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PRINTED CIRCUIT BOARDS. RELIABILITY OF INTERCONNECTIONS

Stability of metallization of holes to thermomechanical pressure is provided with durability and plasticity of electrodeposited copper.
Distinctions in factors of thermal expansion of copper and dielectric of bases of printed circuit boards create powerful thermomechanical factors of rupture of metallization of apertures, destructions of internal interconnections in multilayered structures of printed-circuit boards. Standard norms of requirements for the depth of metallization of apertures, its durability and plasticity of copper were established in the course of manufacture of ordinary printed-circuit boards with reference to use of traditional technologies of soldering by tin-lead solders. Return to consideration of the copper plasticity problem has been caused first of all by transition to lead-free solders initiated by the all-European Directive RoHS [1], featuring a high temperature of soldering. Higher temperatures create large deformations of metallization of holes, which forces us to reconsider the requirements for plasticity of copper. At the same time, there is a general tendency to reduction of the diameter of metalized holes, and consequently to reduction of the area of metallization cross-section. Smaller sections have smaller resistance to rupture. Therefore, along with good plasticity, metallization of holes of printed-circuit boards should provide higher resilience to rupture as well. In this reference, deformation of metallization of holes when heating to soldering temperatures has been studied. The purpose of researches is to revise norms as regards plasticity of copper in holes of printed-circuit boards. It has been shown that the plasticity of copper deposition in holes of modern printed-circuit boards should not be less than 6% [2]. Current copper plating electrolytes allow us to reach plasticity of copper of 12-18% [3].

Keywords: *printed circuit boards, interconnection, plasticity of copper.*

The gist of the problem

The elements of interconnections are exposed to thermal loads in the process of manufacturing, assembling and cyclic changes in temperature during operation of the equipment. Differences in temperature coefficients of linear expansion (TCLR) of conductive structures and dielectric create thermo-mechanical tensions of various intensity in electrical connections. In longitudinal directions reinforced by fiberglass patches, differences in TCLR are so small that they do not affect the strength of connections of the longitudinal structure.

In the transversal direction perpendicular to the plane of the reinforcement, the differences are so significant in linear expansion ($17 \cdot 10^{-6}$ for copper and $(100\ldots400) \cdot 10$ -6 for dielectric basis) that thermomechanical tensions occurring due to temperature loads can break interlayer connections.

It is known that the resistance of metalized holes to thermo-mechanical loads is ensured by the depth and plasticity of metallization. Standard requirements for metallization on these quality criteria have been established during the years of practice in manufacturing and maintenance of electronic devices with printed assemblage with a thickness of boards in relation to the diameter of a hole from *1:1* to *3:1*. With the size of through holes less than 0.3 mm this ratio can be as high as *10:1…20:1*. In such constructions of multilayer printed circuit boards (MPCB), the ration of rigidity of apertures' metallization and their surrounding material of the bottom board is not in favor of metallization, since in conditions of thermal effects the deformation of metallization of holes substantially increases (Fig. 1). This phenomenon is aggravated by the decline in copper metallization of plasticity with an increasing temperature of soldering.

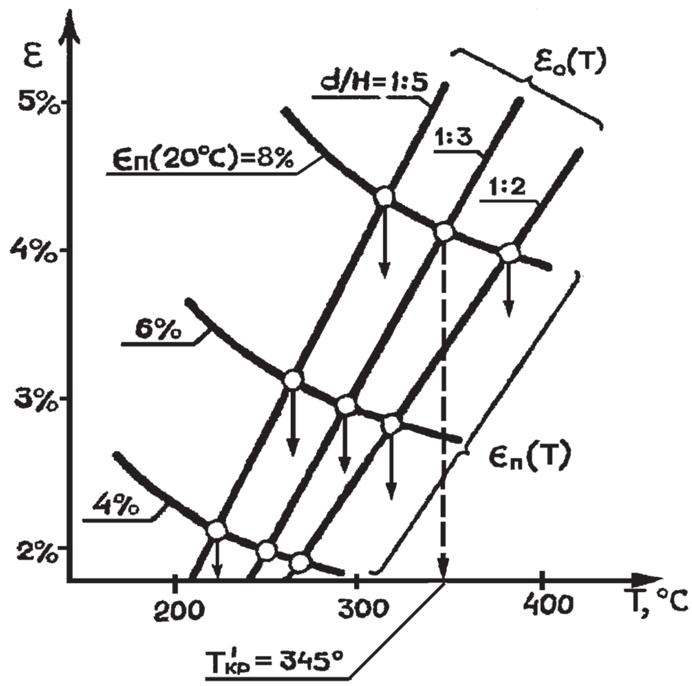

Fig. 1. The toughening of requirements for the plasticity of metallization
with the diminution of the diameter of through holes

Statistics show that an especially big stream of failures in interlayer connections is observed equipment systematically exposed to cyclic changes in temperature (thermo cycles). According to the data of the long-term operation of one of aviation systems, printed circuit failures are distributed as follows: metalized holes are 24%, inner connections are 72%, printed conductors of internal layers are 0.1%, isolation is 2%, soldering is 2.5%, breaks of wires are 0.3%, others are 0.6%. Comparison of the number of failures of MPCB in stationary equipment functioning in a relative constancy of temperatures and in airborne equipment shows the difference in nearly three orders of magnitude, that making us believe that, if the level of variable thermo-mechanical tensions exceeds a certain limit, there is a process of gradual accumulation of damages, which ends in fatigue destructions of connections.

Model of thermo-mechanical stressing

Thermo-mechanical stress during heating causes the stretching of metallization along the axis of a hole (axial tensions) and the curving of contact pads, with the largest concentration of which being on the junction with the metal cylinder of a hole (curve tension). A typical distortion of the form of a hole in case of heating is schematically shown in Fig. 2 and in the picture of microslice in Fig. 3.

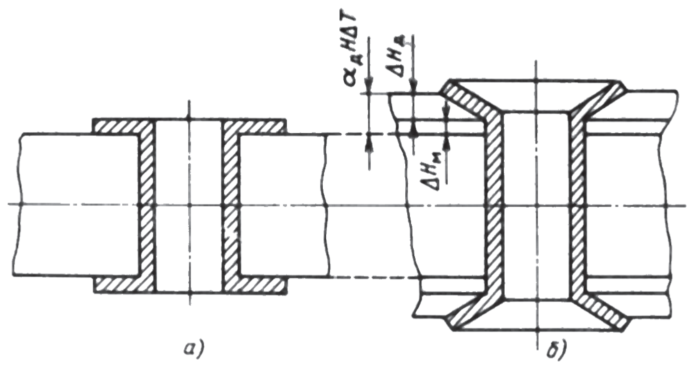

Fig. 2. Distortion of metalized holes when heated

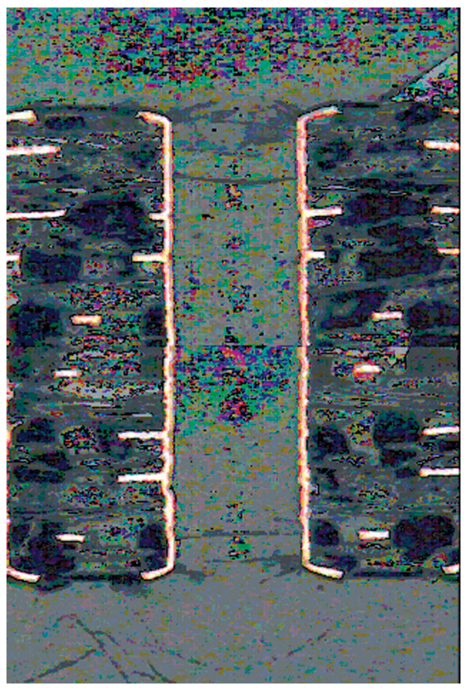

Fig. 3. Microslice of metalized holes after a thermo shock

In general, the relative deformation σ_Z of metallization under temperature loads can be represented as the sum of the elastic ε_Y and temperature ε_T deformations. Elastic deformation is $\varepsilon_Y = \sigma E$ (E is module of elasticity). Temperature deformation is $\varepsilon_T = \alpha(T\text{-}T_0)$. Hence, the thermo-mechanical stress is $\sigma = E\ [(\sigma_Z - \alpha(T\text{-}T_0)]$. Thermo-mechanical efforts in each of the elements of a metalized hole:

$$F = E[(\ \sigma_Z - \alpha(T\text{-}T_0)]\ h\ dZ.$$

To determine the characteristics of thermo-mechanical deformation of metallization, let us write an equation of equilibrium assuming that the sum of all thermo-mechanical efforts arising in components of *metallization-hole walls* system has to be zero (Fig. 4):

$$\int_0^{h_M} E_M[(\varepsilon_Z - \alpha_M(T - T_0)]hdZ + \int_{h_{\text{Д}}}^{0} E_{\text{Д}}[(\varepsilon_Z - \alpha_{\text{Д}}(T - T_0)]hdZ = 0.$$

After integration and transformation it can be shown that the deformation of copper in transversal direction *Z* is:

$$\varepsilon_Z = (\alpha_D - \alpha_M)\,(T - T_0)\,(1 + J_M/J_D)^{-1}, \tag{1}$$

where α_D and α_M are TCLR, J_M and J_D are relative rigidity of copper and dielectric.

If ε_Z exceeds the limit of elasticity of copper deposit in a hole (or $\sigma_R > \sigma_{PL}$), ring rapture of metallization occurs.

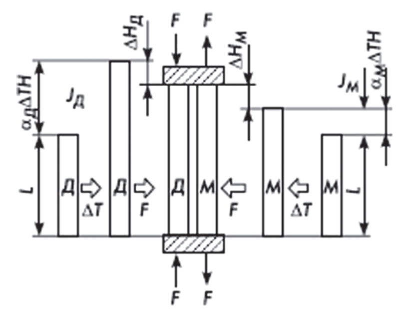

Fig. 4. Model of axial thermo-mechanical stresses

If the forces of adhesion of metallization with walls of a hole are small, shift tensions can be realized in rupture of internal connections. Shift stress should evidently increase with an increasing distance of junction from the neutral axis *0--0* (Fig. 5). The distance of shift, if it occurs, can be determined on the basis of general views. But if the coupling forces hold metallization on junctures of a hole, then an increasing tension of shift in the conditions of rising temperature stress is equal to $\sigma_{Sh} = G(\alpha_D - \alpha_M)\Delta T$. The value of destructive shift stress is determined based on the experimental values of pulling of metallization from a hole. Figure 6 shows a picture of destruction of an internal connection resulting from shift of metallization in relation to the walls of a hole.

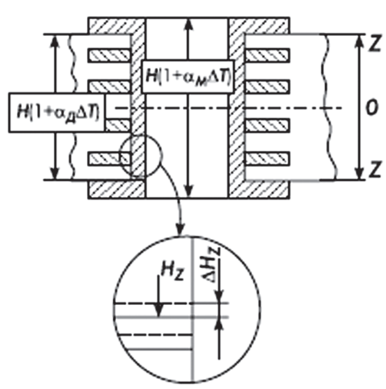

Fig. 5. Shift of metallization from ends of contact pads of inner layers

Fig. 7 shows a chart of temperature deformation of freely expanding cylinders of copper, polymeric composite dielectrics and the resulting temperature deformation of their aggregate, and Figure 8 shows a deformation-strain diagram. The curve of temperature expansion of dialectic basis has a fracture at the temperature of glass transition *Tg*. The zone of elastic deformation of copper is limited to the value ε_Y.

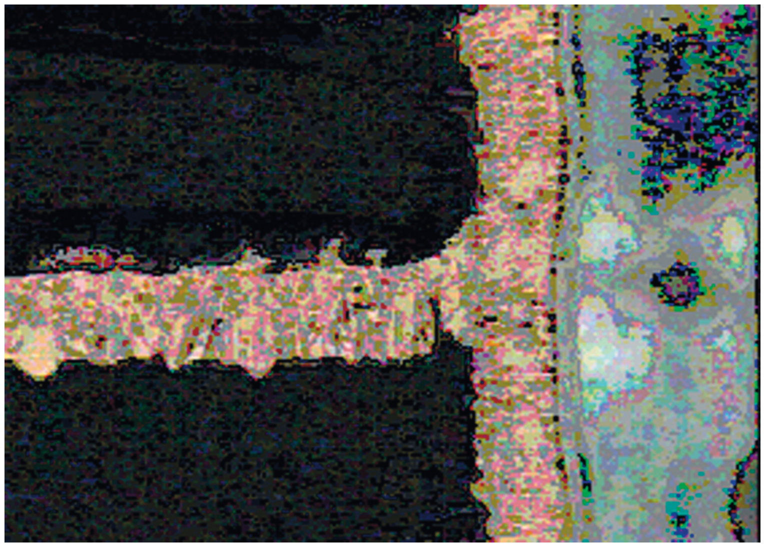

Fig. 6. Picture of the microslice of destructed internal connection

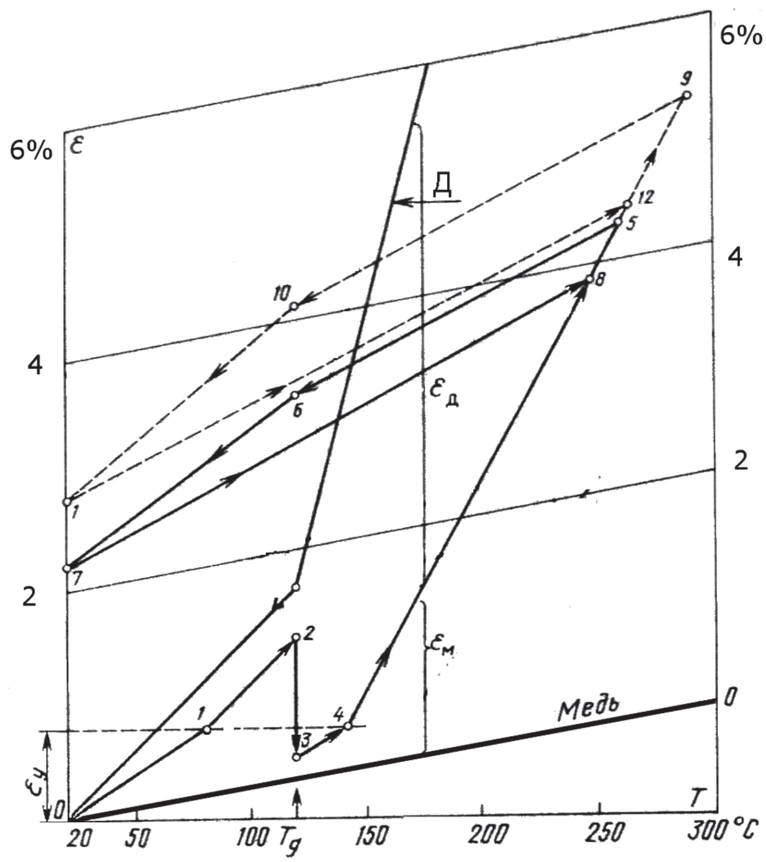

Fig. 7. Graph of temperature deformation of metallization
of aperture received by graphical and analytical method

On 0-1 section, the shift module of copper corresponds to a section of elasticity, i.e. has a value G_M, the module of dielectric is equal to $G_Д$. The distribution of deformations of dielectric and copper yields to the ratio: $\alpha_D/\alpha_M = G_M S_M / G_D S_D$, where S_M and S_D are squares of cross section of loading of a copper cylinder and dielectric around it suffering from the load. When at point 1 the deformation of copper moves to a section of fluidity (1-2), its module decreases, so metallization of a hole is deformed practically following the free expansion of dielectric. Under the temperature of glass transition *Tg*, dielectric

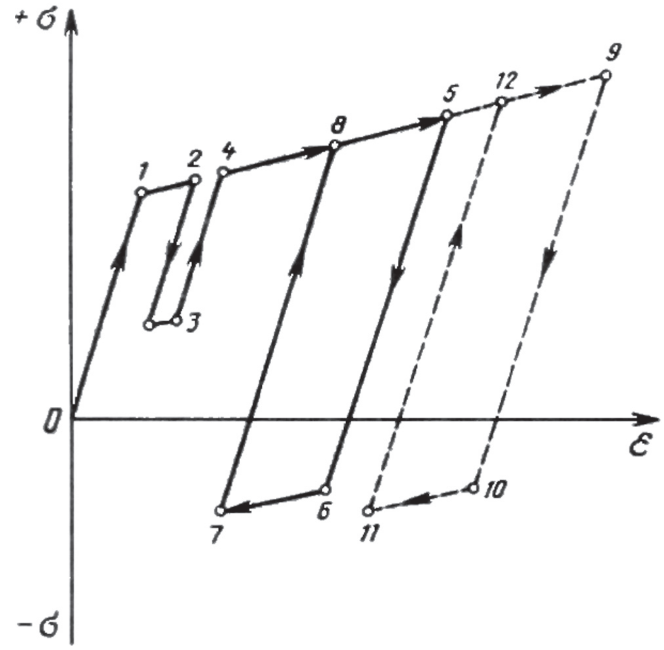

Fig. 8. Chart of deformation-strain

basis loses its rigidity, and due to that a copper cylinder is unloaded. Its deformation takes on a value that corresponds to point 3. When moving beyond the glass transition temperature *Tg*, dielectric begins to grow intensively. However, initially this does not result in a large extension of copper till its deformation does not exceed the limits of elasticity (section 3-4). Correlation of deformations of dielectric and copper on this section looks like:

$$\alpha_D / \alpha_M = G_M ' S_M / \, G_D ' \, S_D \, . \tag{2}$$

Curves 5-6-7-8-5 and 9-10-11-12-9 show the changes of the linear dimensions of a metalized hole in case of cooling and a repeated cycle of heating-cooling for soldering temperatures 260°C and 290°C, respectively. The presence of hysteresis in the diagram of temperature deformations reveals a certain percentage of plastic deformation of copper, which is a harbinger of fatigue destruction under cyclic temperature stress.

Methodology of experimental researches

One knows the basic principles of researching stresses in metallization of through holes using micrometrical sensors of shifting that register growth of thickness of the dielectric basis and metal cylinder of a through hole as MPCB is heating. Increase of the accuracy of measurements in a wide temperature range is ensured by using a quartz sample holders and shift passing rods. There have been attempts to use attachable strain gauge microsensors for measuring small elongations (extensometers) to study deformations of metallization of through holes during soldering. Comparison of measurement results of thermal expansions using these two methods obtained by different authors demonstrates their ambiguity due to the uncertainty of a starting base in the first case and low sensitivity of strain measuring to small samples, where MPCB belongs to, in the second case.

The author has used his own methodology to study thermo-mechanical stresses when the hole to be analyzed itself is used as a stain gauge sensor to measure its temperature deformations. In this case one uses the following assumptions. The relation of ohmic resistance change with deformation:

$\Delta R/R = k\varepsilon$, where k is the tensosensitivity of an element (in this case of a metalized hole itself). Since $R = \rho H/S$, the differential form of expression $\Delta R/R$ looks like $dR/R = d\rho/\rho + dH/H - dS/S$, where ρ is the electrical resistivity of metallization, H is the thickness of a board (length of the metalized cylinder of a hole), S is the square of cross-section of hole metallization perpendicular to its axis. For low relative lengthening $d\varepsilon = dH/H$, the relative change of cross-section square is $dS/S = -2\mu(dH/H)$. So $dR/R = d\rho/\rho + \varepsilon + 2\varepsilon$, where μ is Poisson's coefficient. Then the tensosensitivity of an element, i.e. the metallization of a hole is

$$k = (dR/R)\,\varepsilon^{-1} = (1 + 2\mu) + (d\rho/\rho)^{-1}. \tag{3}$$

Expression (3) consists of two parts: the geometrical part depending on ρ and reflecting electrical resistance changes only by changes in the size of a metal cylinder due to its longitudinal deformation, and the physical part linked with the change of total resistance of metallization when extending $d\rho/\rho = B\,dV/V$ and reflecting the linear dependence between the change in total resistance and the relative change of volume dV/V. B is Bridgman's coefficient. In the case of one-axial loading occurring in metallization of a hole during heating,

$$d\rho/\rho = B\,(1 - 2\mu)\,\varepsilon. \tag{4}$$

Combining (3) and (4), we get:

$$k = 1 + 2\mu + B(1 - 2\mu). \tag{5}$$

The direct effect of temperature on a change of metallization resistance is taken into account based on a known relation: $\Delta R/R = (+\,234)^{-1}$. For pure copper $B = 1$, at least for the temperature range from 0 to 300°C. Hence, according to (5), the numeric expression of tensosensitivity of hole metallization is equal to 2. I.e. a relative elongation of metallization by 1% leads to a change of resistance of hole metallization by 2%. For researches of deformation within 6% with the distinction of 0.1%, the required accuracy of measurement of resistances was almost ensured by a four-probe method with instruments of the first class precision. To make sure that four probes are contacted, wires to contact pads were soldered using cold gallium soldering that after the formation of solid solutions can withstand temperatures up to 800°C without rupture (Fig. 9).

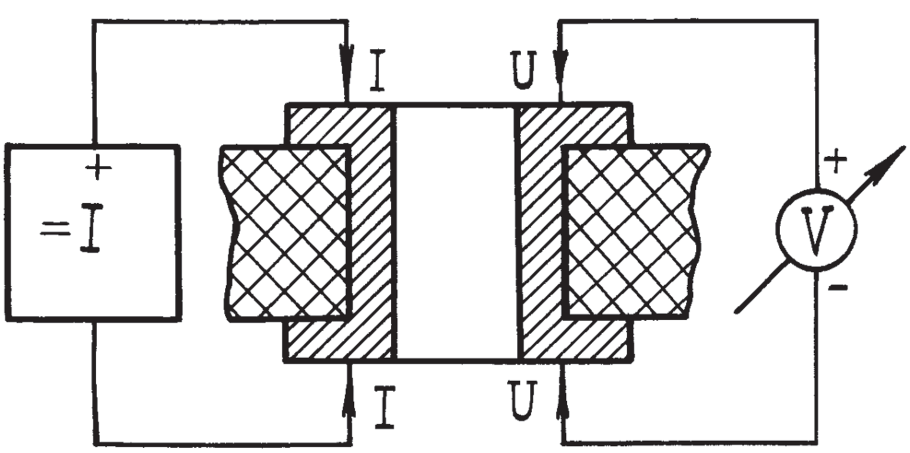

Fig. 9. Scheme of measuring the resistance of hole metallization by four-probe method

Results of experimental studies of deformation

Results of measurement of deformation of a metalized hole with a diameter of 0.8 mm in MPCB of 1.6 mm thick, shown in Fig. 10, are in good agreement with the results of the graphical and analytical analysis based on a nonlinear model of thermo-mechanical deformation of through metalized holes.

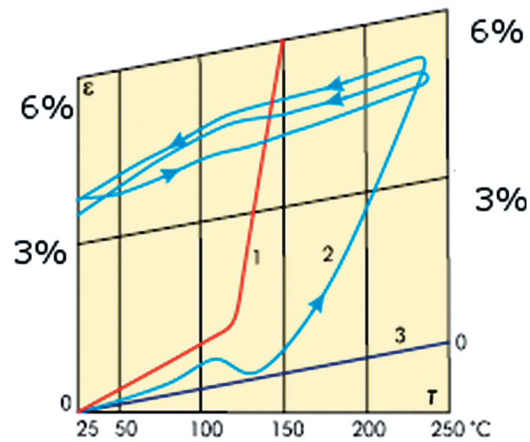

Fig. 10. Experimentally obtained diagrams of temperature deformation of metalized holes: 1 and 3 are charts of free expansion of dielectric and copper; 2 is the experimental chart of deformation of metalized holes

The combination of large deformations of metallization of holes under thermal loads and reduced plasticity of copper may in certain circumstances lead to rupture of hole metallization or metallization shift in relation to the walls of holes, if one does not take measures to increase the plasticity of galvanic deposition for temperatures corresponding to MPCB possible heating. Table 1 shows the threshold temperature values for destruction of interconnections in MPCB.

Table 1. Threshold temperature of the beginning of destruction

Ratio of MPCB thickness to diameter of a hole, *H/d*	**2:1**	**3:1**	**5:1**	**10:1**	**20:1**
Plasticity of metallization, %	Threshold temperature, °C				
4	290	250	220	210	190
6	320	290	260	240	220
8	380	350	320	280	260

In case of high temperature deformations, insufficient plasticity of metallization and shaky coupling of metallization with walls of MPCB through holes, destruction of internal connections may happen. To identify such defect, it is enough after a thermal shock (reflowing) to provoke oxidation (humidity + heat) of touching surfaces of physical contact of hole metallization with ends of internal contact pads, and using the results of measuring the resistance of internal connections to diagnose the reliability of MPCB.

Fatigue low-cycle destructions are only possible when moving in the area of plastic deformation. And the deeper the temperature deformation moves in the area of plastic deformation, the earlier failures of connections begin during operation. The offered methods for monitoring the status of connections in MPCB identify the start of plastic deformation as the emergence of hysteresis in the *temperature-resistance* graph of a circuit element. The studies made allow us to quantify the influence of thickness of metallization of through holes on the temperature corresponding to the start of plastic deformation (Table 2).

Table 2. Start of plastic deformation during heating

Depth of metallization of MPCB hole, μ	**Ratio of MPCB thickness to diameter of metalized through holes (*H/d*)**		
	2:1	**3:1**	**5:1**
	Temperature of plastic deformation start, °C		
10	75	**60**	50
15	85	73	55
20	95	80	60
25	100	85	65
30	110	90	70

Local defects, particularly in the form of ring thinning, significantly reduce the resistance of the metallization of holes to cyclic temperatures.

Studies show the futility of thermal cycling for grading assembled products by identifying the weakened elements of connections: cyclic loads destroy defective items and create fatigue weakening of connections, close to the border of distinction between quality items and defective items. This is also due to the fact that the boundary of quality between good and defective and elements is blurred. There are always intermediate states between them that characterize the possibility of failure for connections due to fatigue phenomena.

Conclusion

Reliability of interconnections in modern electronic equipment is technologically provided by a high level of plasticity of metallization of printed circuit boards resistant to low-cycle fatigue destructions provoked by group heating in case of multistage soldering and troubleshooting repairs of printed circuit boards.

References

1. **Medvedev A.M.** Lead-free soldering. Technology Forum//Technology in electronics industry. 2007, #3.

2. **Medvedev A.** Optimierte Leiterplatten für die bleifreie Löttechnologie (Physikalische Grundlagen der Verbindungszuverlässigkeit) – Electronishe Baugruppen und Leiterplatten – EBL 2008”. Schwabenlandhalle Fellbach. 13 – 14.02.2008.

3. **Shkundina S.E., Semenov P.V., Vashchuk G.A.** Industry standard paves the way to use new chemical processes and high-quality materials// MANUFACTURING OF ELECTRONICS: Technology, machinery, materials. – 2010. – #1.