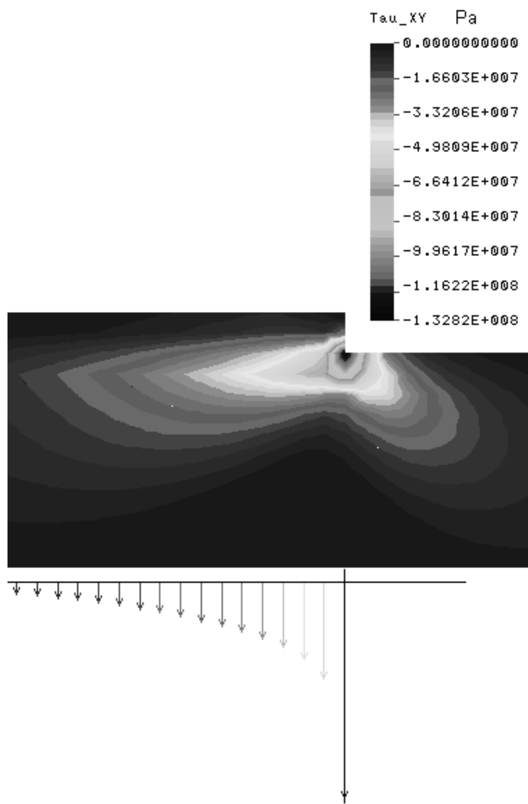

Fig.14 Distribution of shear stress near the edge of the layer 1 – time 2,5 s

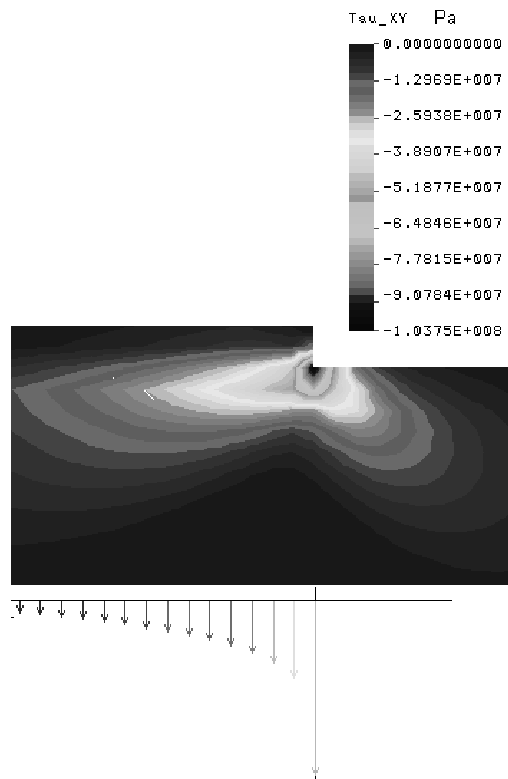

Fig.15 Distribution of shear stress near the edge of the layer 1 – time 3 s

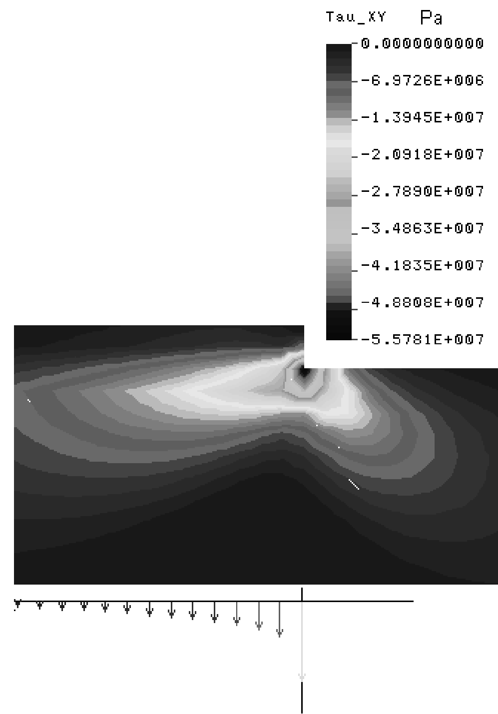

Fig.16 Distribution of shear stress near the edge of the layer 1 – time 4 s

Type of course of shear stress at the layers interface is shown in Fig.17. In a certain instant of time stress reaches its maximal value at the edge of the layer 1(Cu). Stress extends in direction from the edge to the distant L_0, which is the same order of magnitude with the thickness of polymer layer (2). If the maximal value of shear stress at the interface reaches the limit value – shear strength of interface, the separation begins. The resulting course of time dependence. τ_{MAX} from the beginning of the board cooling is shown in Fig.18. As can be seen, in process of rapid, i.e. non-homogenous, cooling there is the instant of time t_{max} in which the peak of shear stress reaches its maximal value.

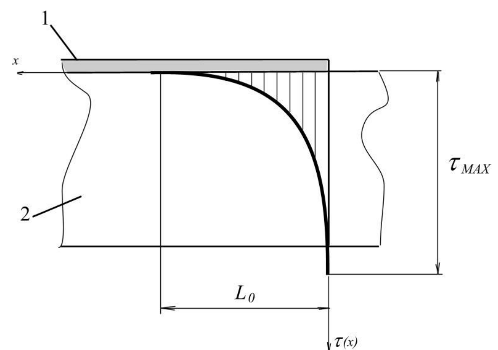

Fig.17 General dependence of shear stress at distance x from the edge of the layer 1 (Cu)

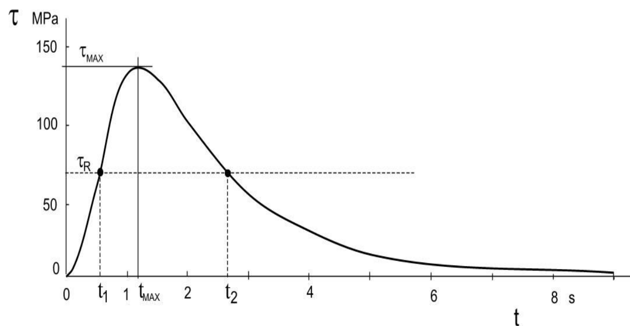

Fig. 18 Time course of boundary maximal shear stress at the layers interface

Since the beginning of cooling the values are increasing to this value and after reaching it they decrease to the zero value when the temperatures in the board evened out. The separation process can be characterized as follows: separation begins after rising of τ_{MAX} to the value of shear strength at the interface τ_R – instant of time t_1.

The edge of Cu layer starts to peel, whereas the edge of layers joints moves in direction of separation and has a value τ_{MAX} variable in time. The process of peeling of Cu layer stops in time corresponding to decrease of τ_{MAX} to the value τ_R in time t_2.

V. Conclusion

Role modelling of thermal stress in this area lies in predicting the possibility of separation, depending on the type of thermal stress and material parameters.A practical application focuses on the issue of recycling of PCB boards with the effort to achieve separation of layers due to thermal stress.

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