Mechanical performances of lead-free solder joint connections with applications in the aerospace domain

Georgiana PADURARU*[,1], Andrei TUDOR[1], Alina PETRESCU[1], Ioan PLOTOG[2]

*Corresponding author
[1]"POLITEHNICA" University of Bucharest, Faculty of Mechanical Engineering and Mechatronics, Department of Machine Elements and Tribology
Splaiul Independentei 313, 060042, Bucharest, Romania
gipaduraru@upb.ro*, tudor@meca.omtr.pub.ro, am.petrescu@upb
[2]"POLITEHNICA" University of Bucharest, Technological and Business Incubator CETTI-ITA, B-dul Iuliu Maniu 1-3, 061071, Bucharest, Romania
ioan.plotog@cetti.ro

DOI: 10.13111/2066-8201.2016.8.1.12

Received: 11 October 2015 / Accepted: 09 February 2016 / Published: March 2016

The 36th "Caius Iacob" Conference on Fluid Mechanics and its Technical Applications
29 - 30 October, 2015, Bucharest, Romania, (held at INCAS, B-dul Iuliu Maniu 220, sector 6)
Section 4. Mathematical Modeling

Abstract: *The paper presents some theoretical and experimental aspects regarding the tribological performances of lead-free solder joint connections, with application in the aerospace domain. In order to highlight the mechanical and tribological properties of solder joint in correlation with different pad finishes, there were made some mechanical determinations using a dedicated Share Test System. The theoretical model highlights the link between the experimental results and the influence of gravitational acceleration on the mechanical and functional integrity of the electronic assemblies that works in vibration environment. The paper novelty is provided by the interdisciplinary experiment that offers results that can be used in the mechanical, tribological, electronical and aerospace domains.*

Key Words: *vibration, share test, lead-free, solder joint, pad finish*

1. INTRODUCTION

For the electronic and aerospace industry, one of the most important aspects generated by the manufacturing in the lead-free technology is to ensure the quality and reliability at the level of the classical lead technology. The quality and reliability of the microelectronics components and assemblies should be considered as an expression of solder joints functionality [1].

One of the three functionalities of the electronic assembly is the mechanical attachment. According to previous studies [1], [2], [3] the mechanical strength of the electronic solder joints depends on the pad finish, for example most brittle fractures were observed on silver immersion (ImmAg) pad finish, hot air levelling (HASL) finish showed a god stability on reflow soldering conditions and no brittle fracture was observed on NiAu finish.

Also in all the experiments a detachment of copper layer from the rigid support was observed.

Starting from the results presented above we decided to verify if the adhesion of the cooper layer depends on the material of the rigid support. The experiment is oriented on common electronic packaging materials since the aim of the work is to add knowledge in order to solve problems from electronics and aerospace industry. A FR4 (woven glass fabric with epoxy resin system) rigid support was used as printed circuit board (PCB).

There were used two types of pad finishes – NiAu (Nickel – Gold electrolytic surface cover) and HASL (the PCB is dipped into a bath of molten solder such that all exposed copper surfaces are covered). As for the solder paste a comparison was made between two types of lead-free solder paste that are the most used at the level 2 of the electronic packaging, SAC305 (almost 70% from the global electronics industry manufacturers) and SN100 (particularly on the Asian and the North American market).

There are several known techniques for adhesion and delamination testing, some of the most common being the tape test, the stud-pull test, the scratch test and the indentation test. The Institute of Interconnecting and Packaging Electronic Circuits trough the IPC-TM-650 Test Manual Methods establishes uniform methods for testing electronic and electrical parts including basic environmental, physical and electrical tests. [4]

For some time, the accepted test method for measuring the adhesion in the printed circuit boards industry was the peel strength test. However, it is now accepted that this technique was not adequate enough in detecting failures related to delamination during reflow and wave soldering. [5]

The mechanical properties of solder joints follow several standards, which can be applied for testing their integrity – solder ball shear, solder ball cold or hot ball. The solder ball shear test is performed according to JEDEC standard Solder Ball Shear JESD22-B117A [6, 7]. This test method applies to solder ball a shear force testing prior to end-use attachment. Solder balls are sheared individually, force and failure mode data are collected and analysed. Both low and high speed testing are comprised in this standard. Solder ball shear is a destructive test.

2. EXPERIMENT DESCRIPTION

The fabrication process of the electronic module, made using the Surface Mount Technology (SMT), starts with the printed circuit board (PCB) that assumes the construction of the interconnection structure on a rigid or flexible support according to an electrical given template. Deposits of connection paste through dispensing or using special projected patterns are made on the dedicated surfaces from the interconnection structure corresponding to the terminals (pad). The electronic components are placed with terminals on the deposit paste resulting in a PCB assembly.

The interconnection between the electronic components and pads is made through the reflow process using a specifically soldering thermal profile that ensures the melting of the solder alloy and its solidification, with controlled heating and cooling speed.

The mechanical tests were “shear test” type performed on a Multi-Functional Bond Tester Condor 70-3 (Fig.1), fully motorized for pull and shear, destructive or non - destructive applications with capability of 400 N maximum force on all axes and possibilities to measure the maximum force and to take the imagines from the process in real time [1]. The equipment consists of an X/Y stage basis and a mounted Z stage.

The printed circuit board, PCB, is fixed on the horizontal stage, while stepper motors allow PCB positioning. The selected test method was Shear Test destructive using the Shear sensor 100N.

The shear force was applied in the middle of the tested component in order to be decomposed uniformly on both joints. The resulting force is displayed by the equipment together with important graphics. The main diagrams used for the present analysis are the variation of the force versus time, and the variation of the force versus distance.

The solder paste was deposited by using a LPKF ZelPrint LT300 manual printer. After printing the quality of the solder paste deposits was checked by optical inspection using a SMT microscope. Misalignment of deposits, insufficient or excess of solder paste had to be avoided in order to ensure the same experimental conditions to all probes. The criterion of the optical inspection was to comply with the requirements for electronics industry standards [8]. Following the optical inspection, the reflow soldering process was performed. The equipment used was a VPS machine SLC309 produced by IBL-Löttechnik GmbH. VPS uses the vapours of a liquid with high boiling point temperature (240ºC), commercially named GALDEN, in order to transfer the heat to the ensemble PCB – solder paste – electronic components. The electronic components mounted on printed circuit board are 1206 resistors with 3.2 mm length, 1.6 mm width and 0.55 mm thickness. The approximate weight of one resistor is 0.0089 grams.

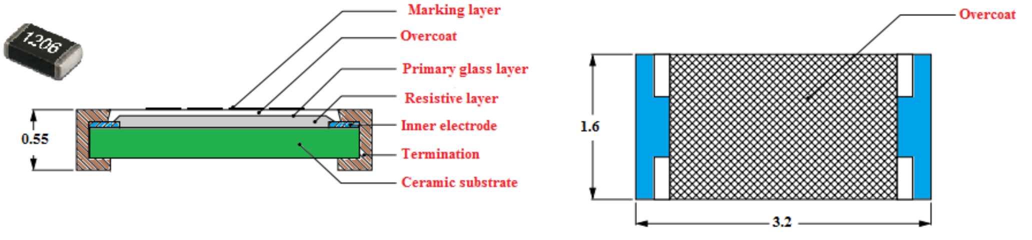

Fig. 1 Chip resistor (1206)

3. EXPERIMENTAL RESULTS AND CONCLUSIONS

After the experiments were finished the following results were obtained:

Table 1 Results obtained for SAC 305 solder paste

SAC 305			
Pad – finish	Sample	NiAu	HASL
Force [N]	1	166.02	186.65
	2	189.54	186.11
	3	178.61	214.98
	4	192.51	195.91
	5	169.37	204.62
Average		179.21	197.65

Table 2 Results obtained for SN 100C solder paste

Sn100C			
Pad – finish	Sample	NiAu	HASL
Force [N]	1	227,84	199.49
	2	228.24	222.94
	3	234.47	214.95
	4	229.20	209.13
	5	233.61	213.75
Average		230.67	218.05

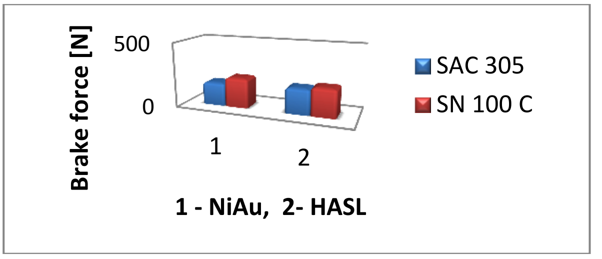

Fig. 2 Average brake force chart

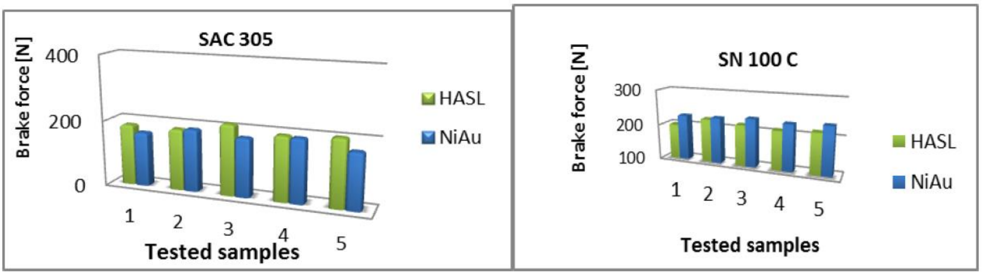

Fig. 3 Brake force variation for SAC 305 and SN 100C solder pastes

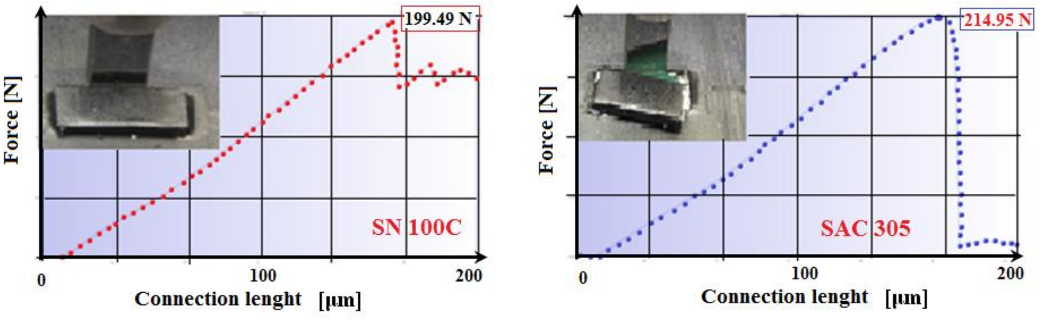

Fig. 4 Force variation for SN 100 C (ductile fracture) and SAC 305 (brittle fracture)

After the experiment two types of fractures were observed, namely: ductile – characterized by "tearing" of the bounding and significant plastic deformation and brittle – characterized by fibrous structure without plastic deformation and having a granular structure.

From mechanical point of view for the electronic connections it is preferred to have a ductile comportment in order to take over the elastic deformations that can appear during mechanical stress. A brittle connection must be avoid because of the low reliability.

Regarding the pad finishing for NiAu brittle fractures were observed; while HASL finish shows a good stability, the fracture force vary between 197.5 -218.05 N.

4. THEORETICAL MODEL

The theoretical model tries to highlight the link between the experimental results and the influence of the gravitational acceleration on the mechanical and functional integrity of the electronic assemblies that works in vibration environment.

Starting from the experimental results we tried to find a connection between the breaking force and the gravitational acceleration having as common point the electronic component mass.

We consider that the electronic component is mounted on printed circuit board and operates in a vibration system. The component has the mass m and applies a shear strain on the electronic joint in the separation zone; this strain appears because of the inertia force generated by the vibratory working regime.

The solder joint connection (solder joint and electronic component) is considered to be an elastic system with the rigidity (k), defined by the elastic modulus E, length L and section A along the solder joint ($k=E\cdot A/L$).

The self-movement differential equation of the system in x direction under the elastic force influence is:

$$m\frac{d^2x}{dt^2}=-kx\,, \tag{1}$$

with t-time and $p^2=k/m$ notation we can determine the electronic component vibratory movement characteristics toward the solder joint. [9] R.

The self-pulsation of the component in solder joint

$$p=\sqrt{\frac{k}{m}} \tag{2}$$

is independent of the initial conditions.

A disruptive force acts on the electronic component

$$F=F_o\cos(\omega t) \tag{3}$$

were F_o is the disruptive force amplitude, considered constant for a constant vibratory working regime under the amplitude aspect, and ω is the disruptive force pulsation.

The basic equation of the movement becomes

$$m\frac{d^2x}{dt^2}=-kx+F_o\cos(\omega t)\,. \tag{4}$$

with the notations $p^2=k/m$, $q=F_o/m$, the differential equation (4) is linear with constant coefficients, uneven.

The general solution of this equation is [9]

$$x=\frac{q}{p^2-\omega^2}\left(\cos\left(\omega t\right)-\cos\left(pt\right)\right). \tag{5}$$

Depending on the vibratory working regime (force F_o and pulsation ω) in which the electronic component – solder joint system is found (k, m), the movement elongation (5) can take two forms:

Speed
$$v_x=\frac{dx}{dt}=\frac{q\omega}{p^2-\omega^2}\left(\frac{p}{\omega}\sin(pt)-\sin(\omega t)\right) \tag{6}$$

Acceleration
$$a_x=\frac{dv_x}{dt}=\frac{q\omega^2}{p^2-\omega^2}\left(\frac{p^2}{\omega^2}\cos(pt)-\cos(\omega t)\right) \tag{7}$$

In this case, the electronic component is submitted to a force F_t, which requires the solder joint to shear:

$$F_t = ma_x + mg$$
$$\tau = \frac{F_t}{A_c} = \frac{m(a_x + g)}{A_c} \tag{8}$$

where g is the gravitational acceleration, A_c is the contact area between the electronic component and the support.

The strains variation on one solicitation cycle for three amplitudes of the elongation disruptive vibrator field is exemplified in Fig.5.

The calculation program is realized in MATHCAD 2000, and it allows determining the strains for any characteristics of vibrating field (x_{ov}, ω) and for the system own vibrator (p).

It is observed that the strains range after an alternating cycle and the fatigue phenomenon is the cause of removal from operation.

The characteristics of the solicitation cycle of the solder joint are illustrated in fig.6 (the amplitude ($\tau_v = (\tau_{max} - \tau_{min})/2$) and in Fig.7 (the variation coefficient ($R_c = \tau_{min} / \tau_{max}$)), respectively.

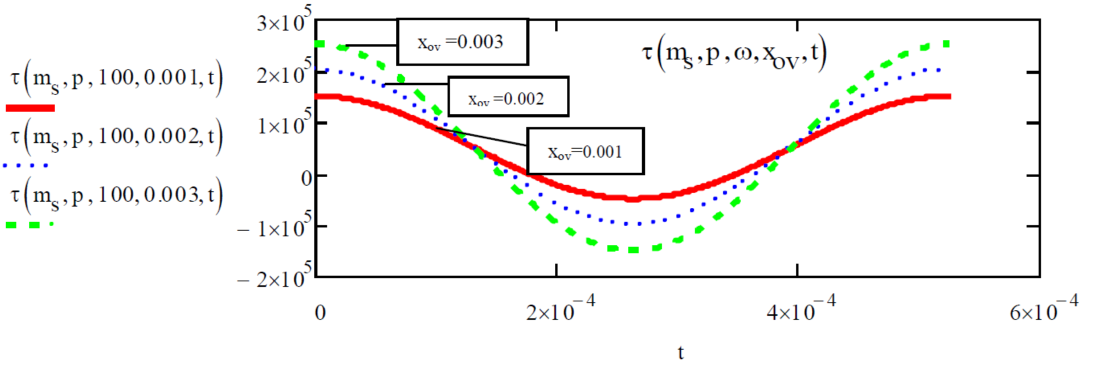

Fig. 5 The evolution of shear strain

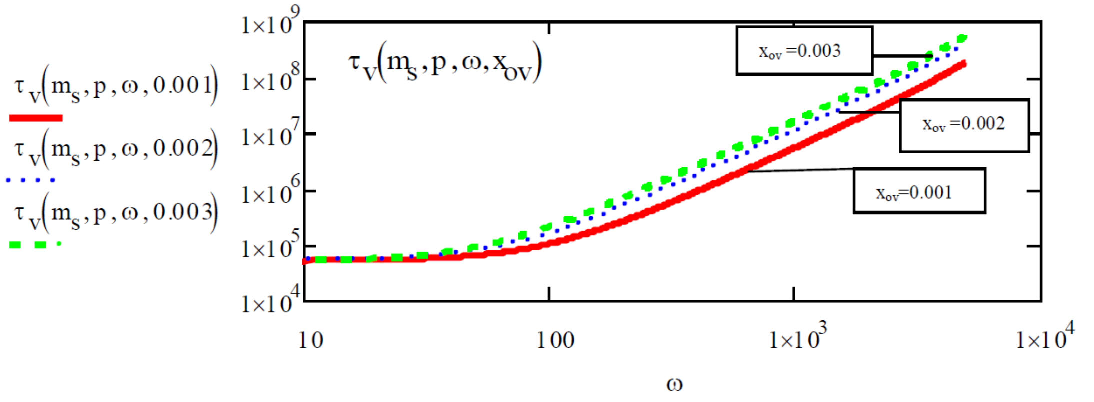

Fig. 6 The evolution of the strain cycle amplitude

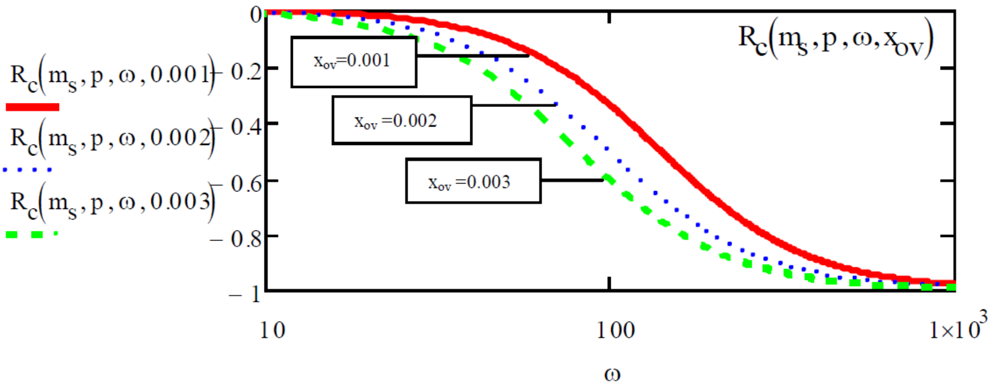

Fig. 7 The evolution of the cycle asymmetry coefficient

In this case the fatigue resistance at shear it is considered like [10]

$$\tau_v^{m_\tau} N_c = \tau_{cr}^{m_\tau} = const \quad (9)$$

where m_τ is the specific parameter of the fracture through the fatigue of the solder joint material; N_c- the number of cycles up to breakage under the tangential tensions amplitude τ_v; τ_{cr}- critical tension from breakage, determined by shear test to one single cycle. From the expression (9) the number of load cycles (N_c) at a known amplitude can be determined. On the basis of the disruptive vibration period (T= 2π/ω) it stands out the durability of the operation without failure of the solder joint in a specific gravitational field from aerospace with a vibrator system. So, in fig. 8a,b it is explained the length of function L_h (hours) of a resistor solder joint.

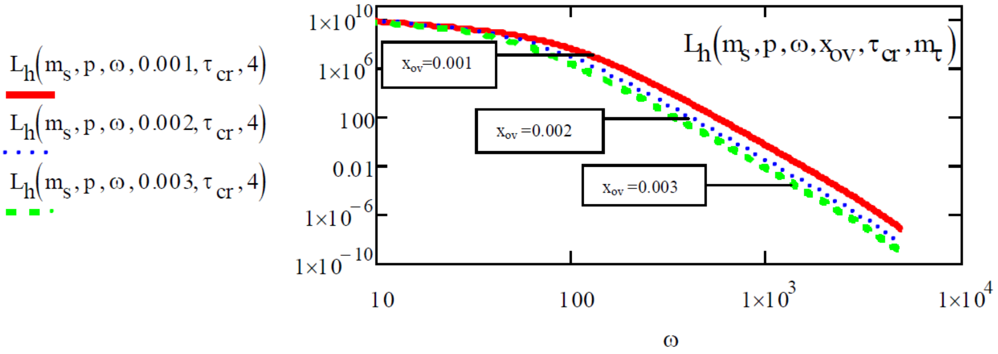

Fig. 8a The evolution of the lenght of function for the ductile material SN 100C

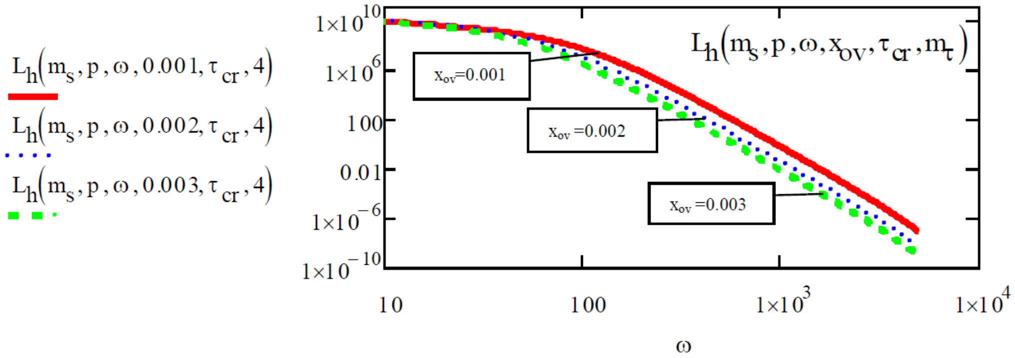

Fig. 8b The evolution of the lenght of function for the brittle material SAC 305

From fig. 8a and fig. 8b the superiority of the SAC 305 solder joint compared to the SN 100 solder joint can be noticed. For example, when the solder joints are in a gravitational field and a vibratory regime with a 100 rad/s pulsation, the lifetime of the SAC 305 solder joint is $3.85 \cdot 10^7$ hours, while the SN 100 has a lifetime of $2.85 \cdot 10^7$ hours.

5. CONCLUSIONS

From the technological point of view, a significant superiority cannot be determined between the two solder joints.

Following the research conducted, we observed that the SN 100 solder joint has ductile behavior, while the SAC 305 solder joint has a brittle behavior.

The main cause of the deterioration of the solder joints which are placed in a gravitational field and a vibrational regime is the mechanical fatigue.

The theoretical model and the experimental results allow the analysis of the mechanical performances of the solder joints without lead used in electronics.

REFERENCES

[1] I. Plotog, T. Cucu and all., *Vapor Phase Soldering Technology Applications for PCB with different final terminals*, International Symposium on electronics and Telecommunications 9th edition 2010, pp. 425-428, ISBN 978-1-4244-8458-4.

[2] I. Plotog, T. Cucu, et.al., *Solder Joints Mechanical Functionality Tested by Shear Forces Methodology*, International Symposium on Electronics and Telecommunications - ISETC 2010, 9th Edition, Timisoara, 11 – 12 November, 2010, ISBN 978-1-4244-8458-4.

[3] I. Plotog, M. Branzei, et.al, *Solder Joints Quality Assessment as Function of Vapour Phase Soldering Process Parameters in the terms of 4P Soldering Model*, European Microelectronics Packaging Conference – EMPC 2011, Brighton, 12th-15th September 2011.

[4] * * * Technical Committees of the Institute of Interconnecting and Packaging Electronic Circuits (IPC), *IPC-TM-650 TEST METHODS MANUAL*, revision E, 2003.

[5] G. Willems, P. Watté, Predicting PCB delamination in lead-free assembly, pp10-16, *Global SMT&Pakaging*, Volumme **10**, number 9, September 2010, ISSN 1474-0893.

[6] * * * JEDEC STANDARD, 2006, Solder Ball Shear JESD22-B117A JEDEC Solid State Technology Association.

[7] A. Pietrikova, J. Durisin, J. Urbancik, *Reliability of Pb-free solder joint under different test conditions*, International Symposium for Design and Technology of Electronic Packages, 14th edition 2008, pp. 85-88, ISSN 1843-5122.

[8] * * * IPC – IPC-S-816 SMT Process Guideline and Checklist, July1993.

[9] R. Voinea, D. Voiculescu, V. Ceausu, *Mecanica*, (in Romanian), Ed. Didactica si Pedagogica Bucuresti, 1983.

[10] L. A. Sosnovskiy, *Tribo-fatigue*, Springer, 2005.