From MEMS Strip to MEMS Unit: a Comprehensive Simulation Approach to Warpage

Andrea Ratti
STMicroelectronics
Agrate, Italy
andrea.ratti@st.com

Daniele Simoncini
STMicroelectronics
Agrate, Italy
daniele.simoncini@st.com

Annabel Adolfo
STMicroelectronics
Calamba, Philippines
annabel.balahadia@st.com

Marco Del Sarto
STMicroelectronics
Castelletto, Italy
marco.delsarto@st.com

Alex Gritti
STMicroelectronics
Agrate, Italy
alex.gritti@st.com

Patrick Fedeli
STMicroelectronics
Castelletto, Italy
patrick.fedeli@st.com

Luca Maggi
STMicroelectronics
Agrate, Italy
luca.maggi@st.com

Teresa Napolitano
STMicroelectronics
Arzano, Italy
teresa.napolitano@st.com

Mark Andrew Shaw
STMicroelectronics
Agrate, Italy
mark.shaw@st.com

Jefferson Talledo
STMicroelectronics
Calamba, Philippines
jefferson.talledo@st.com

***Abstract* - The paper suggests a simulation flow methodology suitable for MEMS package designers that can help R&D teams to develop industrially feasible products by achieving consistent warpage prediction results, both at unit and strip levels. Strip-level-wise, one of the most important findings of this activity is the direct impact of raw material selection. Unit-level-wise, it allows checking a priori and in different conditions (inside the socket or mounted on a PCB for example) stress distribution on different elements of the assembled MEMS unit.**

Keywords — Strip Warpage; MEMS; package warpage; thermo-mechanical FEM simulations; MEMS packaging.

I. INTRODUCTION

MEMS (Micro Electro-Mechanical Systems) package design is the challenge to couple sensing or actuating principles expressed by a silicon structure with the external environment [1]. It must accommodate both the emerging push of the miniaturization trends and the rise of more complex MEMS dies. Consequently, silicon content inside the package is continuously increasing, leading to the growing relevance of the warpage phenomenon [2]. Warpage consists of bending of the structures once undergone to temperature stress path caused by material properties mismatch and is one of the major concerns which accompany semiconductor products throughout their manufacturing life [3]. High warpage values may affect MEMS performances in many contexts:

- Assembly (strip level warpage) → workability issues
- Testing (unit level warpage) → socket to MEMS interaction - calibration issues
- Soldering (unit level warpage) → MEMS to board compatibility issues

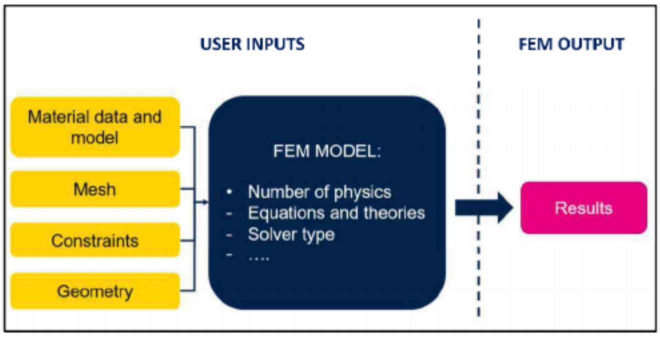

Fig. 1. Schematic overview of FEM focusing on user inputs and FEM outputs.

It starts in the Front-End, when the first layers are deposited on bulk crystalline wafers; it changes concavity, shape, order of magnitude, it is carried out and addressed in different hi-tech machines, but it never disappears, even during its final application on customer PCBs (Printed Circuit Board).

This paper intends to describe the warpage evolution and the measurement techniques exploited for warpage assessment in Back-End. MEMS products are assembled in panels and are typically moulded. These structures suffer from warpages as well as single assembled units. This structural bending affects the package interaction with the testing machine and PCBs.

As reported in Fig. 1, this study can be approached with varying parameters, study setups and assumptions, that may lead to consistently different results. Consequently, one of the hardest parts of the task is to select the ones that allow the best fit with experimental data, starting from scratch.

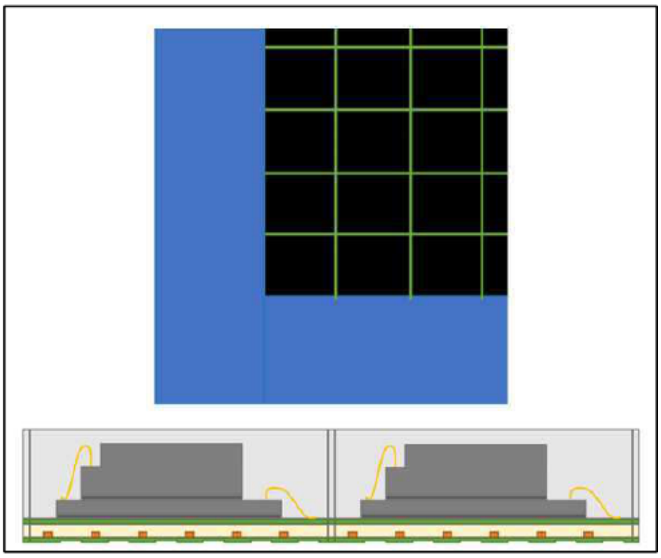

Fig. 2. Above, schematic top view of a strip portion. Blue part is the strip rail, green the sawing street, black the units. Below, schematic view of a strip section: green is the solder mask, beige the core material, orange the metals, black the DAF, dark grey the silicon, gold the wires and light grey the moulding compound.

II. Strip Warpage

Most of the motion MEMS devices are assembled in panels called “strips” to increase productivity. As shown in Fig. 2, strips are made of single units (their overall number depends on the size of the device itself) juxtaposed one to the other, sawing streets (parts of the strip interposed among units, where the singulation is performed using a rotating saw blade to separate the individual devices when the assembly is completed) and the strip rail (the outer part of the strip, used as guides for handling within the assembly equipment). The strip stack-up is usually made of a couple of elements (Fig. 2) - solder mask, metal, core material, die attach film, silicon, and cured moulding compound - but the relative amount of these elements can vary consistently depending on the device.

Stacking up many different materials may lead to warpage issues during assembly. The reason behind this is mostly a Coefficient of Thermal Expansion (CTE) mismatch among the different elements, meaning that parts already stacked together, thus constrained, tend to expand and contract differently when the strip undergoes the several thermal cycles needed during the assembly (or to solder the device onto the customer board) [4]. Internal stress (any dimensional change of the MEMS - being MEMS mechanical sensors and actuators - due to stress can have implications on the device performance) and physical bending/tilting (this often implies workability problems, leading to machine downtimes and production yield losses) of the strip itself are generated. Excessive warpage may cause not only lower productivity but even the inability to produce: before moulding it can generate problems in strip handling or clamping during die attach and wire bonding; after moulding it is not possible to singulate within package tolerances.

Fig. 3. Strip warpage classification.

Marketing trends consisting of continuous device height reduction foster the vulnerability toward this phenomenon: in particular, a substrate thickness reduction amplifies the bending possibility. Being the strips in a rectangular shape, warpage can be properly classified into some categories: coil set warpage, crossbar warpage and twisted warpage. Each of them can show positive or negative curvature (Fig. 3).

Related to different needs in production line, the assembly flow is divided in two main phases: Front of Line (FOL) and End of Line (EOL). FOL includes all the assembly steps before moulding, whereas EOL covers all the remaining ones. This distinction is important since warpage magnitudes depend not only on the applied temperature, but also on the applied constraints typical of each assembly step (internal, such as the die attach, or external such as the shape of the strip carrier). Until the strip is considered part of FOL, layout design modifications can be applied and are effective to correct the warpage phenomenon, whereas once in EOL a change of materials is required as an effective way to compensate for warpage.

It is now clear that being able to predict and manage the warpage has thus become a key factor in ensuring productivity and reducing costs and time-to-market. Warpage has become a criterion for the choice of assembly materials. To speed up this selection process, the possibility of forecasting the impact of certain materials on the overall stack-up should be investigated. Moreover, a clear picture of the stress distribution inside the strip ensures better performances of the final device and the possibility to forecast some kind of failures.

A. FEM model setup

The Finite Element Method (FEM) is the tool we selected to perform this predictive analysis, even though MEMS structures are not always easy to mesh. They are full of high aspect ratio features, that cannot be easily managed: lots of (more than 90%) good small elements – element aspect ratio < 5 – are needed to accurately mesh thin layers, consequently requiring high computational power. To overcome this problem, simplifications should be performed on the model geometry, the numerical models exploited to fit the material properties and the kind of simulation carried out.

Geometric simplifications concern different parts of the units, and consequently of the strip:

- Substrate: based on the I/O quantity and routing complexity, the strip substrate can have two or more metal layers. For motion moulded MEMS, these are the typical stack-up structures: solder mask bottom, metal bottom, core, metal top, solder mask top. It is evident then that the strip itself is a composite material, obtained by lamination. This is probably the most difficult to mesh part of the die/strip, and consequently, different approaches have been tested. It is possible to group them into two main categories: Hard Geometrical Simplification (HGS) and Soft Geometrical Simplification (SGS):
  - HGS: it consists of the substitution of the overall substrate with a single bulky parallelepiped of the same height as the real substrate (Fig. 4A). The material applied to this bulky element is fictitious, and it features properties that result from the

application of composite materials mixing rules to the original stack up. The most important ones to be calculated are the Young Modulus ($E_{composite}$) and the Thermal Expansion Coefficient ($\alpha_{composite}$) [5]:

$$\alpha_{composite} = \frac{\alpha_1 E_1 V_1 + \alpha_2 E_2 V_2 + \cdots}{E_1 V_1 + E_2 V_2 + \cdots} \quad (1)$$

$$E_{composite} = E_1 V_1 + E_2 V_2 + \cdots \quad (2)$$

This method doesn't consider the influence of the geometry of the different parts the substrate is made of on the overall warpage behaviour. Moreover, the exploited formulas were developed for composite materials, where fibre and matrix are clearly divided and oriented. The results obtained using this procedure don't fit the experimental ones as expected.

- SGS: it consists of the substitution of the overall substrate with multiple stacks of bulky parallelepipeds of the same height as core material and prepreg (Fig. 4B1). Stock material is considered, both for prepreg and core materials, where the volume occupied by metallic layers is assigned to the core. Strip warpage wise, the contribution of metallic layers can be considered negligible [6]. The results obtained exploiting these simplifications are the ones that better fit the experimental ones.

- Dice: here the level of detail can be increased more and more. Strip level wise, to get good results it is enough to represent them as bulky blocks of monocrystalline silicon. Moreover, there is no need of representing wire bodings, being low in the amount of metallic material and not shaped in a bulky way. Die Attach Film (DAF) and Film on Wire (FOW) should be introduced as bulky parallelepipeds (Fig. 4B2).
- Mould: it can be shaped as the remaining part of the stack up, up to the nominal thickness of the package (Fig. 4B3). Together with silicon and core material, it is one of the main responsible for the final shape of the overall strip. Laser marking is not considered.

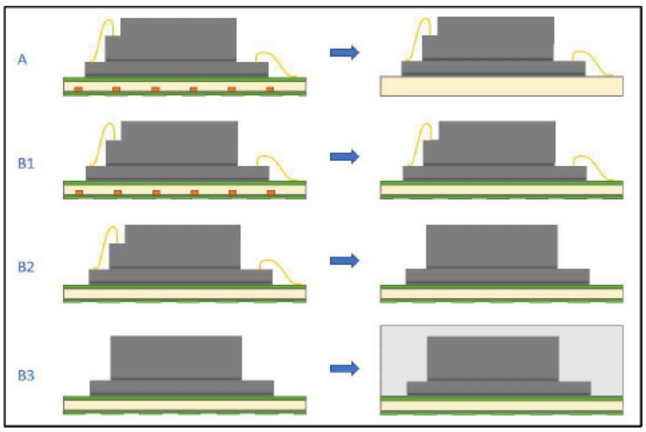

Fig. 4. A: substrate HGS simplification. B1: substrate SGS simplification. B2: dice simplification. B3: mould compound simplification.

Fig. 5. Automatic Optical Measurement machine.

Simplifications of the kind of analysis carried out consist of the performance of a static study instead of a dynamic one. It is assumed that the behaviour of the system being simulated does not depend on time, and the applied loads are constant. Also in this case, choice was made due to the lack of experimental data that described the dynamic behaviour of materials and to reduce the computational load of the analysis.

Simplifications on the numerical models exploited to fit the material properties affect all the materials considered in the study: they have been all considered linear elastic isotropic materials. This choice was made due to the lack of experimental data that described the real behaviour of materials.

To check for the accuracy of the results and to validate the FEM model, several measurements were done on the warped strips. The system exploited for this analysis is an Automatic Optical Measurement machine, that can scan the whole strip and provide a 3D map of the curved strip (Fig. 5). This kind of investigation is standard only after post mould curing. Consequently, it was possible to tune the FEM model at this step of the process only (temperature profile spans from 298K up to 523K). This is just one of the two moments of the process of interest, where high warpage values are highlighted: critical warpage values can also be seen after the first die attach (still part of the FOL).

B. Results

Results of the simulations performed with the simplifications above are reported in Fig. 6 and correlated with the experimental results assessed via automatic optical measurements.

The accuracy of the results varies depending on the device: being the outer dimensions of the strip constant as well as the sawing street dimensions and the strip rail dimensions, the number of devices hosted by strips varies significantly depending on their footprint. Selected simplifications imply a small mismatch from the real overall strip behaviour: replicating this mismatch a higher number of times implies a greater deviation from the targeted value. In this case, the meaning of the result relies on the relative comparison of the different tested solutions at design phase. In the plot (Fig. 6), the ideal case (perfect match) is represented by the red dotted line.

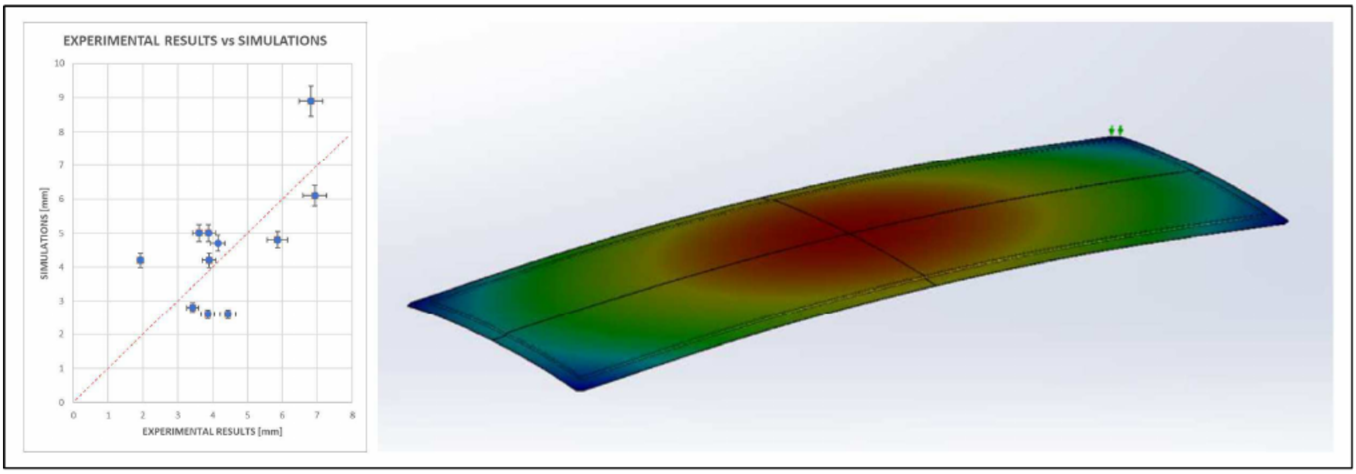

Fig. 6. Above, experimental results compared to simulated ones. The footprint of the simulated devices ranges from 2mmx2mm to 5mmx5mm. Dots placement variation is set to 5%. Below, an example of FEM simulation strip warpage output.

III. Unit simulation and experimental DIC measurements correlation

Assumptions for the analysis reported in this paragraph are:

- This flow doesn't provide a complete connection from strip to unit simulation yet: they are currently still independent. It will be evaluated if it's worth connecting them, also considering the following statements. Anyhow, this flow is suitable for all the packages, not only for the ones assembled in panels.
- The stresses of each unit depend on the manufacturing processes. The boundary conditions for sure impact the final unit stress state and this can lead to a not negligible simplification. Therefore, each additional assembly step should be simulated in a sequential way which feasibility has been proven but the flow is not mature yet.
- Since each unit undergoes a sawing process which might introduce or release some stresses itself, μDIC (Micro Digital Image Correlation) measurements have been performed on a few units. By comparing unit simulations results with these experimental data, it is possible to achieve a reasonable level of confidence on unit level stresses and deformations.

Fig. 7 represents the generic schematic workflow developed in the unit level simulations. It can be grouped in three main steps: package and design simulation, μDIC Measurements and correlation and package deformation transfer to MEMS.

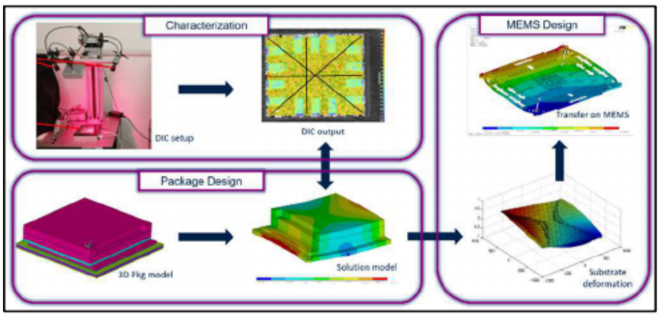

Fig. 7. MEMS unit level simulation workflow.

A. *Pakage design and simulation*

Simulations at the unit level have been performed avoiding the 3D CAD model simplifications required to study warpage at the strip level.

Local deformations are not negligible assessing the stresses induced on the MEMS. Fig. 8 reports an example of the package structures analysed: fully detailed metals, solder mask, core material and die geometry have been considered.

Warpage oriented package simulations have been set up constraining three out of four package corners (free condition) and ranging the temperature according to the investigated process steps [7].

B. *μDIC Measurements and correlation*

μDIC is a widely used and well-known optical measuring technique to evaluate strain and displacement on a specimen [8, 9]. In our application, a stereo microscope has been exploited. Data have been extracted from the samples following the 4 lines path highlighted in Fig.9 on the left.

The output of the analysis has been found slightly noisy. Consequently, a post-processing Fourier analysis-based fitting curve has been applied to the data.

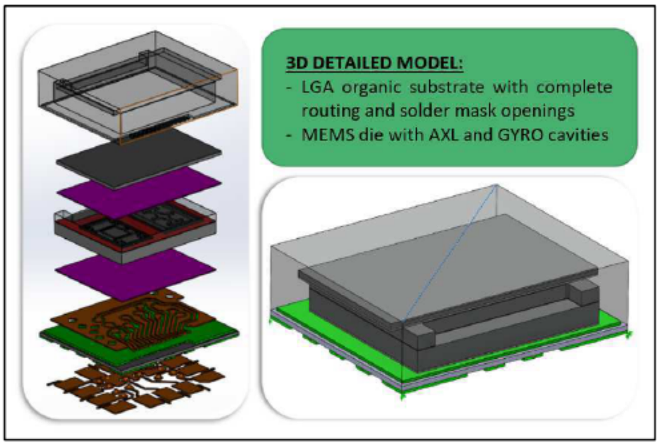

Fig. 8. 3D detailed and exploded model example (on the left) and model representation during simulation with constrains applied (on the right).

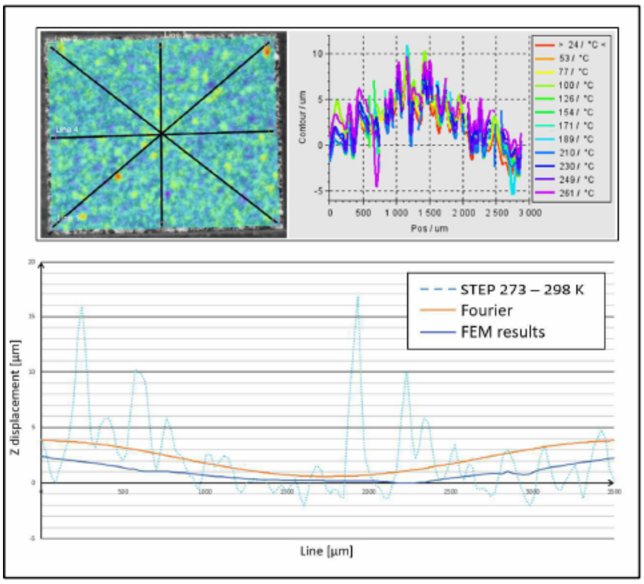

Fig. 9. Upper Box: lines exported from the the µDIC measurements (left) and z displacement example of a specimen. Lower Box: comparison curves between experimental data (light blue line), Fourier analysis (orange line) and FEM results (blue line).

This methodology was found to be effective and consistent with the results coming from the previously described unit-level simulations (Fig. 9 reports the acquisitions made on one of the paths under evaluation). The simulated curves and the experimental ones have been investigated for a few devices showing consistency between the expected results and the FEM model as shown in Fig. 9.

C. Package deformation transfer to MEMS

Once the model has been fitted and the FEM results were comparable with the experimental data, the following step has been to understand the impact of this deformation on the device's performance.

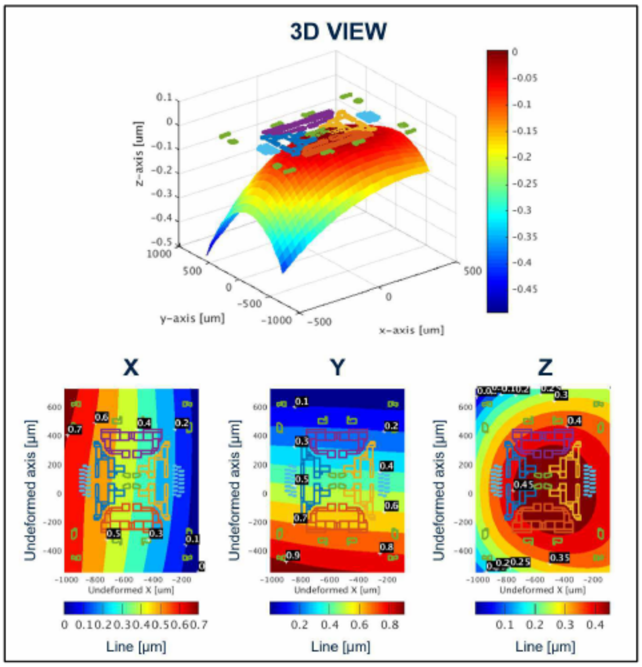

Fig. 10. Example of gyroscope substrate deformation extrapolated by the performed package simulation.

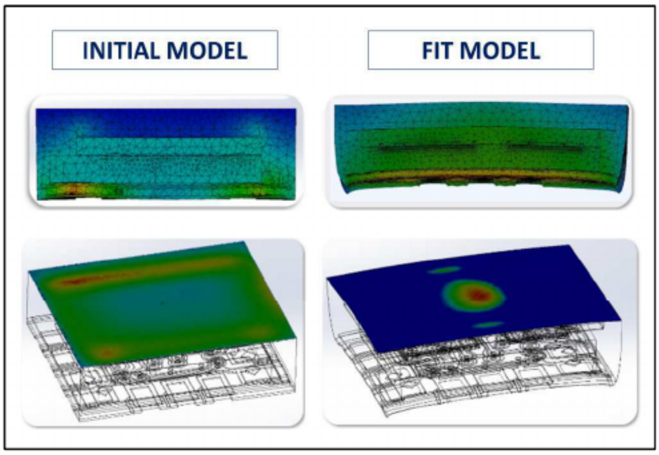

Fig. 11. Initial mode (left) vs fit model (right) with corresponding contact pressure difference.

Belonging MEMS and packages to different orders of magnitude, it was not trivial to bridge the reciprocal impact. The solution has been found in modelling the MEMS cavities inside the silicon performing package level simulation and then transferring the obtained displacement to the MEMS itself as reported in Fig. 10. The MEMS substrate deformation can cause a change in the capacitance between the stator and rotor electrodes, affecting the sensitivity of the gyroscope.

IV. Unit Simulation in Socket

During testing, the socket pushes the MEMS during its insertion, inducing a deformation of the package and of the substrate. The aim of this simulation is to establish a flow able to simulate the interaction between sockets and MEMS and to predict the level of stress and deformation of the device during testing. Socket design and optimization are essential for MEMS performance, being gyroscopes calibration and testing opportunely calibrated through their exploitation. It consists in contacting the I/O of the device with some needles, the so-called "pogo pin", and applying a defined stimulus.

The simulation setup consisted not only of the application of the pogo pin force on the substrate and of the top surface constraining. Since the µDIC analysis showed a bending in the package, it was implemented in the simulation. This step was essential to align the results with the expected ones (Fig. 11).

It was discovered that the yaw axis is not influenced by testing conditions whereas the roll worsens as the applied pogo force increases (Fig. 12).

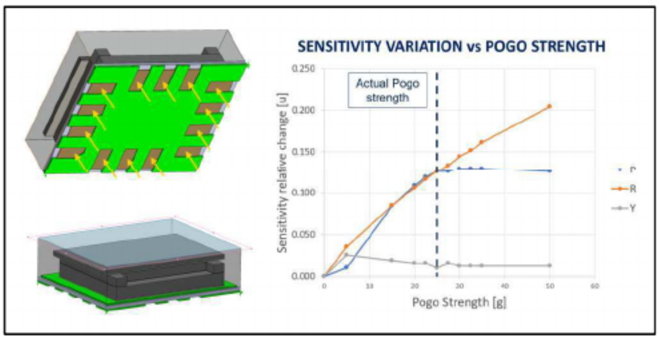

Fig. 12. Package to socket interaction model (left) and outputs (right).

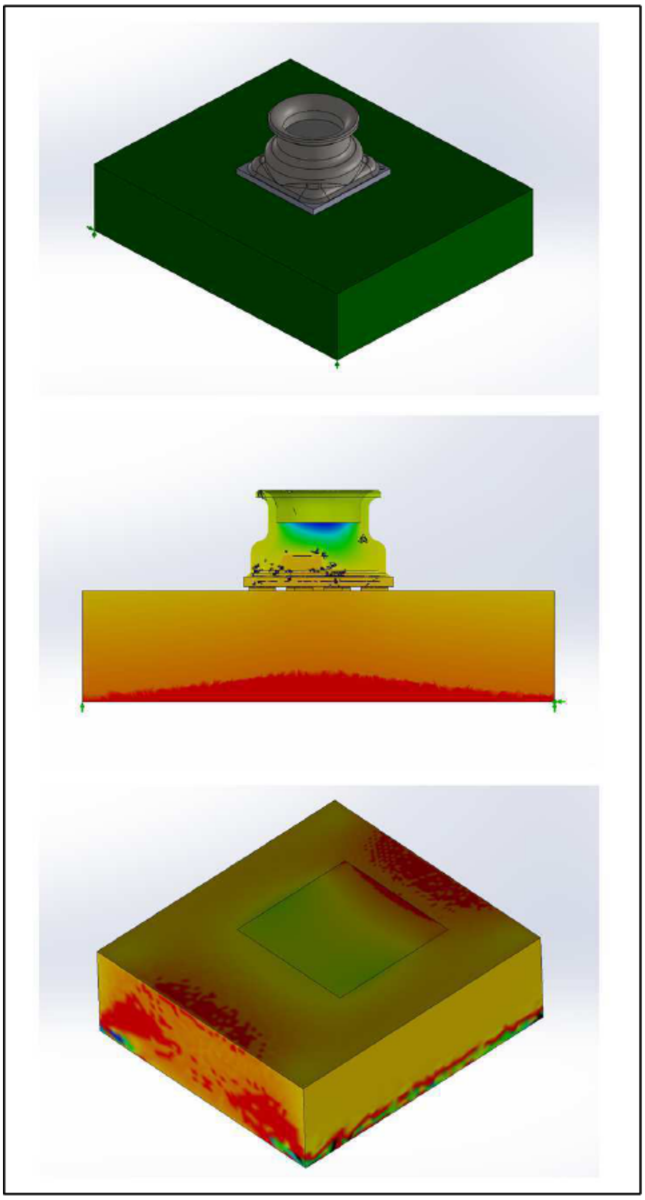

Fig. 13. Results of thermo-mechanical soldering simulations performed on a pressure sensor. 3D CAD model, stress map of the section of the overall assembly and stress map of the MEMS present inside the package.

V. Unit simulation on PCB

Before device usage, even though it is not part of the assembly process, the soldering on the PCB board may represent a final critical step for the MEMS sensor or actuator. The temperature needed for this purpose is relatively high)(about 573K). Once again, the whole stack up of materials may undergo a constrained expansion (or restriction), this time even more bounded due to the presence of the PCB (usually much thicker – and consequently rigid – than the device itself).

Simulations are performed to assess the stress distributions onto the most sensible parts of the MEMS, to avoid any damages and performance corruption.

It is challenging to perform a stress distribution data experimental extraction on an assembled and installed device. Consequently, instead of targeting the output of a certain amount of stress, simulations often try to assess the consistency between the amount of stress generated by a consolidated design and the new generation of the device.

The 3D CAD model exploited for these simulations consisted of a complete device (same degree of detail exploited for unit simulations) mounted onto a PCB through solder paste (Fig. 13).

Conclusions

Comparing the experimentally measured values during different MEMS assembly steps and predicted ones obtained via FEM, an in-depth study of the warpage phenomenon has been performed. A way to consistently simulate warpage at die and strip levels has been found and validated. Predictive analysis integrated into the package R&D design flow can help to prevent or mitigate warpage happening during production and related issues.

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