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ACCELERATED RELIABILITY TESTS OF LEAD - FREE SOLDERED JOINTS

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Key words: reliability tests, accelerated tests, tests of lead-free soldered joints, mechanical shear strength, fatigue strength

Abstract: Important condition for implementation of lead - free technology, according to the RoHS directive of European Community, is the warranty of good quality and reliability of electrical joints executed in new, environment - friendly technology. Especially for small electronic enterprises it is difficult to prove that the product reliability is not lower than before the change. One of the solutions is application of appropriate accelerated test methods. Typical tests applied in Warsaw University of Technology for reliability assessment of solder joints are investigations of mechanical shearing strength at appropriate temperature and fatigue strength in cycling processes. For investigation of fatigue strength are applied different accelerating factors (temperature changes and thermal shocks, cycling of electrical charge and mechanical cycling). The principles and discussion of appropriate test methods are presented.. Some preliminary results show that mechanical fatigue tests may be used for accelerated comparative reliability investigations for certain classes of electronic products.

Pospešeni testi zanesljivosti spajkanih stikov brez svinca

Kjučne besede: testi zanesljivosti, pospešeni testi, testi stikov spajkanih brez svinca, mehanska natezna trdnost, utrujenost materiala

Izvleček: Pomemben pogoj pri upeljavi tehnologije brez svinca v skladu z RoHS direktivo Evropske skupnosti, je zagotovilo dobre kakovosti in zanesljivosti stikov izdelanih z novo, okolju prijazno tehnologijo. Še posebej majhnim podjetjem je težko dokazati, da zanesljivost izdelka ni manjša kot pred spremembo. Ena od rešitev je uporaba ustreznih pospešenih testnih metod. Na Varšavski tehnični univerzi izvajamo tipične teste za določanje zanesljivosti spajkanih stikov, kot so raziskave mehanske natezne trdnosti pri določeni temperaturi in utrujenosti materiala pri cikliranju. Pri raziskavi utrujenosti uporabljamo različne pospeševalne faktorje (temperaturne spremembe in termične šoke, cikliranje električnega naboja, mehansko cikliranje). V prispevku pokažemo principe in opišemo ustrezne testne metode. Nekateri uvodni rezultati kažejo, da teste mehanske utrujenosti lahko uporabimo pri pospešenih primerjalnih raziskavah zanesljivosti za določene razrede elektronskih izdelkov.

1. Introduction

Each producer of electrical and electronic equipment must prove that the product reliability is not lower than before the change. One of the solutions is application of appropriate test strategy and accelerated test methods.

By planning and selection of type and parameters for reliability tests of lead - free soldered joints are considered general relations between data sets concerning design, technology and manufacturing factors (solder data, soldering process characteristics and soldered joints characteristics), applied test parameters and required functions determining definition of the failure, shown on fig 1. As failure criteria are chosen the measured changes of electrical resistance /1/ and extent of the cracks formation.

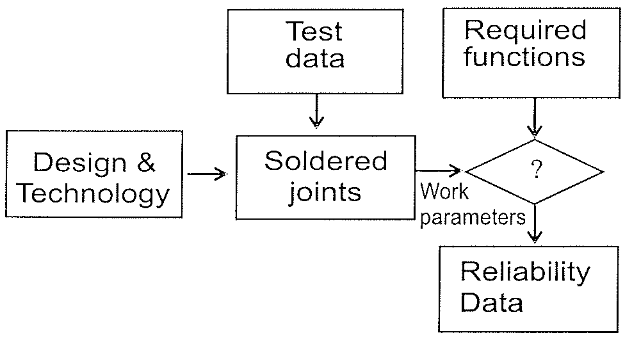


Figure 1: Scheme of data sets for reliability testing.

Preliminary results showed that thermal cycling, thermal shocks cycling and mechanical fatigue tests may be used for accelerated comparative reliability investigations for certain classes of electronic products.

2. Design, technology and manufacturing factors

2.1. Impact of design and technology on reliability issues

The data concerning design (especially applied materials and surface finishes), manufacturing factors and quality inspection characteristics influencing the properties of lead - free joints shall be determined.

Essential data of design and technology can be divided in following groups:

- soldered materials and surface finishes
- solder and flux data (type, composition, melting temperature, surface energy)
- quality and solderability data of soldered materials
- surface treatment before soldering (e.g. plasma treatment)
- composition and properties of flux and solder paste
- soldering process characteristics (soldering temperature, soldering time, temperature profile, soldering atmosphere, etc.)
- soldered joints characteristics (shape, dimensions, mechanical properties, temperature resistance and quality data determined by visual inspection) of the joints soldered with new alloys.

At present alternative solders are principally based on Sn - Cu, Sn - Ag and Sn - Ag - Cu eutectic alloys. Compared to eutectic SnPb38 solder with melting temperature 183 °C these alloys show some principal differences and strong dependence on the solder composition..

Higher melting temperature (227 °C for SnCu0,7 , 221°C for SnAg3,5 and 217°C for SnAg3,8Cu0,7) is critical for soldering of electronic components with soldering temperature resistance 250°C. The Cu content in wave soldering must be sharply controlled. Temperature window (fig.2) is smaller and new solutions of heating equipment (solder wave, reflow ovens) must be applied.

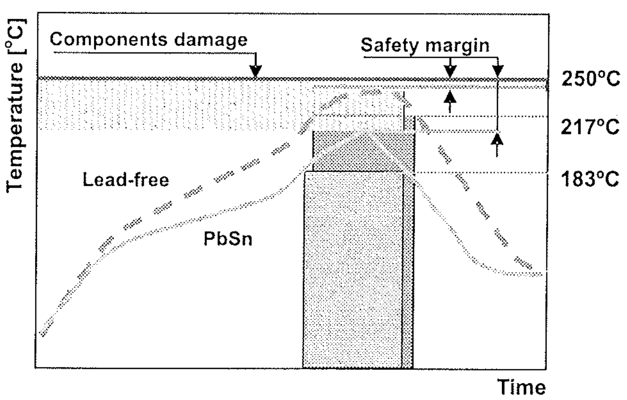


Figure2: Temperature window for SnPb and lead-free reflow soldering

Higher surface energy, smaller wetting force and longer wetting time of lead - free solders are unfriendly for joints quality and soldering productivity. New methods and new parametric data of soldering ability testing are necessary. In many cases these problems must be solved by soldering in nitrogen (N_2) atmosphere. New solutions of soldering equipment are also needed.

The creep rates by deformations of new solders are up - to 100 times lower than by Sn-Pb solders /2/ /3/. This property must be considered by development appropriate fatigue test methods and calculation of accelerating factors.

Poor soldering ability, low creep rate and higher melting temperature are influencing on the thermal and mechanical fatigue resistance. Modification of fatigue test methods and test data will be also necessary.

2.2. Test samples of solder joints

As samples of solder joints for reliability tests can be used:

- Electronic equipment
- Electronic modules
- Test samples

By choice of test models following criteria are applied:

- Representation of investigated product
- Charge conditions
- Simplicity of failures detection
- Measurements ability

3. Working and test conditions

3.1. Working conditions and degradation processes

The real working conditions of soldered joints are the base for selection of appropriate test methods. Soldered joints in electronic modules are subjected to a variety of mechanical and thermal charges as:

- thermal shock during soldering and cooling,
- mechanical charges during manufacturing process,
- thermal stress during storing and transportation,
- mechanical vibrations and shocks during transportation and operation,
- high and low temperatures during transportation and operation
- variation of temperature and thermal shocks during transportation and operation.
- electrical operating power changes

These charges influence following degradation processes:

- relaxation of mechanical and thermal stresses,
- corrosion of the solder, soldered parts an insulating parts,
- diffusion processes,
- whiskers growing
- fatigue and wear,

The solders are specific materials working at temperature near melting point. Especially for the objects working at increased and constant temperature, investigation of diffusion processes, metallurgical transformations as growth of the grains, decrease of the strength and corrosion are very important. The creep strain rate $\acute{\varepsilon}$ in certain limits can be determined from Arrhenius law /4/:

$$\acute{\varepsilon}_c = A\,\sigma^n e^{-(Q/RgT)}$$

where (for eutectic solder): A = 1,84.10^{-4} (MPa)$^{-n}$ - experimentally determined constant, n = 5,2 (experimentally determined), Q = 50KJ/mol - activation energy, Rg = 8,313.10^{-3} KJ/molK, T - absolute temperature.

The Arrhenius Law can be applied for assessment of relaxation of mechanical stresses, corrosion and diffusion processes.

Simplified model of linear deformations and stresses, with disregarded flexion of the PCB is shown on the figure 3. The length initial of the component not soldered is L_0. After heating of the component or heating of both: component and PCB by different thermal coefficients or mechanical deformation of the PCB the length of the component increase to L_1.

Total increase of the component length in relation to the PCB will be ΔL:

$$\Delta L = \Delta T_C \alpha_C \ - \ \Delta T_B \alpha_B + \Delta L_M$$

where: ΔT_C, ΔT_B - temperature changes of the component and PCB respectively, α_C, α_B - thermal expansion coefficients, ΔL_M - mechanical deformation.

However, the length of soldered component will be only L_2 because of compression by the force F_C causing the diminution ΔL_C. At the same time the deformation of the PCB and solder joints under the stretching force F_B will be ΔL_B.

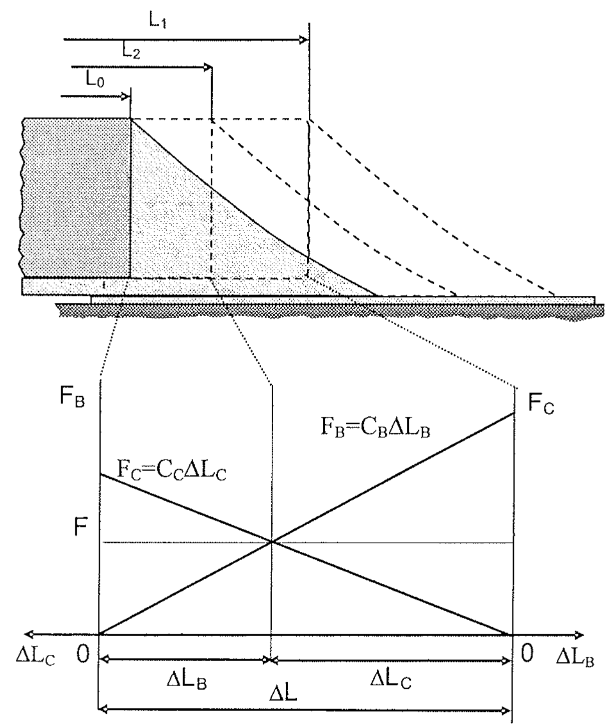


Figure 3: - Linear deformations of the component - solder - PCB system

Mechanical charge of the soldered joints (e.g. compression of the component and stretching of the PC board) can be determined from the balance condition:

$$F_C = F_B = \Delta L_C c_C = \Delta L_B c_B = F$$

where: c_C and c_B are the rigidity of the component and PCB with solder joints respectively, and finally:

$$F = \Delta L c_C c_B/(c_C + c_B).$$

It is only approximate value because of simplifications applied and omission of nonlinearity, creep phenomena and plastic deformations.

Good instrument for preliminary studies and selection of test conditions is the finite element modelling of the mechanical system created by soldered component. Example of mechanical deformations of chip resistor 1206 and Flip Chip soldered joints after PCB flexion are shown on fig. 4. FEM models are helpful for understanding of the damaging process and determining the test conditions and optimal shape of the soldered parts.

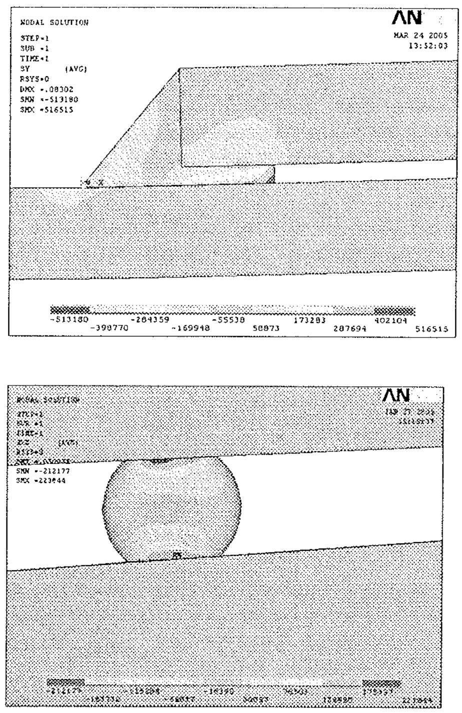


Figure 4: FEM model of the chip resistor and Flip Chip soldered joints

3.2. Accelerated Test Methods

The main accelerating factors by investigation of life time are applications of appropriate range of test temperature and mechanical load of soldered components and PCB in following tests:

- dry heat (for acceleration of physical and chemical processes)
- temperature cycling

- thermal shocks
- mechanical cycling
- electrical power cycling
- thermo mechanical charges.

3.3. Thermal cycling and thermal shock tests

The changes of temperature (fig.5) are the source of stress - relaxation enhanced creep and fatigue of the solder joints and thermo-mechanically induced failures /5/. The mean number of cycles to failure and acceleration factor can be determined by use of experimentally determined models and appropriate empirical relationships.

The rapid temperature changes result in large transient thermal gradients resulting in warping of the surface of the assembly. The test is appropriate for comparative reliability investigations, especially for the products working in thermal shock conditions, e.g. automotive under hood.

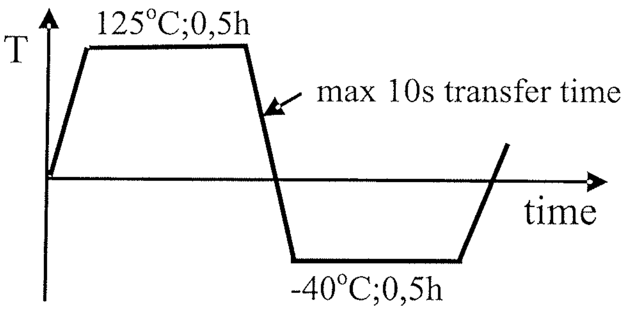


Figure 5: Thermal shock cycle

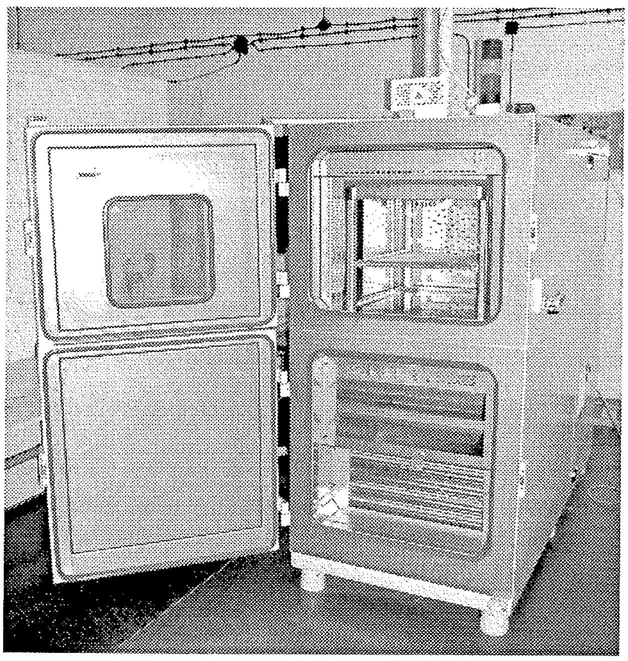


Figure 6: Two Zone Temperature shock chamber

It is performed in dual chamber test equipment (fig.6). By appropriate programming and sample configuration in two zones (heat zone and cold zone) the compatible temperature gradient can be achieved. The costs of the test are relatively high. Because of cost problems broad application of the thermal shock tests by implementation of the lead - free technology in small enterprises seems to be limited.

3.4. Electrical power cycling

By power cycle tests are generated deformations caused by changes of the power from on to off conditions of real component (mainly resistor) soldered on the PCB. The power cycling may more accurately replicate field use conditions than temperature cycle testing, as well both temperature and power cycle tests can be applied simultaneously.

3.5. Mechanical cycling

The deformations and stresses shown on fig. 4 can be obtained by stretching, warping or bending of the PCB. Different schemes of mechanical load are shown on fig 7.

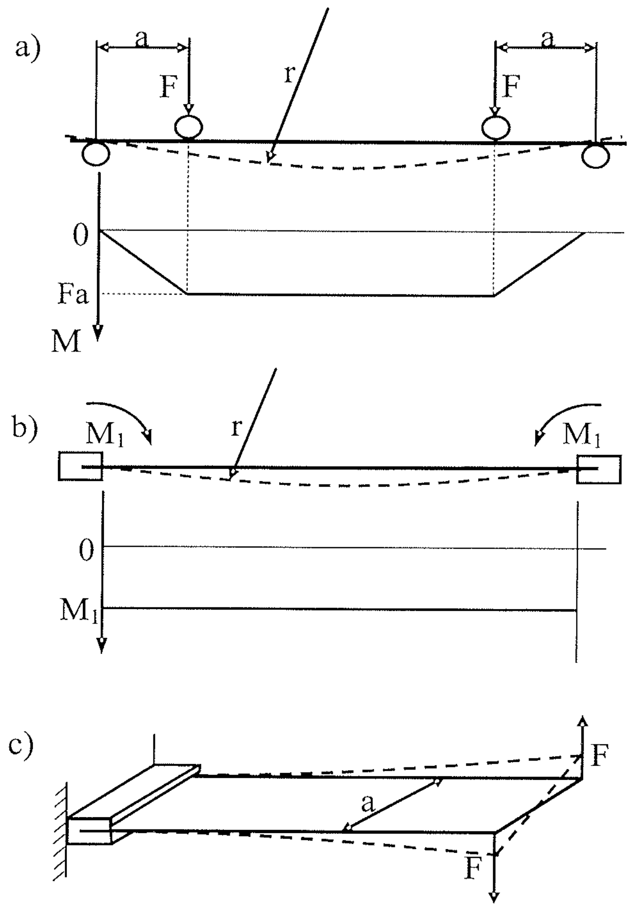


Figure 7: Charge systems of the PCB by mechanical tests; a) bending by force F , b) bending by moment M, c) warping with moment Fa

Very useful is the flexing system shown on the scheme 7b because of constant moment M and flexion radius r and uniform charge conditions for all components soldered on whole surface of the PCB. Preferably the PCB can be bent cyclic in one or two directions. By mechanical cycling tests is induced the solder creep fatigue phenomena. The necessary test acceleration factor can be obtained by selection of appropriate strain range.

3.6. Mechanical fatigue test stand

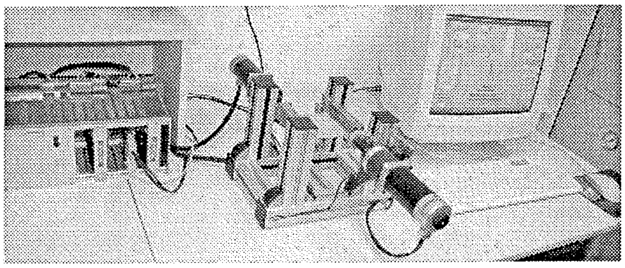


Figure 8: Mechanical fatigue test stand

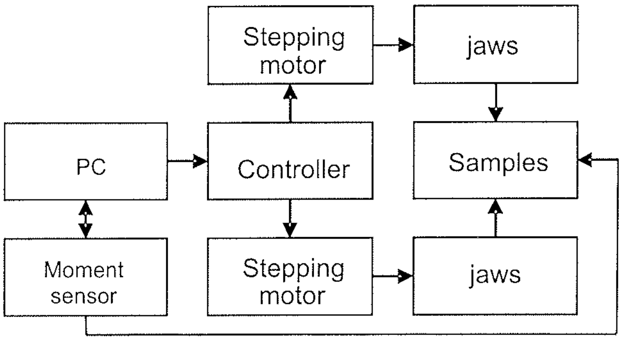


Figure 9: scheme of mechanical test stand

General view of laboratory stand for mechanical fatigue tests is shown on the fig.8. Block scheme is shown on fig.9. The stand consist of bending jaws, two servomotors, and motor controller.

The main parameters of mechanical cycling: bending velocity, time intervals t_1, t_2, t_3, t_4, bending angle α and bending moment M (fig.10) are controlled by PC.

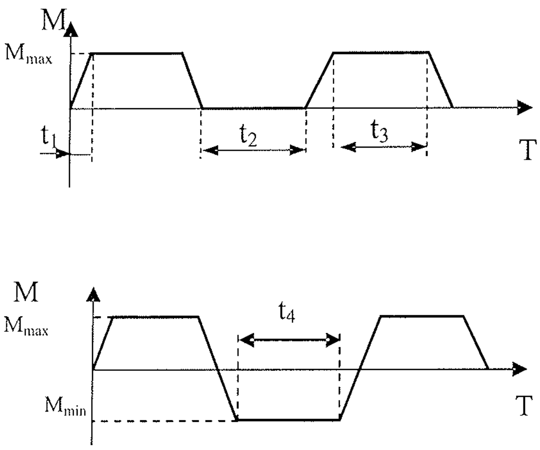


Figure 10: Mechanical testing schedule; a)one - side, b) two - side flexion

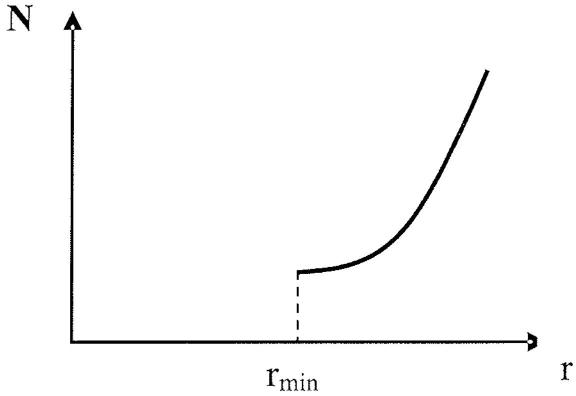


Figure 11: Number of cycles N to failure as a function of bending radius r (preliminary data for PbSn soldered 1206 resistor)

Preliminary tests, performed for SnPb eutectic solder, showed that mechanical bending cycling has in relation to thermal cycling following advantages:

- uniform charge of all components on the test board,
- large range of acceleration factor can be achieved by appropriate choice of the bending radius (fig.11),
- verification of materials and manufacturing process parameters relative test results can be achieved in short time,
- good accessibility of tested joints for verification and measurements (fig.12),
- low cost of testing equipment and necessary energy,
- environmental compatibility.

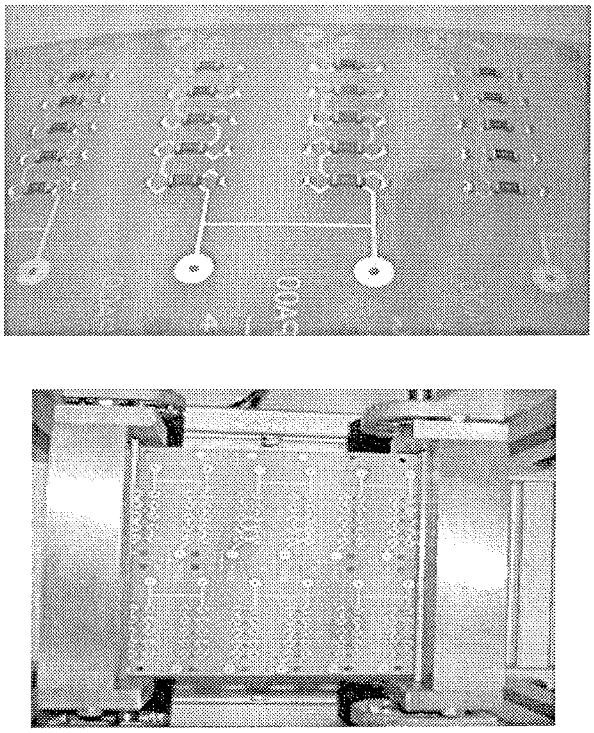


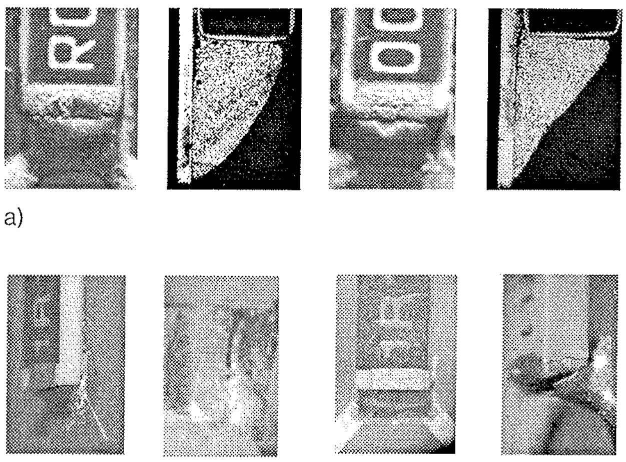
Figure 12: PCB sample fixed in the jaws

4. Required functions and failure criteria

Choice of required functions and parameters is very important for determining of the failure criteria and failure definition. In certain solutions the interconnections can be evaluated visually during the test, however precise definition of such failures and their detection during the tests is problematic. Application of electrical parameters (resistance, impedance, noise) as the failure criteria is more objective. The most important parameter is the value and stability of electrical conductance of all soldered joints. Good criterion is the stability of electrical resistance. During the tests performed in Warsaw University of Technology the resistance changes more than 10 moms were defined as failures /1/. The resistance increase 20% was also admitted as failure definition in IPC-9701.

5. Failures data collection and analysis

Failures of occurred during thermal shock and mechanical cycling are shown on fig.13a and 13b. By mechanical cycling smaller number of cycles is necessary.



a)

b)

Figure 13: Failures of solder joints; a)after 2000 thermal shocks, b)after 100 mechanical cycles

Dependent of the results of the tests the failures data can be expressed in following forms;

- Absence or presence of failures
- Time to first failure
- Number of failures as time function
- Cumulative distribution function F(t)
- True reliability R(t) = 1 - F(t)
- Density function
- Mean time to failure (MTTF)
- Failure rate λ
- Graphical presentation
- Confidence intervals
- Statistical distribution (exponential, Weibull,..)

Some examples are shown on figures 14, 15 and 16.

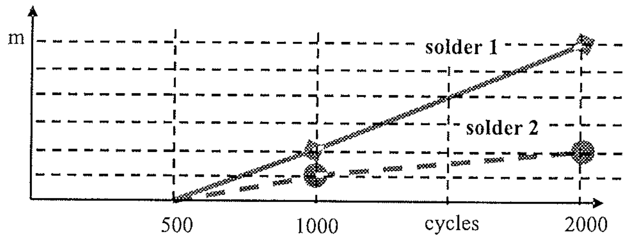


Figure 14: Number of failures m after thermal cycling of soldered joints for 400 joints

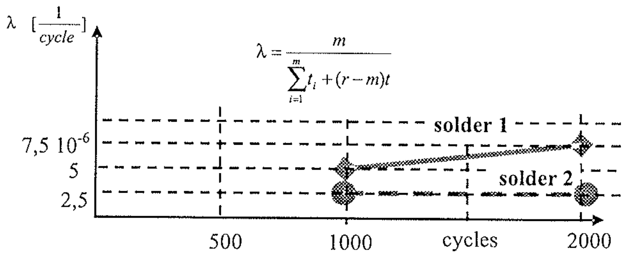


Figure 15: Failure rate λ calculated for the test sample 400 joints

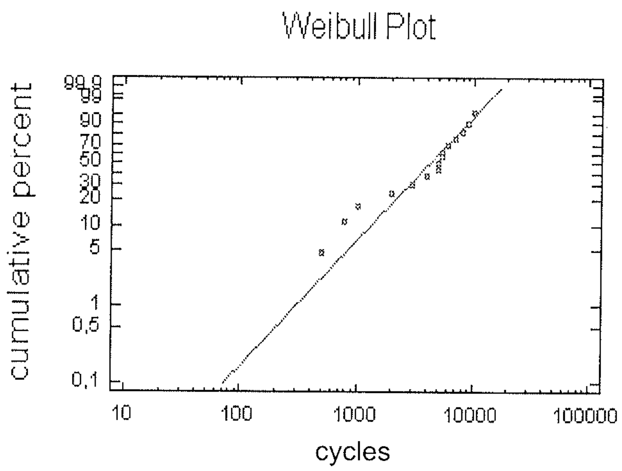


Figure 16: Presentation of failure data on Weibull plot

6. Conclusions

Reliability of soldered joints is the critical problem by implementation of lead - free technology. Up to date the reliability data of electronic products after removal of hazardous substances are unsatisfactory.

This paper showed preliminary results of investigations and analysis of thermal and mechanical cycling method for testing of solder joints. Preliminary test showed that application of only mechanical cycling as routine verification by small producers of electronic equipment will be very useful, however further detailed investigations, comparison with thermal cycling and electrical cycling tests, determination the test parameters and analysis of obtained results for different solders are necessary.

Developed laboratory stand enables further investigations, concerning test life correlations for SnPb and lead free soldered joints achieved in accelerated tests realized by different methods, and determination of application area for mechanical cycling method.

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