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STRENGTH ANALYSIS OF SOLDER JOINTS USED IN MICROELECTRONICS PACKAGING

BADANIA WYTRZYMAŁOŚCI POŁĄCZEŃ LUTOWANYCH STOSOWANYCH W MONTAŻU W MIKROELEKTRONICE*

The aim of the research was the problem of damage accumulation for solder alloys used in microelectronics packaging due to creep and fatigue as a result of a combined profile of loading conditions. The selected failure modes affect the lifetime of contemporary electronic equipment. So far the research activities are focused on a single failure mode and the problem of their interaction is often omitted. Taking into account the failure modes interaction would allow more precise lifetime prediction of the contemporary electronic equipment and/or would allow for reduction of time required for reliability tests. Within the taken research framework the reliability analysis of solder joints was conducted for the Sn63Pb37 solder alloy using the Hot Bump Pull method. The results of the presented research contain: reliability tests, statistical analysis and the problem of a damage accumulation due to a combined profile of loading conditions.

Keywords: *microelectronics, solder alloys, reliability, damage accumulation.*

Celem badań był problem kumulacji uszkodzeń dla stopów lutowniczych stosowanych w montażu w mikroelektronice w wyniku zmęczenia i pełzania na skutek złożonego profilu obciążeń. Wybrane rodzaje uszkodzeń przyczyniają się do ograniczenia czasu życia współczesnych urządzeń elektronicznych. Aktualnie prowadzi się badania z wykorzystaniem jednego rodzaju uszkodzeń i często pomijany jest problem ich wzajemnej interakcji. Uwzględnienie problemu wzajemnej interakcji pozwoliłoby na bardziej precyzyjne prognozowanie bezawaryjnego czasu pracy współczesnych urządzeń elektronicznych i/lub przyspieszenie testów niezawodnościowych. W ramach zrealizowanych badań przeprowadzono analizę wytrzymałości połączeń lutowanych dla stopu lutowniczego Sn63Pb37 z wykorzystaniem metody Hot Bump Pull. Wyniki przedstawionych badań obejmują: analizę wytrzymałości, analizę statystyczną oraz problem kumulacji uszkodzeń w wyniku złożonego profilu obciążeń.

Słowa kluczowe: *mikroelektronika, stopy lutownicze, niezawodność, kumulacja uszkodzeń.*

1. Introduction

Electronics is one of the quickest developing discipline of contemporary science and engineering. Due to the constant pursuit for miniaturization and integration most of the electronic components are designed and manufactured in the so-called micro scale. For this reason, the special term microelectronics was established among professionals. Nowadays, microelectronic components are an integral part of every industrial or home use electronic device. Unfortunately, like other devices, also microelectronic components experience a limited lifetime. One of the basic problems regarding their reliability are connections. In microelectronics packaging [17] soldered, glued and bonded connections are used, of which solder joints are the most important [13, 15, 27]. Most damages of the to solder joints occur as a result of thermomechanical loading, and their direct cause is stress resulting from the mismatch of coefficients of thermal expansion of the joined materials [17, 35, 40]. It is estimated that about 65% of damages in microelectronics packaging is associated to thermomechanical problems [2, 38].

Reliability is defined as an object property that determines its proper operation under given environmental conditions, over a defined period of time. Mathematical description of the reliability allows for probability assessment of the object failure in the defined operating conditions. One of the traditional ways of reliability prediction of joints in electronics packaging is theoretical analysis based of the so-called bimaterial interface. Bimaterial interface refers to the mechanical connection of two materials with different thermomechanical properties. Strength analysis requires in this case knowledge on stress distribution in the joint and nearby region. There are two possible failure modes: crack and delamination. The analytical solution for the bimaterial interface was proposed for the first time in 1925 by Timoshenko [30]. The solution referred to the structure deformation and maximal stress in the interface region. While the analytical solution describing the stress distribution in the interface region was proposed in 1989 by Suhir [29]. Analytical description of the stress distribution in the bimaterial interface region is difficult and requires a number of simplification, e.g. geometry of the structure and linear material model. Therefore, in modern engineering applications, numerical methods based on simulations using the FEM analysis are preferred [39, 41]. The FEM method allows simulations of real interface geometry and taking into account nonlinear material models. Additionally, along with the strength, numerical methods allow an inclusion during analysis failure criteria in order to predict reliability. Failure criteria are closely connected with the failure mode and material type. In microelectronics failures are recognized through reliability tests while the corresponding failure criteria are determined experimentally. The above problem was published lately in 2018 in a form of the standard document IPC/JEDECC-9301 "Numerical Analysis Guidelines for Microelectronics Packaging Design and Reliability" [24].

Due to dynamic development of electronic industry and a rapid changes of microelectronic technologies the crucial issue is an advanced research concerning reliability analysis as a consequence of

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** constantly growing integration and miniaturization of the electronic components. Solder joints are a good example of the above trend, as their dimensions being smaller than 100 μm are comparable with the dimension of single grains. Taking into account both the solder joint dimensions and different loading conditions of electronic components it came out that reliability prediction methods used in macro scale are not appropriate for micro scale [36]. For this reason, it is necessary to develop, on the one hand, advanced measurement techniques, typical for microelectronic technologies, while on the other hand, advanced methods of predicting failures due to thermomechanical loads [25]. The above requires knowledge on material behavior as a function of stress, temperature and time, which is refereed as rheology. One of the typical problems concerning rheology is analysis of creep and fatigue phenomena [20]. It should be underlined that in many fields of engineering, both fatigue and creep are treated as the main failure modes. Many researchers also emphasize the important role of their interactions, especially at elevated temperatures [10, 34]. In case of solder joints, used in microelectronic packaging, failures due to material creep and / or fatigue caused by thermomechanical loadings play a vital role in order to predict reliability accuratly [4, 6, 16].

2. Packaging and reliability of solder joints in microelectronics.

The concept of microelectronic packaging is associated with a number of activities and technological stages leading to a functional device. The goal of packaging is to provide good electrical connection, appropriate mechanical properties and heat transport. In order to achieve that, there are used various joining techniques such as bonding, soldering, gluing. As a result of the above diversity packaging techniques were divided into levels [8, 31]:

- zero: carried out at the production level and concerns the mounting of components on the semiconductor wafer surface,
- first: concerns the problem of making connections on the silicon chip and its packaging in an enclosure,
- second: packaging of silicon integrated circuits and other electronic components both active and passive on the surface of printed circuit board PCB,
- third: assembly of electronic modules in the form of individual PCB and other components in order to achieve the functional blocks and finally into a complete electronic device.

All types of connections used on the mentioned packaging levels must meet the reliability requirements in order to ensure long-term and appropriate operation of the device. The current research was devoted to the analysis of the solder joint reliability used at the second packaging level [12].

In fact, the goal of the research was to run a series of experimental strength tests of solder joints used in microelectronic packaging due to a combined loading profile. This allowed for analysis of typical failure modes, as creep and fatigue and additionally their interaction phenomenon. According to authors, the used measuring technique and the obtained results will allow in the future more accurate prediction of the solder joints strength at micro scale, and thus improve the reliability of microelectronic components. The presented research refers to the solder joints made with the traditional solder alloy $Sn_{63}Pb_{37}$. It should be underlined, that the EU directive RoHS (Restriction of Hazardous Substances) limited, starting form 2006, the sell of new electronic equipment in the EU region that contain hazardous substances such as e.g. lead solder alloys. Nevertheless, the same directive, introduced a number of exceptions to that rule, in cases where replacement of a certain material would be difficult or impossible and additionally in the case of research and development application. Traditional lead solder alloy $Sn_{63}Pb_{37}$ is characterized by a unique thermomechanical material properties and allows for durable and consistent connection of components. For this reason it is still used in the case of such equipment as medical, military, etc. Additionally, due to high strength of solder joints made with this alloy, it is used for comparison reasons of reliability tests in scientific research. Besides, the cited directive does not restrict the use of the alloy in the case of amateur applications.

Unfortunately, reliability tests are long-lasting and costly basically due to the fact that the results require statistical analysis. The advantage of such a procedure is the ability of estimation of the durability time of the device, while the basic disadvantages are:

- statistical analysis requires running a high number of single tests, which leads to long-lasting experiments; it is assumed that in the case of microelectronics components the realiability tests last from a few over a dozen of months,
- analysis of a single failure mode leads to a wrong reliability prediction, because in real operating environmental conditions there coexists a number of different failure modes and their interactions.

Currently there are only a few research reports containing description and results of strength analysis of solder joints in micro scale due to an interaction of failure modes as a result of combined loading profile [4,6,11]. For this reason, the presented results fit into a current research trend devoted to the problem of simultaneous occurrence of different failure modes and including the scale of analysis. The key problem was the measurement of small (from an order of fraction and up to a couple of micrometers) displacements, that occur in the joint and its nearby region. The periodically changed force applied to the solder joint allowed observation of both elastic and inelastic displacements.

2.1. Solder alloys and solder joints in microelectronics

As it is been mentioned earlier, in reference to EU directive RoHS, currently used solder alloys in microelectronics are subjected to restrictions concerning the problem of reduction of hazardous substances that can affect the environment. Unfortunately, replacement of traditional lead solder alloys requires technological changes, e.g. higher soldering temperature, adaptation of assembly lines for soldering at higher temperatures, adaptation of electronic components for assembling at a higher temperature, introduction of new fluxes enabling adequate surface wetting of solder alloys requiring higher temperatures, etc. On the other hand it should be underlined that traditional solder alloy based on lead and tin ($Sn_{63}Pb_{37}$) posses very good thermomechanical properties. In case of the lead-free solder alloys mainly are used such metals as tin, silver and copper, which establishes abbreviation for such alloys as SAC (SnAgCu). As the percentage content of each metal can be different therefore there is variety of alloys, e.g. SAC305 ($Sn_{96.5}Ag_{3.0}Cu_{0.5}$) [3,9].

Mechanical behavior of solder joints depends on various factors: alloy microstructure, content of intermatallic compounds, the size of a joint or sample, the cooling rates after the joint is created or the aging process. Other important factors are: thermomechanical load profile, spread of thermomechanical properties of materials, etc. So far research studies of solder alloys and joints in microelectronics contributed to the elaboration of simplified models characterizing their mechanical behavior and analysis methods based on classical mechanics and lately numerical simulation techniques. The key research problems are mathematical material models of solder alloys, which describe their behavior as a result of thermomechanical loads. In that case both simple and combined models are used. There is also used another classification criterion, which is linearity: linear material models, e.g. elastic and non-linear material models, e.g. plastic, viscous [33, 35].

2.2. Reliability of solder joints in microelectronics

Accurate reliability prediction of solder joints in microelectronic packaging requires application of different experimental techniques and methods, numerical tools as well as taking into account various physical phenomena. It should be underlined that in the case of solder joints in microelectronics, reliability evaluation is usually carried out for a selected single failure mode i.e. the phenomenon of fatigue or creep [1,19,23]. It is worth mentioning that quite often during reliability analysis the problem of residual stresses is neglected. Residual stresses are the result of the performed technological processes. In order to minimize their influence, the technological processes are designed in such a way so the build-in stresses are relaxed, through slow cooling or additional heating process [40].

2.2.1. Fatigue phenomenon

The fatigue phenomenon of the solder alloy describes influence of a cyclic changing thermomechanical loading as a function of time on the solder joint reliability. As a consequence, deformation of a joint occurs, which is then followed by a complete or significant damage. A characteristic feature of the fatigue failure is that a damage can occur at stress level much lower than it is specified by the material strength. Fatigue strength is measured by counting load cycles to failure, which can be converted into time. There are various factors that affect the number of load cycles: the type of load, its value, sequence and duration. In addition, in the case of fatigue, two types of tests can be distinguished:

- low-cycle fatigue (generally<1000), it is associated with the use of high stress value, which leads to the significant inelastic deformations during each cycle, and thus the short lifetime of the tested material,
- high-cycle fatigue (generally>1000), it is associated with the use of small stress value, which leads to elastic deformations during each cycle, and thus to the increased lifetime of the tested material.

An example of a popular test, frequently used in microeletronics packaging, is the low-cycle analysis with an application of the Coffin-Manson empirical model, which relates a dissipation of an inelastic energy ΔW with the fatigue strength N_f:

$$\Delta \mathrm{W} = \mathrm{C} \cdot N_f^a \tag{1}$$

where coefficients C and a are material constants, which are estimated through experimental tests, while amount of inelastic energy ΔW is estimated basing on a hysteresis strain-stress in a selected fatigue cycle [22, 32].

2.2.2. Creep phenomenon

The creep phenomenon of solder alloys, often referred as a "cold flow", occurs in the case of constant or time dependent thermomechanical loads, which leads to permanent deformation, also known as creep deformation. Creep may or may not lead to the material failure. If the joint is unable to accumulate the energy resulting from the load, then it may be transferred to the nearby joint region or may lead to the irreversible deformation as e.g. crack. The creep phenomenon affects practically all materials, but in most cases this process is very slow in time and depends on such parameters as temperature and stress:

$$\varepsilon = f\left(t, T, \sigma\right) \tag{2}$$

where ε is a creep strain, t is a time, T is a temperature, σ is a stress. In mechanics, e.g. for metals and their alloys, the creep phenomenon is observed in the case when the stress value exceeds the yield point or below, the so-called diffusion creep, when the homologous temperature is greater than 0.4 [7]:

$$T_h = \frac{T_o}{T_t} > 0,4 \tag{3}$$

where T_h is a homologous temperature, T_o is an ambient temperature, T_t is a material melting temperature. The melting temperature for $Sn_{63}Pb_{37}$ is *456K*, thus the solder alloy homologous temperature, for room conditions, is higher than 0.6. In the case of bimaterial structures, as e.g. solder joints, the creep is activated by the stress, which is the result of an ambient temperature change and a difference of the coefficients of thermal expansion of the joined materials. The yield stress for the solder alloy $Sn_{63}Pb_{37}$ is around *40MPa*, while the stress value can be estimated using the following formula:

$$\sigma = \Delta\alpha \Delta T \frac{a}{h} \tag{4}$$

where σ is a stress, $\Delta\alpha$ is a difference of the coefficients of thermal expansion of the joined materials, ΔT is a temperature change, a is a distance from a neutral point of the joined materials, h is a thickness of the joint. The creep phenomenon leads to a change of soldered joint parameters due to physical phenomena occurring in the material, e.g. diffusion at grain boundaries, dislocations, cracks and voids [14]. It is also necessary to mention an additional factor having a significant impact on a creep phenomenon of the solder joints in electronics applications, which is an increase of a joint local temperature as a result of the electric current.

2.3. Problem of a damage accumulation.

One of the most crucial problems associated with testing and analyzing the strength of the solder joints in microelectronics packaging is an occurrence of a number of failure modes at the same time or their interaction. For this reason, it is necessary to take into account the problem referred as a damage accumulation. One of the most popular ways to take it into account in engineering applications is a method named by their authors as Palmgren-Miner's method [21]. The method is based on summing partial damages for given fatigue cycles, and allows for determination of the equivalent load amplitude, which is consistent in terms of the total damage with the case of variable load amplitude [28]:

$$\sum_{\mathrm{i}=0}^{k} \frac{n_i}{N_i} = 1 \tag{5}$$

where n_i is a number of cycles for a given load value, N_i is a fatigue limit for a given value of the load amplitude, while k is a number of selected values of load amplitudes. Unfortunately, this hypothesis assumes a lot of simplifications, which means that the result of reliability prediction is error biased. Additionally, the hypothesis refers rather to macroscopic scale and does not include phenomena occurring at the micro scale, which is characteristic for the microelectronics packaging [11]. In the case of simultaneous occurrence of two different failure modes, i.e. fatigue and creep phenomenon, the alternative is to use the linear superposition principle. The principle can be written in a form of the mathematical formula as a sum of fractional parts for both phenomena at a given load amplitude [18]:

$$\sum_{\mathrm{i}=1}^{k} \frac{n_i}{N_f} + \sum_{\mathrm{i}=1}^{k} \frac{\Delta \mathrm{t}_i}{T_c} = 1 \tag{6}$$

where Δt_i is a time interval for a given load amplitude at a constant level, while T_c is a time to object failure at this load amplitude. The first term of the equation describes fractional part for the fatigue cycle, and the second term is responsible for the creep phenomenon. Similarly, to Palmgren-Miner's hypothesis, it is assumed that failure occurs when the accumulated damage value equals *1*. In this case, the equation solution yields a straight line on the solution graph that represents the cumulative reliability of the object. Unfortunately, this model is based on certain simplifications, and thus the obtained results depend, among others on material properties. Moreover, the hypothesis assumes that time intervals Δt_i as a result of compressive or tensile stresses have a similar effect and do not take into account the problem of material hardening or softening. Nonlinear models of damage accumulation refer to those materials whose mechanical or physico-chemical properties change during the reliability tests, which requires additional tests. This is a reason why in the case of engineering application the linear model is preferred. Figure 1 presents the hypothesis of linear damage accumulation and the problem of material hardening and softening phenomena for non-linear models [12].

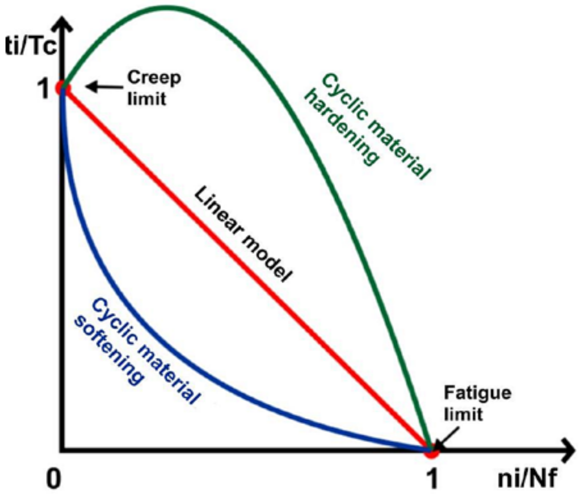


Fig. 1. Linear damage accumulation model and a corresponding hardening and softening phenomena for nonlinear material models

2.4. Statistical analysis

The reliability assessment is usually based on analysis of failures causes and then probability assessment of their occurrence in the given conditions. In order to achieve that, it is necessary to know typical loads, failure modes and the corresponding failure criteria. Unfortunately, the results of reliability tests are defined by random variables, and therefore a quantitative description of reliability requires the use of probabilistic characteristics and probability distributions. In the reliability science, in order to describe the object lifetime, sometimes referred as time-to-failure, probability distributions of failures as a function of time *f(t)* are used. In microelectronics packaging the durability time *t* of an object can described by the two-parameter Weibull distribution:

$$f(t)=\frac{\beta}{\lambda}\cdot\left(\frac{t}{\lambda}\right)^{\beta-1}\cdot e^{-\left(\frac{t}{\lambda}\right)^{\beta}} \tag{7}$$

where β is a shape parameter, λ is a scale parameter. Thus, the probability value that an object will fail by time *t* can be estimated by the cumulative distribution function *F(t)*:

$$F(t)=1-e^{-\left(\frac{t}{\lambda}\right)^{\beta}} \tag{8}$$

The purpose of reliability research is to estimate the values of probability distribution coefficients and to determine selected reliability parameters. In practice, it is convenient to use the concept of time-to-failure of an object corresponding to the numerical value of the scale parameter λ regardless of the value of the shape parameter β. Time-to-failure can be estimated by taking an assumption that $t=\lambda$, thus:

$$F(\text{t}=\lambda)\simeq 0.632 \tag{9}$$

As an alternative solution that one can use is an associated reliability parameter, which is referred as an object strength. For example time-to-failure parameter is correlated with the fatigue strength as follows:

$$F\left(\bar{N}_f\right)\simeq 0{,}632 \tag{10}$$

In engineering practice the scale coefficient λ, corresponding to the fatigue strength, is estimated through graphical methods, which significantly reduces a number of experimental tests. This method allows additionally for:

- estimation of the failure criterion required by numerical prototyping, which means that extracted experimentally time-to-failure is adopted in numerical prototyping as a failure criterion, which in turn allows building empirical failure models as, e.g. the Coffin-Manson model,
- running the so-called accelerated tests, e.g. thermal; in this case, the shift along the abscissa axis on the Weibull plot, depending on the load amplitude, allows for a significant reduction of time required for performing complete reliability tests.

Figure 2 presents an example Weibull plot and a graphical method for experimental data analysis, including estimation of the fatigue strength and failure acceleration coefficient *n* [37].

a)

b)

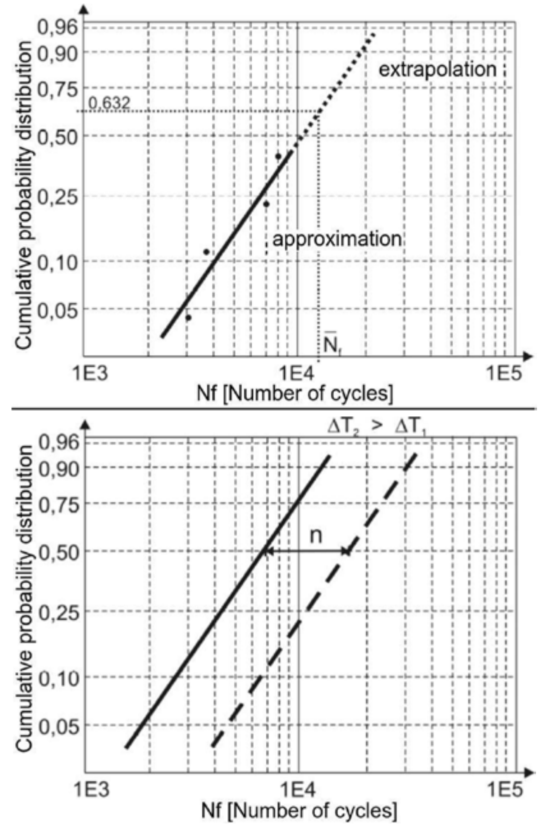


Fig. 2. Example of a graphical analysis method based on the Weibull plot: (a) approximation and extrapolation (b) accelerated thermal tests.

3. Description of the research and achieved results

One of the novel methods, which allows testing of solder joints due to the combined profile of loading conditions, is the Hot Bump Pull HBP method, designed by Nordson Dage company. This method is based on testing the strength of joints by melting a pin into the solder joint and thus allows the study of the phenomenon of creep and fatigue in a microscale. The method allows the use of several methods concerning strength tests: destructive, fatigue, creep and combined creep-fatigue. Within the presented research, a fatigue and creep tests were used, which allowed to develop an appropriate measurement technique and algorithm for reliability model identification of solder joints in the microscale due to fatigue and creep and additionally their interaction [5].

Different testing methods for solder joints are possible thanks to variety of cartridges, that can be exchanged according to the experimental requirements. Available cartridges allow testing wire connections, solder balls, etc, using different tests, such as: pulling, compression, shearing and bending. At the same time, the included software helps the user setting up various test parameters, as:

- maximal and minimal force value,
- dwell time for the maximal and minimal loading value,
- speed of fall and rise time of the combined loading profile,
- setting up and selection of the defined or predefined temperature profiles.

The presented preparing measuring technique was based on testing the strength of solder alloy balls, which corresponded to BGA technology, using a copper pin [12]. It should be underlined that, all the tests were run for $Sn_{63}Pb_{37}$ solder alloy This refereed to the first stage of research devoted to reliability analysis of solder joints used in the microelectronics packaging.

3.1. Method of making test samples, solder joints and carrying out reliability tests

Before carrying out reliability tests, it was necessary to design and manufacture appropriate test samples in the form of a solder joints between the solder and test pin. The figure 3 presents the following stages of preparing test samples:

- test samples in the form of copper squares etched on the glass-reinforced epoxy laminate FR4 and covered with a thin layer of gold,
- 2 solder balls used in BGA technology were placed on the surfaces covered with a thin layer of flux,
- test samples were heated up to the temperature exceeding the melting point of a solder alloy.

After setting up appropriate test samples and placing them on the sample holder, it was then possible to make solder joints. The figure 4 presents the following stages of making solder joints between the test sample and copper pin:

- stage I, after applying a small amount of flux to the test needle, a reference point and depth of sinking the pin was set - half of the average sample height,
- stage II, the pin was heated up and sink into the test sample within the so-called flow time, in order to make a solder joint,
- stage III, the prepared test sample with solder joint was slowly cooled down in order to avoid the formation of undesirable residual stresses.

In the first place the strength tests were made, which consisted of pulling the pin with a given force and speed until the connection was destroyed. In this way, the range of forces and velocities of the test pin were determined for the following strength tests. All the tests were performed at room temperature. Figure 5a presents the results of the performed tests. It can be concluded from the achieved results, that

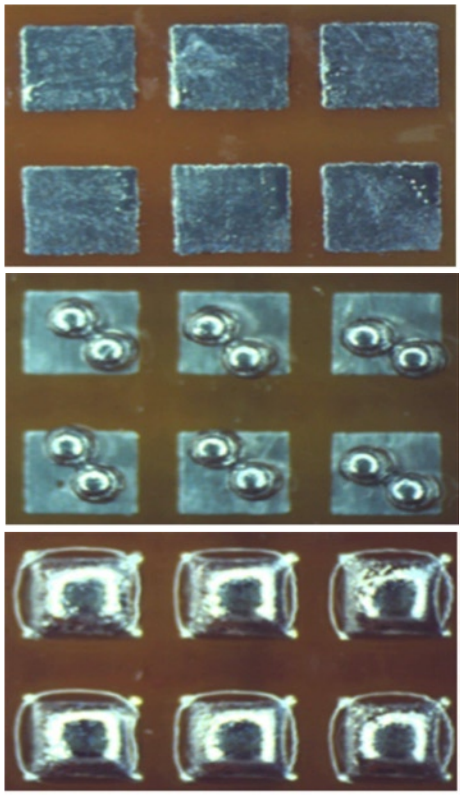


Fig. 3. The following stages of preparing the test samples

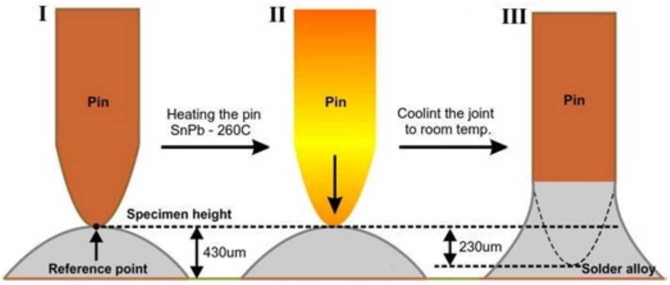
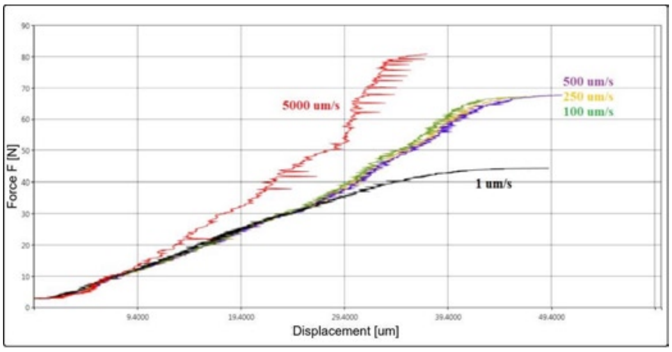


Fig. 4. The following stages of making the solder joint between the copper pin and test sample: (I) setting the reference point and sinking depth, (II) sinking the pin, (III) cooling down the test sample

the high speed of the pin movement, of the order of *5000μm/s*, leads to higher force values and thus cause the early joint failure, which in reverse means that the solder alloy behaves as a brittle material. On the other hand, the low speed of the pin movement, of the order of *1μm/s*, leads to creep phenomena, which is undesirable in the case of pure fatigue tests. Because of this, in order to run reliability tests, it was assumed to select the speed of the pin movement to *500μm/s*, which on one hand allowed avoiding the hardening phenomenon of the material due to the high speed pin movement but on the other hand allowed to reduce the overall testing time. The reduction of testing time is very crucial in research that requires statistical analysis, which is associated with the need to carry out many single tests.

In the second place the strength tests were done with the defined loading profile and test parameters, which is presented in the figure 5b. The profile consisted of two parts responsible for the both fatigue and creep phenomena. The creep part depended on dwell time Δt_i, which varied in the range of *1* to *80s*. The force amplitude varied in the range of *18* to *63N*. Additionally, an initial force value *F* was assumed *3N*.

a)



b)

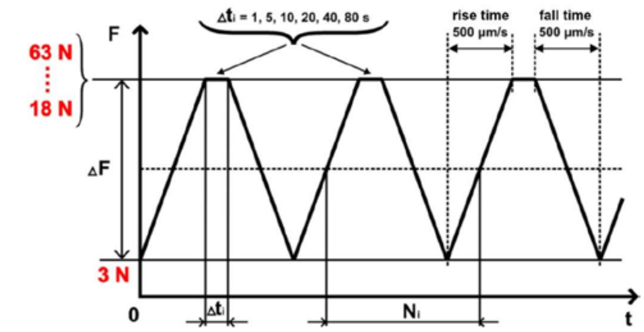
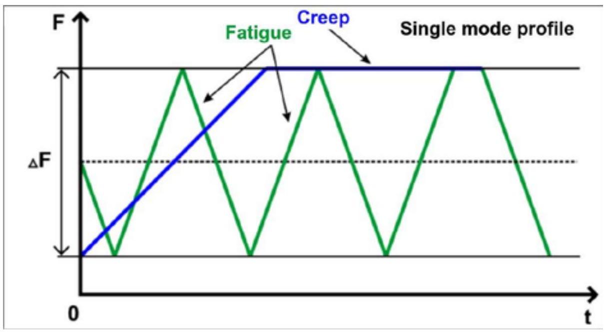


Fig. 5. Results of the reliability tests for different speed of the test pin movement (a) and the assumed profile of the loading for the reliability tests (b)

a)



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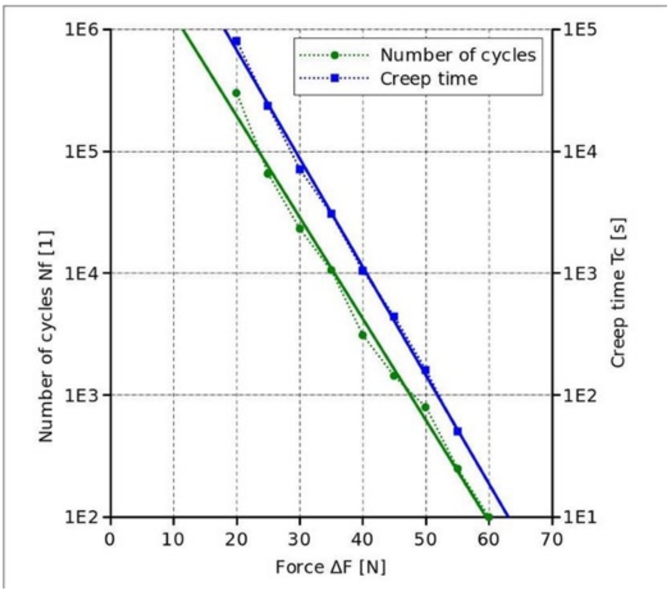


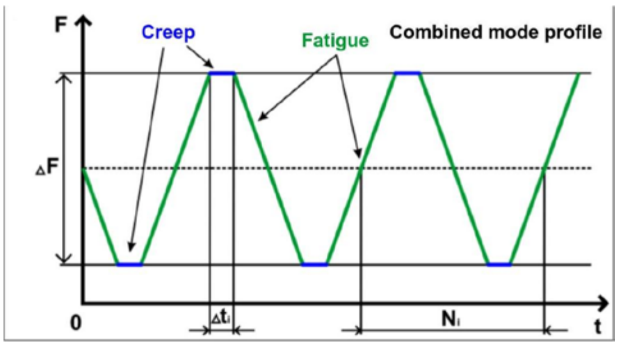
Fig. 6. Loading profile (a) and test results for a single failure mode, i.e. creep and fatigue (b)

3.2. Reliability tests

During the first stage of the research, strength tests were performed for a single selected failure mode, i.e. in succession for fatigue and creep. The tests allowed assessing the maximal number of fatigue cycles *N* and creep time *t* leading to the solder joint failure at a given force amplitude ΔF. The assumed combined loading profile and achieved results are given in the figure 6.

According to the achieved results, it can be concluded that both modes of failure, i.e. fatigue and creep, depend exponentially on the force amplitude ΔF. The results allowed estimation of test parameters for the creep-fatigue failure interaction, referring for dwell time values Δt_i. Figure 7a presents the combined load profile and the corresponding results for strength tests.

a)



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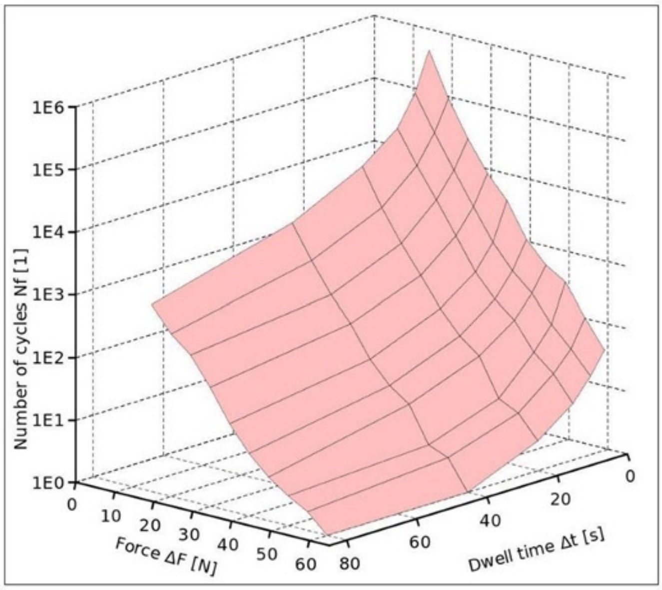


Fig. 7. Combined loading profile (a) and test results for the creep-fatigue failure interaction (b)

According to the achieved results (Fig. 7b), it can be concluded that the number of fatigue cycles to failure in the case of creep-fatigue tests depend not only on the force amplitude ΔF, but additionally on the interaction between both failure modes, which are creep and fatigue. It can be noticed that the creep participation reduces significantly number of cycles to failure N_f.

3.3. Statistical analysis.

Reliability analysis can be done with the help of random variables and thus, as it was mentioned earlier, requires statistical methods. For this purpose, two-parameter Weibull distribution is the most often used. Unfortunately, detailed analysis of the Weibull statistics requires

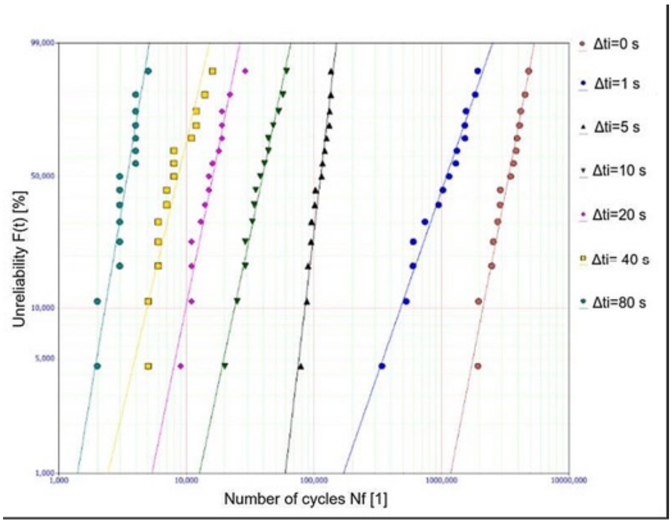
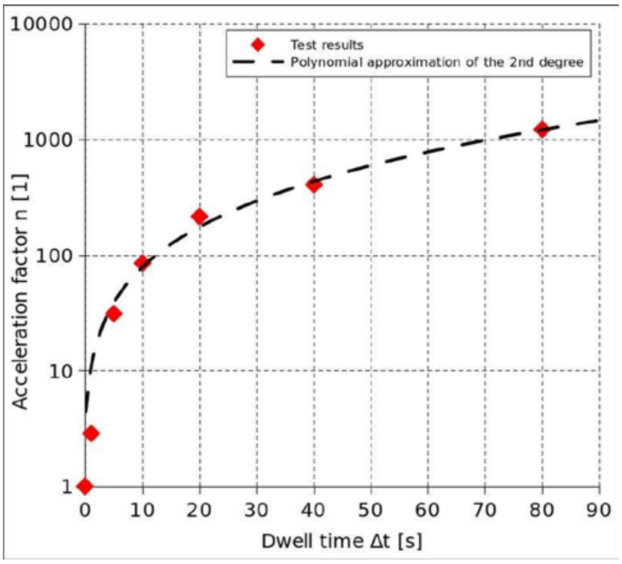


Fig. 8. Weibull statistical analysis for the performed reliability tests in the case of a single and combined failure mode for the force amplitude ΔF equal 40 N

a)



b)

	Ftigue - cycles [1]	Dwel time Δti [s]						Creep-time [s]
		1	5	10	20	40	80	
β	4,05	2,28	6,64	3,72	3,86	3,33	4,72	3,16
λ	3673	1283	118	43	17	9	3	271

Fig. 9. Results of the statistical analysis for the force amplitude ΔF equal 40 N: a) coefficients of the Weibull distribution i.e. the shape β and scale factor λ, b) values of the failure acceleration coefficient n.

many single tests. Figure 8 shows the test results for a selected value of the force amplitude ΔF equal *40 N* – the total number of single tests in the presented case was higher than *100* [26].

Based on the statistical analysis results, the coefficients of two-parameter Weibull distribution were determined, i.e. the shape β and scale factor λ. Results of the analysis are given in table 9a. The failure acceleration coefficient n, describing the reduction of a number of fatigue cycles N_f leading to failure as a result of dwell time Δt_i, was also estimated. The results are shown in the figure 9b.

3.4. Model of damage accumulation

As it was mentioned earlier, the research goal was reliability analysis with the use of creep-fatigue tests for solder joints in microscale, which are typical in microelectronics packaging. Figure 10 presents the damage model accumulation achieved on the basis of performed experimental tests and the following statistical analysis.

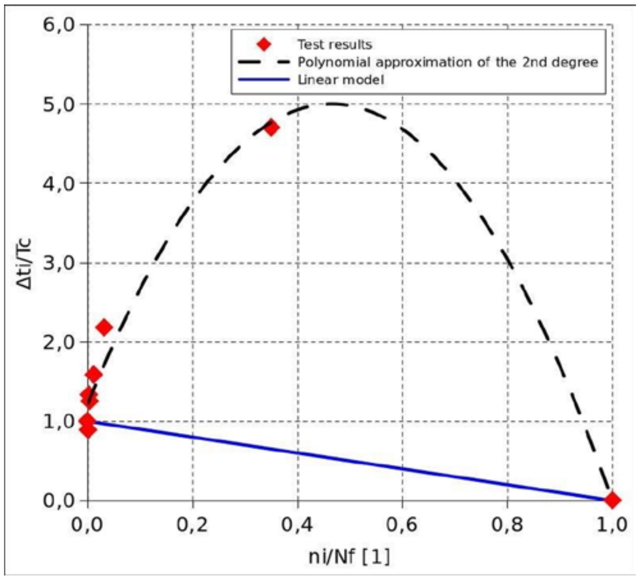


Fig. 10. Damage accumulation model achieved on the basis of the performed experimental tests and statistical analysis

Basing on the achieved results it can be concluded that solder alloy $Sn_{63}Pb_{37}$ analyzed with a combined loading profile in order to induce the failure interaction manifests cyclic hardening phenomenon, which leads to reduction of the joint strength. The material with every fatigue cycle becomes more brittle and thus susceptible to the formation of cracks that finally cause the solder joint failure. According to the result presented in the figure 10, it can be stated that the obtained damage accumulation model reveals non-linear behavior and significantly deviates from a theoretical curve for the linear model.

4. Summary

The manuscript contains results for the first stage research concerning strength analysis of solder joints used in microelectronics packaging due to a combined loading profile. The proposed loading profile allowed for analysis of typical failures modes of solder alloys, which is creep and fatigue and additionally interaction of the both. Within the performed research a combined creep-fatigue test was introduced based on the Hot Bump Pull HBP measuring technique developed by Nordson Dage company. The presented results contain strength analysis of solder joints for a traditional $Sn_{63}Pb_{37}$ solder alloy, done in room temperature, as follows:

- strength analysis of a single failure modes and their interaction,
- statistical analysis for a combined loading profile,
- comparison of the linear model of the damage accumulation with the model achieved on the basis of performed experimental strength tests.

The final conclusion, based on the presented results, can be formulated as follows:

- the proposed methodology of testing solder alloy strength makes it possible to take into account the phenomenon of failure mode interaction, i.e. creep and fatigue,

- the creep phenomenon for the tested solder alloy in the microscale plays an important role for the creep-fatigue tests even at room temperature, at which the strength tests were carried out,
- a popular among engineers the linear failure accumulation model is not suitable for predicting the strength of solder joints in the microelectronics concerning the combined creep-fatigue tests.

It should be underlined, that analysis of a single failure mode leads to wrong predictions, because the real working conditions of electronic components are characterized by existence of a couple of failure modes, which is due to the combined environmental loading profile. Taking into account the above, the next research should contain such problems as:

- application of a different damage accumulation model in case of solder joints in microelectronics for the combined creep-fatigue tests, i.e. one of non-linear models or relatively simple model for use in engineering practice refereed as double linear model [18],
- running comparative tests for lead-free solder alloys and for other ambient temperatures,
- developing a strength criterion, which would allow reliable prediction of the solder joints strength in microelectronics packaging as a result of fatigue and creep failure mode due to the combined loading profile.

In conclusion, it can be stated that the proposed methodology concerning reliability tests and the presented results of strength analysis of solder joints in microscale would allow for a more precise reliability prediction of the modern electronic components and / or an implementation of the accelerated reliability tests.

References

1. Arra M, Shangguan D, Ristolainen E. Characterization of mechanical performance of Sn/Ag/Cu solder joints with different component lead coatings. Soldering and Surface Mount Technology 2004; 16(1): 35-43, https://doi.org/10.1108/09540910410517031.
2. Bisschop J. Failure mechanisms in plastic package IC's. Proceedings of 2nd EuroSimE Conference 2002: 328-331.
3. Bukat K, Hackiewicz H. Lutowanie bezołowiowe, Warszawa: Wydawnictwo BTC, 2007.
4. Chicot D, Tilkin K, Jankowski K, Wymysłowski A. Reliability analysis of solder joints due to creep and fatigue in microelectronic packaging using microindentation technique, Microelectronics Reliability 2013; 53(5): 761-766, https://doi.org/10.1016/j.microrel.2013.01.008.
5. DAGE UK Hot Bump Pull/Hot Pin Pull, 2011.
6. Dasgupta A, Oyan C, Barker D, Pecht M. Solder Creep-Fatigue Analyses by an Energy Partitioning, Journal of Electronic Packaging 1991; 114(2): 152-160, https://doi.org/10.1115/1.2906412.
7. Dowling NE, Kampe SL, Kral MV. Mechanical Behavior of Materials, Pearson Prentice Hall, 2018.
8. Felba J. Montaż w Elektronice, Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej, 2010.
9. Ganesan S. Lead-free Electronics, John Wiley & Sons Inc., 2006, https://doi.org/10.1002/047000780X.
10. Holdsworth SR. Component assessment data requirements from creep-fatigue tests, ASTM International 2011; 1-14, https://doi.org/10.1520/JAI103583.
11. Jankowski K, Wymysłowski A. Life prediction of lead alloy based on multi-failure criteria. 18th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems 2017; 1-5, https://doi.org/10.1109/EuroSimE.2017.7926217.
12. Jankowski K, Wymysłowski A, Chicot D. Combined loading and failure analysis of lead-free solder joints due to creep and fatigue phenomena, Soldering & Surface Mount Technology 2014; 26(1): 1-6, https://doi.org/10.1108/SSMT-10-2013-0029.
13. Judd M, Brindley K. Soldering in Electronics Assembly, Elsevier Ltd., 1999, https://doi.org/10.1016/B978-075063545-5/50004-2.
14. Kim DH. Reliability Study of SnPb and SnAg Solder Joints in PBGA Packages, The University of Texas at Austin, 2007.
15. Kisiel R. Podstawy technologii montażu dla elektroników, Wydawnictwo BTC, 2012.
16. Lau JH. Solder Joint Reliability, Boston MA: Springer, 1991, https://doi.org/10.1007/978-1-4615-3910-0.
17. Lau JH. Thermal Stress and Strain in Microelectronic Packaging, US Springer, 1993, https://doi.org/10.1007/978-1-4684-7767-2.
18. Manson SS, Halford GR. Practical implementation of the double linear damage rule and damage curve approach for treating cumulative fatigue damage, International Journal of Fracture 1981; 17: 169-192, https://doi.org/10.1007/BF00053519.
19. Matkowski PK, Dudek R, Kreyssig K. Reliability testing of SnAgCu solder joints under combined loading. Micromaterials and Nanomaterials 2011; 13: 86-91.
20. Miller D, Priest RH, Ellison EG. A review of material response and life prediction techniques, Materials 2015; 8(11): 7757-7769, https://doi.org/10.3390/ma8115418.
21. Miner MA. Cumulative Damage in Fatigue, Journal of Applied Mechanics 1945; 12 (3): 159-164.
22. Nelson W. Accelerated Testing, New York: Wiley, 1990, https://doi.org/10.1002/9780470316795.
23. Nguyen J, et al. Backward compatibility study of lead free area array packages with tin-lead soldering process, IPC - Printed Circuits Expo and the Designers Summit 2006.
24. Numerical Analysis Guidelines for Microelectronics Packaging Design and Reliability, IPC/JEDEC-9301: 2018.
25. Qu J. Thermomechanical Reliability of Microelectronic Packaging. Comprehensive Structural Integrity 2007; 8: 219-239, https://doi.org/10.1016/B0-08-043749-4/08040-X.
26. ReliaSoft, https://www.reliasoft.com/, 2019.
27. Seraphim DP, Lasky R, Li CY. Principles of Electronic Packaging, New York: McGraw-Hill, 1989, https://doi.org/10.1115/1.3226524.
28. Stone D, Wilson R, Li CY. The Mechanisms of Damage Accumulation in Solders during Thermal Fatigue. Proccedings of 36th Electronic Components Conference 1986: 630-635.
29. Suhir E. Interfacial stresses in biomaterial thermostats, Journal of Applied Mechanics 1989; 56: 595-600, https://doi.org/10.1115/1.3176133.
30. Timoshenko S. Analysis of bi-metal thermostats, Journal of the Optical Society of America 1925: 233-255, https://doi.org/10.1364/JOSA.11.000233.
31. Tummala RR. Fundamentals of Microsystems Packaging, McGraw Hill, 2001.
32. Tummala RR, Rymaszewski EJ, Klopfenstein AG. Microelectronics Packaging Handbook, Springer Science+Business Media Dordrecht,

1997, https://doi.org/10.1007/978-1-4615-6037-1.
33. Van Driel WD. Virtual Thermo-Mechanical Prototyping of Microelectronics Devices, The Netherlands: PrintPartners Ipskamp, 2007
34. Wareing J. Mechanisms of high temperature fatigue and creep-fatigue failure in engineering materials, United Kingdom: Applied Science, 1983.
35. Wymysłowski A. Numeryczne metody projektowania termomechanicznego w montażu elektronicznym. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej, 2007.
36. Wymysłowski A, Dowhań Ł. Application of nanoindentation technique for investigation of elasto-plastic properties of the selected thin film materials, Microelectronics Reliability 2013; 53(3): 443-451, https://doi.org/10.1016/j.microrel.2012.10.009.
37. Zahavi E. Fatigue design - life expectancy of Machine Parts, A Solomon Press Book, 1996.
38. Zhang GQ. The challenges of virtual prototyping and qualification for future microelectronics, Microelectronics Reliability 2003; 43: 1777-1785, https://doi.org/10.1016/S0026-2714(03)00299-3.
39. Zhang GQ, Ernst LJ, de Saint Leger O. Benefiting from thermal and mechanical simulation in microelectronics, Dordrecht: Kluwer Academic Publishers, 2000, https://doi.org/10.1007/978-1-4757-3159-0.
40. Zhang GQ, van Driel WD, Fan XJ. Mechanics of Microelectronics, Dordrecht: Springer, 2006, https://doi.org/10.1007/1-4020-4935-8
41. Zienkiewicz OC, Taylor R, Zhu JZ. The Finite Element Method: Its Basis and Fundamentals, Elsevier Butterworth-Heinemann, 2005.

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