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STRENGTH OF ELECTRONIC COMPONENTS ENCAPSULATED WITH COMPOUND UNDER THERMAL IMPACTS

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Abstract. *Electronic packages with complete encapsulation by compound are in the research objective for the represented study. Encapsulation designed to provide reliable protection against all climatic impacts and increases mechanical strength of the package becomes the reason for potentially destructive mechanical stress that appears when packages are subjected to thermal impacts due to internal mechanical interaction between sealed components and sealant caused by difference of their physical and mechanical characteristics. The Lame-Gadolin theory that considers interaction of compound thick-walled cylinders in form of axially symmetric problem has been substantiated for the stress calculations in electronic components represented as the solids of revolution surrounded by the layer of compound and subjected to simultaneous action of pressure and temperature. Statically indeterminate problem was solved with considerations in the material properties and compatibility in deformations in order to define radial, tangential stresses and strain in both electronic components and compound. Calculation formulas for radial and tangential stresses in both electronic component and compound, and the contact pressure at the boundary between two joint cylinders were represented for the case of stabilized temperature drop, which represent the ultimate thermal impact on the encapsulated package. The taken considerations provide stress calculation for sealed components at the arbitrary form of encapsulation, what means irrespective to sealant profile, on only condition that compound thickness is 4 times higher than component's external radius. Since materials of copmound and compound are in complicated stressed condition their strength assessment is performed by using third strength theory or theory of greatest tangential stresses.*

Keywords: *strength, stress, strain, electronic package, electronic component, compound, encapsulation, thermal impact, pressure.*

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МІЦНІСТЬ ЕЛЕКТРОННИХ КОМПОНЕНТІВ ГЕРМЕТИЗОВАНИХ КОМПАУНДОМ ПРИ ТЕРМОУДАРАХ

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Анотація. *Об'єктом представленого дослідження є електронні модулі з повною герметизацією компаундом. Герметизація, призначена для забезпечення надійного захисту від усіх кліматичних впливів та підвищення механічної міцності модулів, стає причиною появи потенційно руйнівних механічних напружені, які виникають, в умовах коли модулі піддаються впливу термоударів, через внутрішню механічну взаємодію між герметизованими компонентами та герметиком, викликані різницею їх фізичного-механічних характеристик. Теорія Лама-Гадоліна, яка розглядає взаємодію сполучених товстостінних циліндрів у формі осе-симетричної задачі, обґрунтована для розрахунків напруження в електронних компонентах, представлених у вигляді тіл обертання, оточених шаром компаунду та підданих одночасній дії тиску і температури. Статично невизначена задача вирішувалася з врахуванням властивостей матеріалу та сумісності деформацій з метою визначення радіальних, тангенціальних напружень та деформацій як в електронних компонентах, так і в компаунді. Формули розрахунків для радіальних і тангенціальних напружень як в електронному компоненті, так і в компаунді, а також контактний тиск на межі між двома сполученими циліндрами були представлені для випадку стабілізованого перепаду температур, що представляє граничний тепловий вплив на герметизований модуль. Враховані міркування забезпечують розрахунок напружень для герметизованих компонентів при довільній формі герметизації, що означає незалежно від профілю герметика, лише за умови, що товщина герметику в 4 рази перевищує зовнішній радіус компонента. Оскільки матеріали компонентів та герметику перебувають у складному напруженому стані, їх оцінку міцності проводять за допомогою третьої теорії міцності чи теорії найбільших тангенціальних напружень.*

Ключові слова: *міцність, напруження, деформація, електронний модуль, електронний компонент, компаунд, герметизація, термоудар, тиск.*

Introduction

Miniaturization trend to manufacture ever smaller electronic products and devices causes strength and reliability loss in their components. The special attention is drawn to electronic packages (modules), which are exposed to harsh environment, such as vibration, temperature drops, humidity, pressure and other impacts while their operation. Such packages demand design approaches aimed at environmental protection, one of which assumes using electronic packages designed by applying partial or complete printed circuit boards (PCBs) coating, encapsulation or sealing enclosure (fig. 1), which may be used alone or in combination [1]. Such electronic modules are widely installed on board of land transport, airplanes, rockets, ships, trains etc.

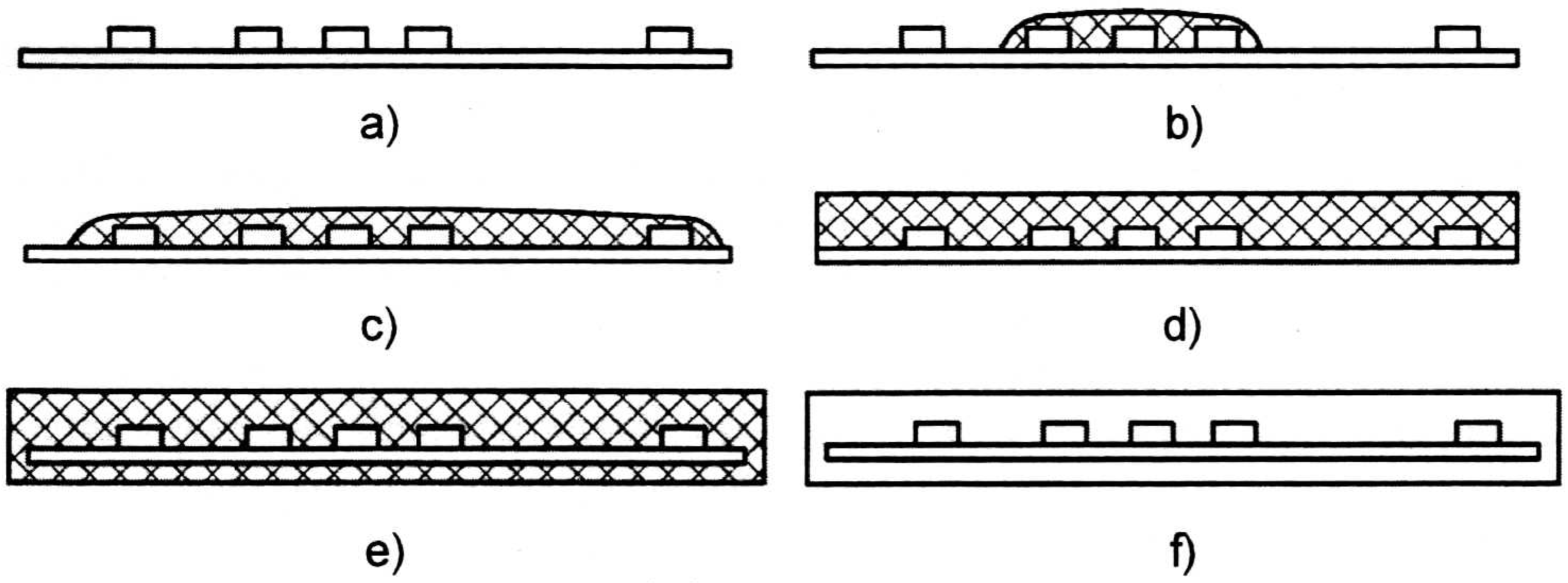


Fig. 1. Types of electronic packages design:
a) unsealed; b) partial substrate coating; c) complete substrate coating;
d) partial encapsulation; e) complete encapsulation; f) sealed enclosure

Electronic packages with complete encapsulation (fig. 1, e) by compound are in the research objective for the current study. Encapsulation provides reliable protection against all climatic impacts and increases mechanical strength of the modules. However, during thermal tests in the temperature range from +70 to –60 deg C within 1 hour exposure at ultimate temperatures or while operation, when subjected to thermal impacts, the modules sustain internal mechanical interaction between sealed components and sealant caused by difference of their physical and mechanical characteristics. This interaction produces mechanical stresses [2] potentially destructive for the weakest links in the module. Compound damages disrupt encapsulation and cause breakdown of the whole module. Destruction or damage to electronic components inside the module causes either breaks of the electric circuit [3] or deviation of parameters and finally, malfunction of the module. Such consequences are irreversible since encapsulated modules are not repairable. Mechanical stresses produced by thermal impacts cause up to 40% of breakdowns in electronics and up to 60% failures in aviation electronic packages, worsen their precision and distort parameters. The costs of such breakages can be very high.

Although the other research [1,4,5] represented solutions for the strength problems in electronic components, development of calculative and experimental methods remains actual for strength assessment in joint system of sealed components and the sealant. Therewith consideration of thermal impacts and real values of physical and mechanical characteristics of joint materials is necessary.

The represented research is aimed at developing stress estimation method for encapsulated electronic packages subjected to thermal impacts.

Research objective representation

Encapsulated packages are designed by applying compound sealing enclosure to printed circuit board populated with electronic components. The majority of encapsulated discrete electronic components vulnerable to stress are represented by solids of revolution. Such components are resistors, ceramic tube capacitors, diodes, sealed pins and others sealed with compound.

Sealing technology is performed by the following steps. Electronic packages, which are PCBs with installed electronic components, and compound are heated to polymerization temperature and therewith receive independent expansion. Then packages get filled and hereby encapsulated with compound, and placed to thermostat until polymerization is finalized, where chemical shrinkage of compound provokes slight contact pressure and stress. At the final step the product is cooled to normal temperature. Since then compound is bonded to electronic components and the package represents a solid body with numerous heterogeneous inclusions.

As consequence of difference in coefficients of thermal linear expansion and other physical and mechanical characteristics the thermal impact produces contact pressure in their contact boundary and hence generates stress in bonded materials.

In most common cases the electronic components represented as the solids of revolution are surrounded by uneven layer of compound. Then the calculation scheme will be represented as the cylinder virtually selected around electronic component in the volume of compound. Hereby this scheme is brought to axially symmetric problem of two cylinders interaction.

Lame-Gadolin theory application

Lame-Gadolin theory describes interaction of compound thick-walled cylinders and considers axially symmetric problem. Thick-walled cylinder is assumed as cylinder whose wall thickness is greater than 1/10 of its average radius [6]. In the calculation scheme (fig. 2) the inner cylinder is forced by external surface contact pressure P and by internal atmospheric pressure P_1; the outer cylinder is forced by internal surface contact pressure P and by external atmospheric pressure P_2.

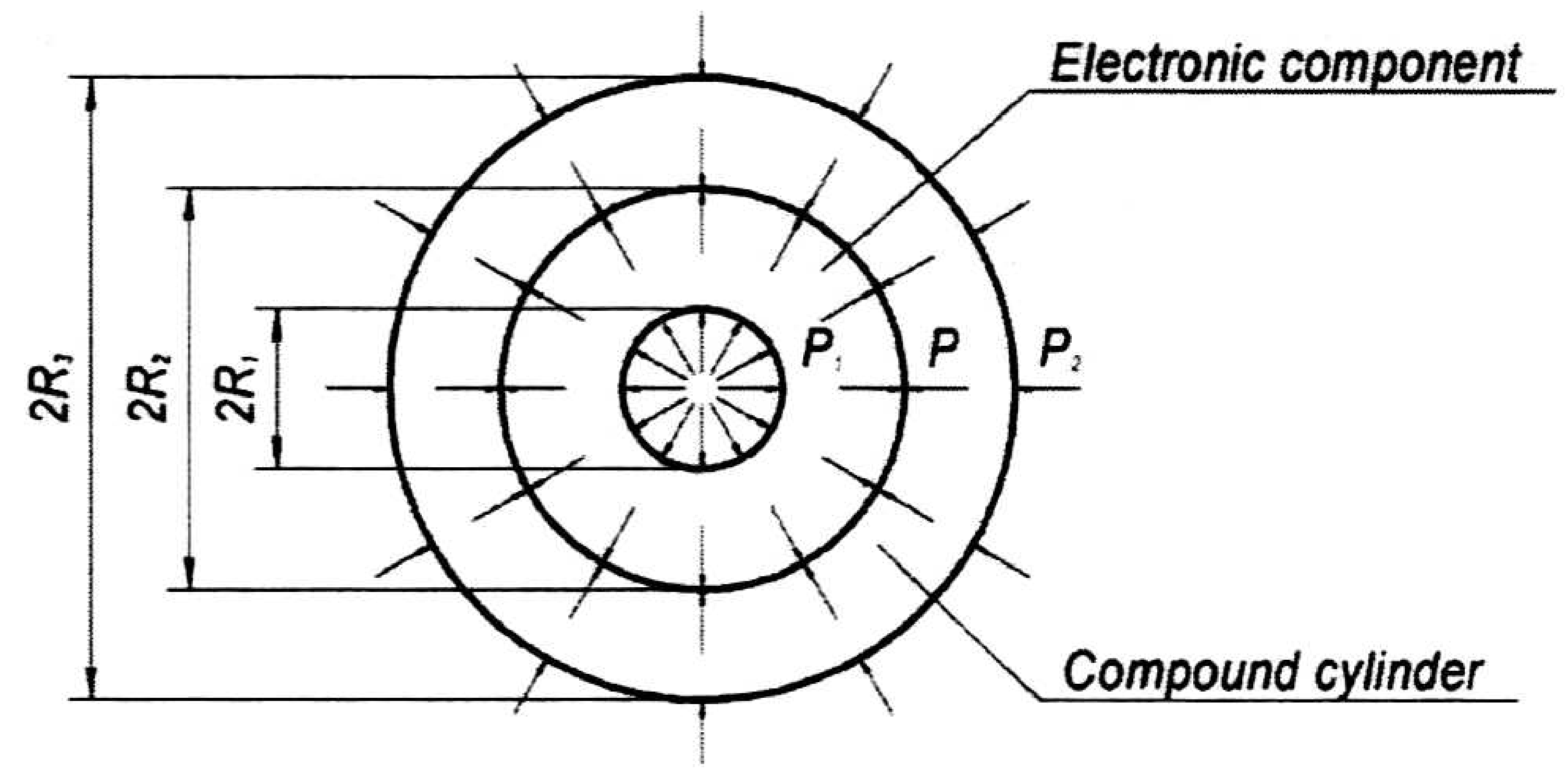


Fig. 2. Axially symmetric problem for compound thick-walled cylinders

The common case is considered when electronic component and compound are forced by pressures P_1, P_2 and by temperature $t = t(r, \tau)$ with respect to cylinder radius r and time τ. Thermal stresses caused by heating or cooling cylinders are added by stresses caused by the pressure. Due to the axially symmetric forces the stresses and strains are also axially symmetric.

The infinitesimal element *acdb* is selected in the volume of cylinder as shown in fig. 3. Normal stresses across element's cylindrical surface of radius r are assumed as radial stresses σ_r, which receive $\sigma_r + d\sigma_r$ increment at $r+dr$ radius increment. Normal stresses across the flat side faces are assumed as tangential stresses σ_t. The stress direction shown in fig. 3 (b) is considered to be positive and the stresses — tensile. The shear stresses are absent due to axial symmetry of the cylinder.

Assuming cumbersome formulas for stress estimation their deduction is skipped so that final expressions are given in the further solutions.

Statically indeterminate structure

Static problem is normally solved by static equilibrium equations for the element loaded by the following forces (fig. 3, c): $\sigma_r \cdot r \cdot d\varphi \cdot dz$ across the inner cylindrical face; $(\sigma_r + d\sigma_r)(r+dr)d\varphi \cdot dz$ across the outer cylindrical face; $\sigma_t \cdot dr \cdot dz$ across the side faces.

Static equilibrium equation represents sum of all forces projected onto the X axis

$$\sum X = -\sigma_r r d\varphi \mathrm{dz} + (\sigma_r + d\sigma_r)(r + dr)d\varphi \mathrm{dz} - 2(\sigma_t dr \sin\frac{d\varphi}{2})\mathrm{dz} = 0 . \quad (1)$$

The transformation of (1) gives the expression

$$r\frac{d\sigma_r}{dr} + \sigma_r - \sigma_t = 0 . \quad (2)$$

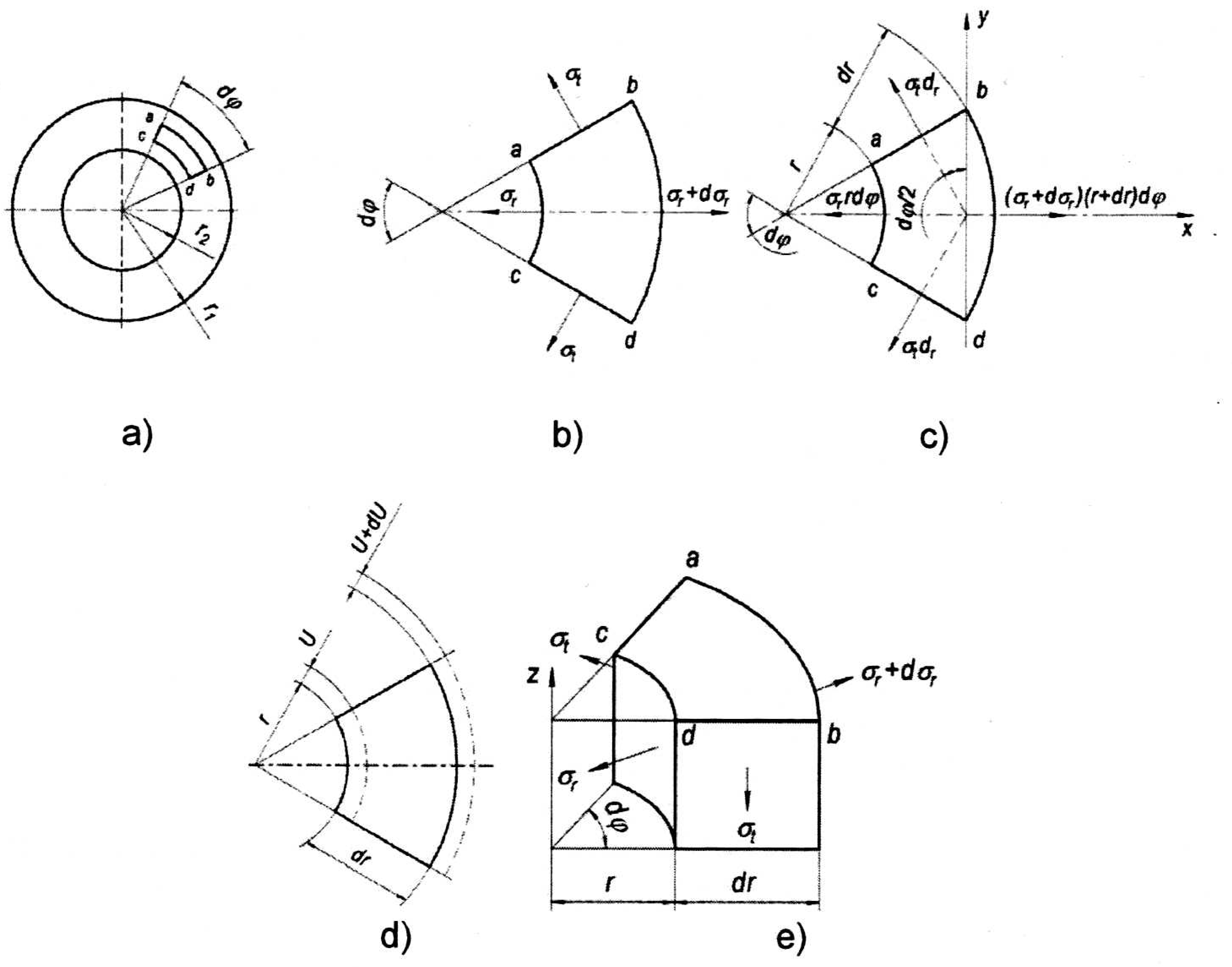


Fig. 3. Strain and stress of infinitesimal element in the volume of cylinder

Since there are two unknowns stresses σ_r and σ_t, but only one equilibrium equations, it does not have a unique solution. The structure is therefore classified as statically indeterminate. Considerations in the material properties and compatibility in deformations are taken to solve statically indeterminate systems or structures [6].

Compatibility in deformations defines mutual deformation in the contact boundary between two jointed cylinders. The element (fig. 3, d) sustains axially symmetric strain and causes radial displacements of all points in the cylinder. *U* stands for radial displacement of cylindrical surface with radius *r*, then displacement of cylindrical surface with radius *r+dr* is represented as *U+dU*.

Radial and tangential engineering extensional strains are expressed correspondently as

$$\varepsilon_r = \frac{dU}{dr}; \ \varepsilon_t = \frac{U}{r}. \tag{3}$$

Considerations in the material properties include coefficients of thermal linear expansion for the strain and stress calculations. Thermal change is represented by Δt, which is radius *r* and time τ variant: $\Delta t\ (r,\ \tau) = t\ (r,\ \tau) - t_0$, where $t\ (r,\ \tau)$ — temperature distribution along the cylinder radius, t_0 — initial body temperature, τ — time.

Hooke's law in expanded form expresses strain of element as sum of strains caused by pressures and thermal expansions. Radial, tangential and axial strains are expressed correspondently as

$$\begin{gathered}
\varepsilon_r = \frac{1}{E}(\sigma_r - \mu\sigma_z - \mu\sigma_t) + \alpha\,\Delta t \\
\varepsilon_t = \frac{1}{E}(\sigma_t - \mu\sigma_z - \mu\sigma_r) + \alpha\,\Delta t\,, \\
\varepsilon_z = \frac{1}{E}(\sigma_z - \mu\sigma_r - \mu\sigma_t) + \alpha\,\Delta t = const\,.
\end{gathered} \tag{4}$$

Solutions of these equations for stresses are represented as

$$\begin{gathered}
\sigma_r = \frac{E}{(1+\mu)(1-2\mu)}\left[(1-\mu)\varepsilon_r + \mu\varepsilon_t + \mu\varepsilon_z - (1+\mu)\alpha\,\Delta t\right], \\
\sigma_t = \frac{E}{(1+\mu)(1-2\mu)}\left[(1-\mu)\varepsilon_t + \mu\varepsilon_r + \mu\varepsilon_z - (1+\mu)\alpha\,\Delta t\right], \\
\sigma_z = \frac{E}{(1+\mu)(1-2\mu)}\left[(1-\mu)\varepsilon_z + \mu\varepsilon_r + \mu\varepsilon_t - (1+\mu)\alpha\,\Delta t\right].
\end{gathered} \tag{5}$$

Strain, stress and contact pressure in electronic component and compound

The formulas for radial stress σ_r, tangential stress σ_t and radial strain *U* in material of electronic component (6–8) and compound (9–11) are represented in condition that the low environmental pressures P_1 and P_2 are neglected with respect to much higher contact pressure *P*.

For the case when temperature drop Δt is stabilized calculation formulas for stress and strain (6–11) become expessed as

$$\sigma_{r_1} = -\frac{PR_2^2}{R_2^2 - R_1^2}\left(1 - \frac{R_1^2}{r^2}\right), \qquad (6)$$

$$\sigma_{t_1} = -\frac{PR_2^2}{R_2^2 - R_1^2}\left(\frac{R_1^2}{r^2} + 1\right), \qquad (7)$$

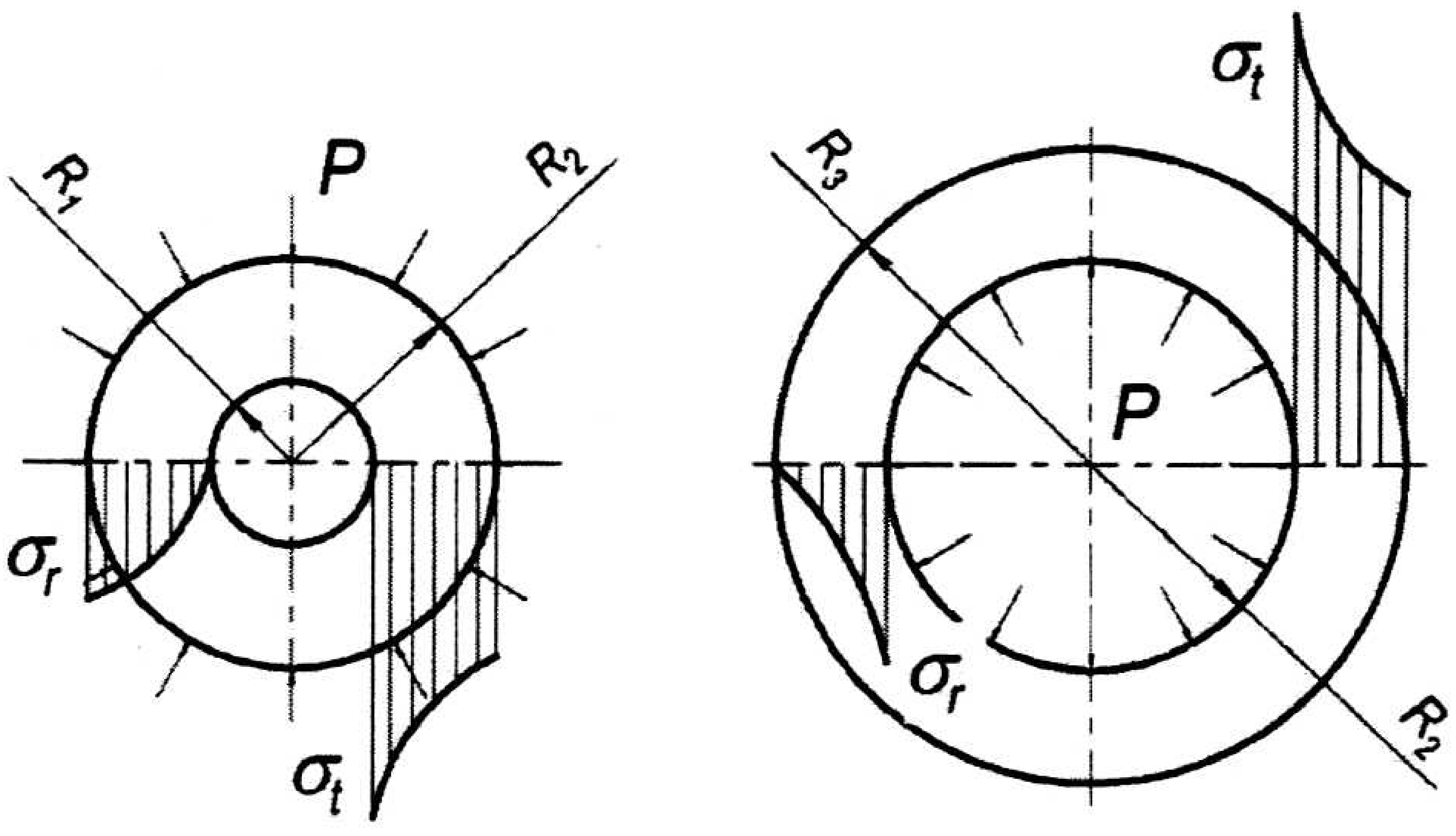
$$U_1 = -\frac{PR_2{}^2}{E_1\left(R_2^2 - R_1^2\right)}\left[r\left(1 - 2\mu_1\right) - \frac{1 + \mu_1}{r} R_1{}^2\right], \qquad 8)$$

$$\sigma_{r_2} = -\frac{PR_2^2}{R_3^2 - R_2^2}\left(\frac{R_3^2}{r^2} - 1\right), \qquad (9)$$

$$\sigma_{t_2} = \frac{PR_2^2}{R_3^2 - R_2^2}\left(\frac{R_3^2}{R^2} + 1\right), \qquad (10)$$

$$U_2 = \frac{PR_2^2}{E_2(R_3^2 - R_2^2)}\left[r(1 - 2\mu_2) + \frac{(1 + \mu_2)R_3^2}{r}\right]. \qquad (11)$$

The stress diagrams in electronic component and compound calculated by formulas (6, 7, 9, 10) are shown in the figure 4.



a) b)

Fig. 4. Tangential and radial stresses diagrams for:
a) electronic component; b) compound

Analysis of formulas (6, 7, 9, 10) specified maximal limit for outer radius of compound cylinder R_3 to consider for calculation, which is 4 times higher than that of electronic component. Indeed, the further increment would only result in 1/16 strain increment. Besides, compound cylinder is assumed as endless large wall at 5–6% error tolerance.

The taken considerations provide stress calculation for sealed components irrespective to sealant profile on only condition that compound thickness is 4 times higher than component's external radius. Since increasing pressure from compound out of the zone of selected cylinder is insignificant with respect to maximal pressure found in solution of symmetric problem it may be neglected in engineering calculations.

Formulas for stress and strain calculation in electronic components and compound are functions of contact pressure *P*. In order to find contact pressure the considerations in compatibility in deformations in the contact boundary between two joint cylinders are taken

$$U_{1/r=R_2} = U_{2/R=R_2}\,. \tag{12}$$

Substation of equations (8) and (11) into (12) and then solution with respect to P gives the expression (13)

$$P = \frac{\left[(1+\mu_1)\alpha_1 - (1+\mu_2)\alpha_2\right]\Delta t}{\dfrac{\left[(1+\mu_1)R_1^2 + (1-\mu_1)R_2^2\right]}{E_1\left(R_2^2 - R_1^2\right)} + \dfrac{\left[(1+\mu_2)R_3^2 + (1-\mu_2)R_2^2\right]}{E_2\left(R_3^2 - R_2^2\right)}}\,. \tag{13}$$

Strength assessment

Since materials of resistor and compound are in complicated stressed condition then their strength assessment should be performed by using strength theory [6]. Using third strength theory or theory of greatest tangential stresses for assessing strength of compound and ceramics of resistor represents the most interest.

Speaking specifically both resistor and compound are in three-dimensional stress. Since the absolute value of longitudinal stress σ_z is considerably less than radial σ_r and tangential σ_t stresses, it can be neglected and the stress condition is assumed as two-dimensional.

Since $\sigma_t > \sigma_r$, by the absolute value, for compound cylinder the following statement is true

$$\sigma_1 = (\sigma_t)_{R=R_2},\ \ \sigma_2 = 0,\ \ \sigma_3 = (\sigma_r)_{R=R_2}\,. \tag{14}$$

Hence the strength condition is expressed as

$$\sigma_{eqv}^{III} = (\sigma_1 - \sigma_3)_{\max} = \frac{2P_c R_3^2}{R_3^2 - R_2^2} \le [\sigma]. \tag{15}$$

Analogous expression can be obtained for ceramic cylinder of resistor.

Conclusions

The Lame-Gadolin theory that considers interaction of compound thick-walled cylinders in form of axially symmetric problem has been substantiated for the stress calculations in electronic components represented as the solids of revolution surrounded by the layer of compound and subjected to simultaneous action of pressure and temperature.

The statement has been made that maximal limit for outer radius of compound cylinder considered for calculation is 4 times higher than that of electronic component, hereby its further increment would result only in under 1/16 strain increment, what allows selecting a cylinder from compound around electronic component with the specified radius and with no respect to its profile.

The mathematical model has been developed for stress estimation in the joint of electronic component and compound, which allows strength assessment for electronic components, represented as the solids of revolution, and also compound, at the arbitrary form of encapsulation, subjected to thermal impacts.

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