

Finite element model for evaluation of low-cycle-fatigue life of solder joints in surface mounting power devices

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Abstract: In this work, the development of a physics based reliability prediction model for thermo-mechanical fatigue of chip solder joints in power converters is illustrated. By this model, the thermo-mechanical stress-strain distribution in the structure is studied by means of Finite Element (FE) method using COMSOL Multiphysics, and the operational life of the solder joints is calculated according to the Coffin-Manson law. As a case study, the estimation of the fatigue life of solder joints in SO8-packaged power MOSFETs is investigated. A stress bench is under design to tune the developed FE model by experimental results.

Keywords: Electronic solder joints, reliability, thermo-mechanical fatigue, finite element modeling.

1. Introduction

The demand for high power density electronic converters calls for methods to evaluate the reliability of the converters themselves. In particular, the reliability of solder joints [1-2] is one of the key factors, if not the most important one, in the determination of the reliability of the overall converter, being the solder joints both the mechanical, the electrical, and often the thermal connections between the electronic component and the board in which the component is placed.

It is well known that the principal way by which solder joints get damaged is thermal cycling, and in particular the thermo-mechanical stress-strain distribution which arises from the different Coefficients of Thermal Expansion (CTE) of adjacent materials [3].

The damaging process of solder joints, which falls in the mechanical fatigue behavior of materials, is a Low-Cycle-Fatigue (LCF) process [4], in which basically the soldering alloy is stressed up into the plasticization area. The simplest law which accounts for LCF-induced

degradation is the Coffin-Manson law, or the extended Basquin-Coffin-Manson law which accounts for High-Cycle-Fatigue (HCF) as well [5].

In this work, we developed a FE model which describes the thermo-mechanical behavior of solder joints of high power density surface mounting devices (SMD), such as those used in low-medium size DC/DC converters for power supplies, both for power MOSFETs and their drivers. As a case study, we used a power MOSFET in SO-8 package mounted on a small FR4 board. In Fig. 1 a photograph of the studied transistor-board configuration is reported, while Fig. 2 shows its 3D physical model.

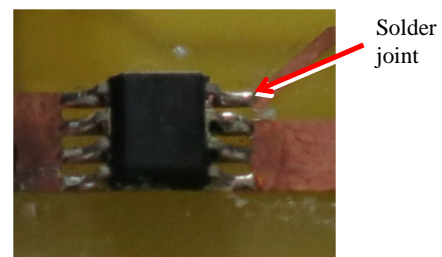


Figure 1. SO-8 packaged device mounted on a small FR4 board.

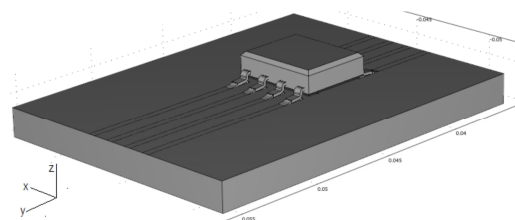


Figure 2. 3D model of an SO-8 packaged device mounted on a small FR4 board.

Thanks to their small size and the capability of handling high power densities, these devices are attractive for designing compact power supplies, such as those for consumer electronics, in which a high-power density is required.

The type and layout of the PCB and the

solder material strongly influence its reliability [6], then a model able to predict thermo-mechanical degradation is mandatory in converters design phase.

The aim of this paper to use the FE analysis to build a thermo-mechanical model of a power transistor subjected to thermal cycles, by exploiting the Coffin-Manson law to obtain indications about the fatigue life of the solder joints, depending on material and geometrical parameters. Creep [7] is an important factor that contributes to the solder joints damaging process, but we are not accounting for it in this preliminary work, which is based on maximum plastic strain components only. This simplifies the model, thus allowing the thermo-mechanical simulation of a whole system, whose lifetime may depend on the degradation of many differently stressed solder joints.

The development of a test bench is also mentioned in the last section, the role of which is to accelerate the thermo-mechanical stress of the devices in order to obtain mechanical degradation (probed by the reduction of thermal and electrical performance) of the solder joints. Once the model will be tuned on the basis of the experimental results, it will be exploited to predict the solder joint life in operating conditions, and to optimize solder material and geometry to improve the converter reliability.

2. The thermo-mechanical model

The purpose of the implemented 3D FE thermo-mechanical model is to predict the effect of thermal cycles on the solder joints of the power transistor, depending on materials and geometrical parameters. Figure 3 shows some details of the model. It computes the multi-axial stress-strain distribution in the device under test. The model is stationary, meaning that it does not account for the solder joints strain-rate (that is, no creep is modeled) but it returns only the maximum values of strain once the structure has reached the thermal (and mechanical) steady state.

To account for this process in terms of life cycles N_f , the Coffin-Manson equation (1) is used [5]:

$$\frac{\Delta \varepsilon_p}{2} = \varepsilon'_f (2N_f)^c \quad (1)$$

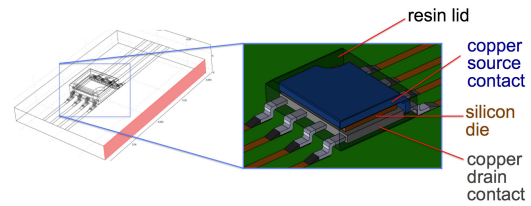


Fig. 3. 3D model geometry implemented in COMSOL.

where $\Delta \varepsilon_p/2$ is the strain to which the sample is subjected (obtained from the FE model), N_f is the number of load reversal (i.e., half of the number of loading cycles), and ε'_f and c are characteristic parameters of the soldering alloy. The determination of $\Delta \varepsilon_p$ is easy when the specimen is axially loaded (it is actually driven by the loading test routine), while for multi-axial loading, as in the case of solder joints, determining the value of $\Delta \varepsilon_p$ that has to be used in (1) is all but straightforward. This calls for a criterion with which analyzing the strain data obtained from FE simulations, which will be fully explained in the next section.

The model by which the mechanical characteristic of the materials is described has been kept simple. The FE model is non-linear, since the solder alloy material model accounts for the plasticization region, as shown in Fig. 4. If the plasticization in a given material can be neglected, the mechanical behavior of that material will be described simply by defining E [GPa], the Young's modulus.

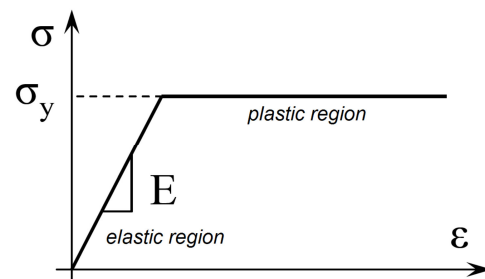


Fig. 4. Mechanical characteristic of a given material (perfect elasto-plastic); the material is fully described by E (Young's modulus) and σ_y (yield stress).

As already stated, being the solder joints loaded in several directions, the determination of the value of $\Delta \varepsilon_p/2$ to be used in (1) is not straightforward. The choice followed in this work is based on the evaluation of the *maximum* strain in the single solder joint, followed by the

application of (1). This relies on the observation that cracks nucleate close to regions with high stress concentration, and in particular the surface finishing is determinant in ensuring a robust fatigue life.

	K [W/(m·K)]	CTE [$10^{-6} K^{-1}$]	E, ν [GPa, -]	σ_y [MPa]
FR4	0.3	18	22, 0.28	-
Epoxy	0.78	200	1.8, 0.3	28
Copper	400	17	110, 0.35	70
Silicon	163	4.15	131, 0.27	-
SAC305	67	22	46, 0.4	40

Table 1. Thermo-mechanical properties of the materials present in the studied system.

3. The setup of the FE model

The setup of the FE model will be illustrated in this section. The geometry is the one shown in Fig. 3. The system is made of different materials, which characteristics are listed in Table 1. The used materials are: FR4 for the board, epoxy resin for the device package, copper for the device pins, tracks, and internal contacts, silicon for the die and SAC305 (Sn96.5Ag3Cu0.5) as soldering alloy.

It is quite difficult to establish a well-defined value for the parameters E and σ_y of a given soldering alloy, being these values influenced by the shape of the specimen as well as the method used to perform the characterizing test; it is common to find a broad set of values for SAC alloys, ranging from 38 GPa to 54 GPa for E , and from 32 MPa to 47 MPa for σ_y [8]; we used the average value of these sets, as reported in Table 1. Being the alloy made almost entirely of tin, the value of thermal conductivity k [W/(m·K)] is that of tin.

The performed analysis is a thermo-mechanical one: the silicon die dissipates a power P (entered in the model as per unit volume, in [W/m³]) and the device cools down by natural convection, accounted for by a convective coefficient $h = 30$ W/(m²K), assuming the ambient temperature equal to 25 °C. This boundary condition is applied to all the horizontal surfaces in the model.

The stress-strain distribution is then

calculated once the Coefficients of Thermal Expansion (CTEs) for each material are known, provided that a mechanical constraint is defined: in our case, the board is mechanically fixed on the highlighted border, as shown in Fig. 5.

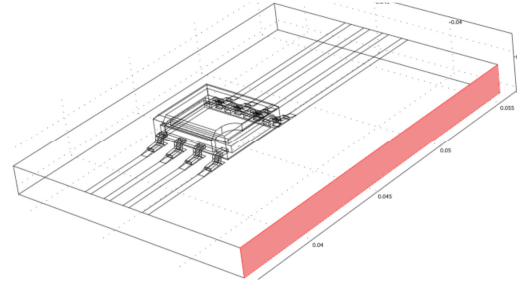


Fig. 5. The board is fixed by applying the corresponding mechanical constraint at the pink border.

As stated above, the model is not time-dependent, but it aims to calculate the maximum strain only, which occurs in the structure. For this reason, the model is cyclically run between two states, the first when the dissipated power is naught ($P = 0$ W), and the second when the dissipated power is at the maximum value, $P = P_{max}$. We performed several tests changing the value of P_{max} , in order to study different power dissipation conditions, in particular $P_{max1} = 0.3$ W, $P_{max2} = 0.4$ W, $P_{max3} = 0.5$ W and $P_{max4} = 0.6$ W, aiming at simulating accelerated life tests.

Each joint is subjected to a multi-axial stress condition, and a meaningful value of $\Delta\varepsilon_p/2$ has to be extracted from the model solution. A simple method is proposed here. (i) Determine the solder joint with the highest degree of plasticization; this can be done by integrating the von Mises stress over the volume of each joint, and averaging it over the joint volume (this relies on the fact that the more plasticized the joint, the most probable the crack development). (ii) Determine its surface with the highest degree of plasticization; it is enough to evaluate the surface-averaged von Mises stress over the joint surfaces (cracks often start from surface defects). (iii) On that surface, evaluate the plastic components of total strain on the considered surface: they are $\varepsilon_{px}, \varepsilon_{py}, \varepsilon_{pz}, \varepsilon_{pxy}, \varepsilon_{pyz}, \varepsilon_{pxz}$. We are interested in $\Delta\varepsilon_{pi}$, that is:

$$\Delta\varepsilon_{pi} = \varepsilon_{pi}(P_{max}) - \varepsilon_{pi}(0), \quad (2)$$

being this difference evaluated for each case

($\Delta\epsilon_{px}$, $\Delta\epsilon_{py}$, $\Delta\epsilon_{pz}$, ...). (iv) The maximum $\Delta\epsilon_{pi}$ found is then used in (1). $\Delta\epsilon_{pmax}$ is calculated as follows:

$$\Delta\epsilon_{pmax} = \max\{|\Delta\epsilon_{px}|, |\Delta\epsilon_{py}|, \dots, |\Delta\epsilon_{pz}|\} \quad (3)$$

The absolute values in (3) are needed since positive as well as negative strain are effective in developing cracks.

For the sake of clarity, the solder joints have been numbered from 1 to 8 (the Gate pin), as shown in Fig. 6.

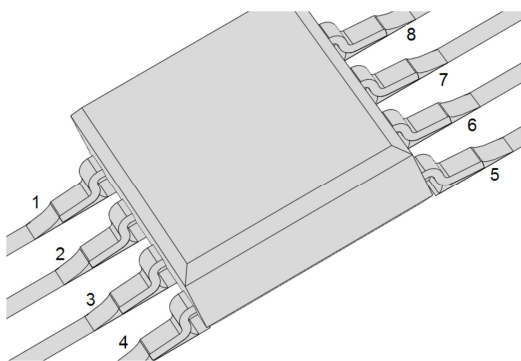


Fig. 6. The solder joints numbered from 1 to 8.

4. Modeling results

A blow-up of the tetrahedron-based mesh is shown in Fig. 7. The mesh has been refined in the solder joint domains, while it grows coarsely moving towards the surrounding domains. Then, the same model is run at different dissipated power levels, as explained in the previous section. The purpose is to localize the most stressed solder joint in several operating conditions, and the most stressed surface on that solder joint.

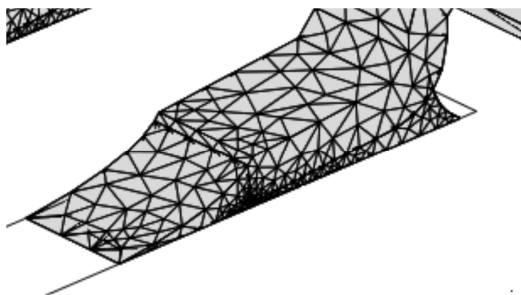


Fig. 7. Detail of the mesh related to the solder joint only.

We run the model at four different power levels: 0.3 W, 0.4 W, 0.5 W and 0.6 W. The maximum temperature reached by the solder joints are 67 °C, 81 °C, 95 °C and 110 °C, respectively; clearly, these are representative of an accelerated life test. From each simulation case, the algorithm presented in the previous section has been applied, and some considerations follow. (i) The solder joints 1, 2, 3 and 4 are always the most stressed; this is reasonable, being those the pins connected to the Drain terminal, with 1 and 4 being the most stressed among this set; they can move more freely than the others, and thus they are more prone to be strained. Fig. 8 shows the normalized von Mises stress per each pin. (ii) The most stressed surface on pin 1 is the lateral surface (the most external one), as shown in Fig. 9. Therefore, the stress-strain state on this surface will be investigated.

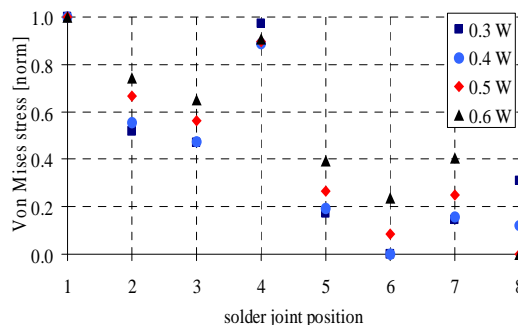


Fig. 8. Plot of normalized von Mises stress (integrated over the joint volume) versus pin position, for different power levels. Pin 1 and 4 are always the most stressed pins.

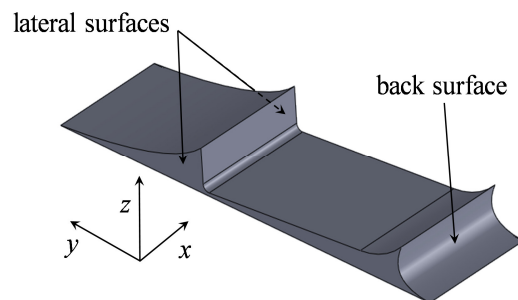


Fig. 9. Indication of solder joint surfaces referred to as “back” (facing the body of the device) and “lateral” (those two on the joint sides), respectively.

We focused on the maximum plastic strain components which occurred in the solder joint, and we found that, even at different power levels, the dominant components are always these two: $\Delta\epsilon_{pxz}$ and $\Delta\epsilon_{pz}$; their values are plotted as a function of the dissipated power in Fig. 10. This means that the solder joint tends to be almost equally lifted up and sheared along the z direction for low power, with the latter contribution becoming more and more predominant as the dissipated power increases.

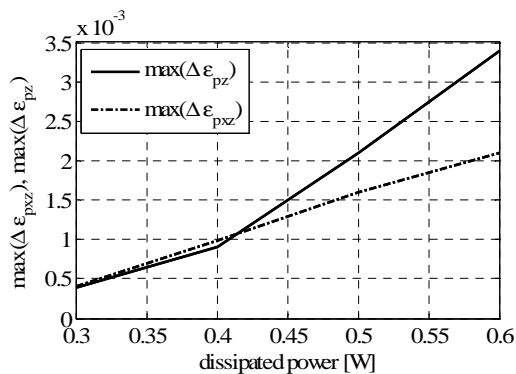


Fig. 10. Plot of simulated plastic strain components $\Delta\epsilon_{pxz}$ and $\Delta\epsilon_{pz}$ versus dissipated power.

5. Test bench development

A test bench was designed and it is under development, in order to validate the model on the basis of experimental data. It basically consists of a PCB with 16 SO8 MOSFETs arranged in a 4×4 matrix fashion, which can be driven in parallel. This means that only $1/16^{\text{th}}$ of the overall board needs to be modeled, since every single device is stressed in the same way as the others, therefore justifying the modeling of only one device. Several boards will be manufactured, in order to stress different 16-wide sets of devices with different powers.

The test bench design features the measurement of: channel temperature (by thermo-sensitive electrical parameter), external temperatures (by IR thermography), drain current and voltages of the MOSFETs. The failure detection strategy can rely on the measurement of a variation in the current sunk by the devices and/or on the increase in the device temperature.

6. Conclusions and future developments

This work shows the set up a three-dimensional, non-linear thermo-mechanical FE model, suitable for studying the fatigue behavior of soldering joints in SO-8 packaged devices mounted on PCBs. A possible method to determine the strain to be entered in the Coffin-Manson relationship, used to obtain the fatigue life of the joints, is shown. The approach can be obviously extended to other packages, once their 3D model is built.

The model will be tuned on experimental data, in which several devices will be subjected to accelerated power cycles, in order to fit the Coffin-Manson law to describe the fatigue strength of the system and extrapolate the fatigue life at the actual operative conditions.

7. References

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