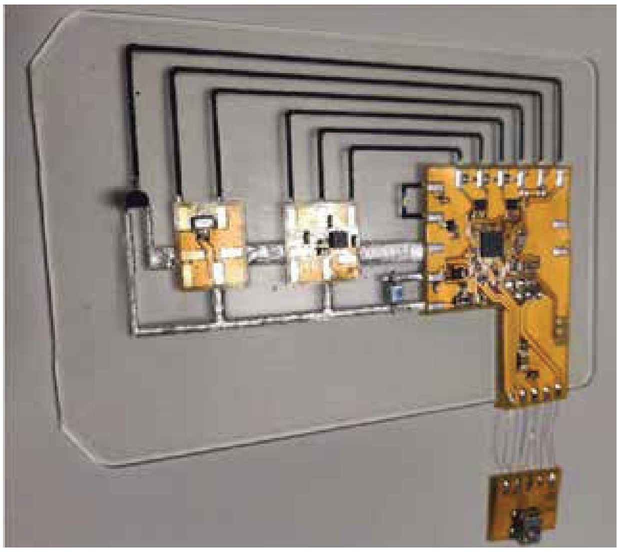
Static and thermal FE analysis of a Flexible Electronic BOard (FEBO) prototype and the characterization of its innovative materials



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An FE model of an experimental flexible electronic board was built to determine its performance in terms of mechanical and thermal distortions, heat and transient thermal flow, thereby detecting critical issues and identifying opportunities for improvement. Commercial sensors were connected to the flexible board (100x40x2mm), which was based on a commercial thermoplastic polyurethane (TPU), with a PEDOT-based conductive resin trapped in a PEGDA network, a biocompatible polymer. Three thermal loads ($\Delta T=175°C$, $\Delta T=100°C$, $\Delta T=50°C$) were applied which revealed critical stresses for high ΔTs but at $\Delta T=50°C$ only the connectors had a critical σ_{vm}, while for $\Delta T=50°C$ + 1mm displacement a critical strain value occurred in one area of the substrate. Heat transient analysis and overheating simulations were performed to determine the heat flow behavior for the photodiode and accelerometer. FE analyses allow more studies to be undertaken to improve material properties and suggest redesign activities for similar concept demonstrators. The funds of the European Union and the Piedmont Region, and agreements with the most important players in SBE (Simulation Based Engineering) software sales and services, allowed the authors (ITACAe srl, Proplast, and Politecnico di Torino) to conduct industrial research and experimental development together with manufacturers and users of innovative technologies to identify, study and optimize the design parameters of the board while simultaneously contributing to its technological development.

A demonstrator of a flexible electronic board concept using novel materials was created with the intention of contributing to forward innovation by building a prototype to be used for different applications. The demonstrator's flexibility is a definite advantage for its applicability since it could be used in various types of structures. The goal of the study was to demonstrate the functionality of a flexible electronic board made from innovative materials and to assess its operating conditions. The novel materials used were also examined in this study, first by characterizing their material properties and then by using finite element analysis (FEA) to understand their capabilities and importance in the demonstrator's design. The proposed analysis aimed to evaluate the mechanical and thermal characteristics of the prototype and to describe its applicability in different mechanical and thermal conditions.

FE software, in particular MSC Apex for the mechanical analysis and Ansys Mechanical for the thermal analysis, was used. This study was conducted as part of a regionally funded "SMART3D" project. Among the partners, contributions to the study presented come from ITACAe, which performed the FE analysis of the demonstrator; Microla, which provided the design characteristics and geometries of the demonstrator; Proplast, which developed and characterized the commercial thermoplastic polyurethane (TPU); and the Politecnico di Torino, which worked on the characterization of the PEGDA/PEDOT used to deposit the conductive traces.

Description of the flexible board

The board consists of several electronic components assembled on a flexible commercial TPU substrate manufactured by Covestro [1]. The initial design had two different configurations, one with a flexible substrate and the other with a non-flexible substrate.

The analyses presented in this article concern the design with the flexible substrate, consisting of a temperature sensor, a pressure sensor, one LED, a photodiode, an accelerometer, and a microcontroller board. The sensors used came from a list of commercial models supplied by one of the SMART3D project partners (Argotec) and, in the end, the following items were selected: temperature sensor “TMP36GT9Z”, pressure sensor “MS5611-01BA03”, LED 1206 SMD, photodiode “BPW34”, a MEMS-based 3-axis linear accelerometer “LIS344ALH”. The microcontroller was made from typical materials for electronic boards, namely copper wired to a rigid polyamide plate. The flexible rectangular substrate was obtained by an injection molding process of the TPU granules. The connections between the sensors were made with the innovative PEGDA/PEDOT material [2].

Layout of the electronic board

The layout of the electronic board is presented in Fig. 1 below, while the sensors’ operating conditions are summarized in Table 1.

Temperature sensor	-55°C <Temp<150°C
Pressure sensor	-40°C<Temp<85°C
Photodiode	-40°C<Temp<100°C
Accelerometer	-45°C<Temp<85°C
LED	-40°C<Temp<85°C

Table 1: Operating conditions of the sensors.

The accelerometer and pressure sensor were mounted on a conventional electronic board while the temperature sensor, photodiode and LED were mounted directly on the flexible substrate. The conventional electronic board increases the stiffness of the flexible board causing relevant stress gradients that will be discussed later. Such change of stiffness is produced by all three boards but the microcontroller area has the greatest effect because it occupies the largest area, as seen in the layout.

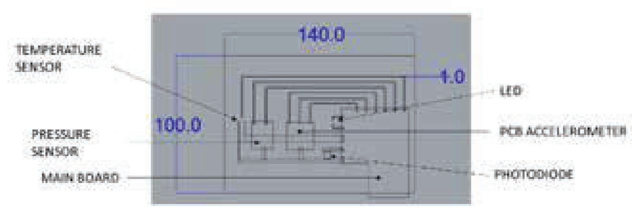


Fig.1 – Schematic layout of the electronic components on the Flexible Electronic BOard (FEBO)

Aim and objectives

The aim of the study is to understand which areas with critical deformations are important and how to modify them in the design of the board. In addition, actually producing the demonstrator will allow the feasibility of manufacturing and assembling it to be determined. Furthermore, the FE modelling presents a practical analytical approach to use while some its methodological limitations can be explored to improve its accuracy.

Last but not least, novel materials were used to fabricate the board. While integrating them into large-scale production could present difficulties, they could pave the way for a whole new manufacturing concept for highly customized electronic devices.

Characterization of the materials

TPU Desmopan 9370AU DPS 070

Polymer matrix

As previously mentioned, the polymer matrix selected was a commercial-grade ether-based thermoplastic polyurethane (TPU) (the Desmopan 9370 AU DPS 070), manufactured by Covestro. This material is specifically formulated for the injection-molding process and, in fact, this technology was processed to obtain a flexible rectangular-shaped board measuring 100x140x2mm.

This polymer was selected to prepare the flexible substrate based on a preliminary feasibility study completed by the SMART3D project in which experiments were done with different thermoplastic polymers, such as polyethylene terephthalate glycol (PETG) and ester-based TPU, processed with different fabrication techniques, namely film cast extrusion and injection molding.

The Desmopan 9370 AU DPS 070 was found to offer the best compromise among processability, flexibility, transparency, and cost and was therefore chosen to prepare the Flexible Electronic BOard (FEBO) prototype.

TPU characterization

The TPU matrix was thermally characterized using thermogravimetric analysis (TGA) in an inert atmosphere (N2) with a temperature range of 50°C to 800°C. This specific test was performed to verify the polymer’s thermal behavior and resistance both at the typical temperature used for the manufacturing process and at the working temperatures of the applied sensors. The test detected a thermal resistance and stability of up to about 300°C.

The flexible polymer was also characterized in terms of its thermal conductivity. This test provided indications regarding the thermal capacity and thermal conductivity of the selected material. As expected for a polymer matrix, TPU was found to be thermally insulating, presenting a thermal conductivity of about 0.2 W/mK, as shown in Table 2.

Material	E (GPa)	Poisson	Density (g/cm3)	Thermal expansion	Thermal conductivity (W/(m·K))	Specific Heat (J/Kg·K)
Copper	122	0.33	8.96	1.7e-5	3.93	386
Silicon	47	0.28	2.332	8e-5	148	700
Polyamide	3.7	0.3	1.34	4.3e-5	0.22	1040
PEGDA/PEDOT	0.021	0.4	0.4	16e-5	0.23	1046
TPU Desmopan	0.011	0.4	1.06	1.24e-4	0.186	2300

Table 2: Material properties

PEGDA/PEDOT

Resin composition

As mentioned earlier, the board consists of a flexible substrate, electronic elements, and conductive polymer wiring. The latter was obtained by selective deposition of a new blend, PEGDA/PEDOT resin. As the name implies, it is prepared using two main ingredients: Poly (ethylene glycol) diacrylate or PEGDA and Poly

(3,4-ethylenedioxytiophene) or PEDOT. PEGDA is a biocompatible hydrogel and forms the “structural” ingredient in the blend. PEDOT is an electrically conductive polymer well-known in the field of printable electronics.

The PEGDA and PEDOT were blended in a ratio of 55:45 of the final resin weight. 1%wt (relative to the PEGDA weight) of the radical photo initiator, IRGACURE 819, was also added. In fact, this resin was intended for use both in the custom fabrication process discussed here, and in commercial stereolithography 3D printers.

Therefore, this liquid mixture can be deposited in layers and then, when irradiated with an appropriate wavelength (in this case 405nm) will polymerize and harden.

Electrically conductive properties of PEGDA/PEDOT

Previous work has demonstrated the varying electrical conductivity of mixtures containing different PEGDA/PEDOT ratios. For the work reported here, the 55:45 ratio was chosen for two main reasons. Firstly, the quantity of PEDOT, which is more viscous than PEGDA, provides a fair compromise between low spreadability (on the substrate) and good flowability (through the syringe and tube used for its deposition).

Secondly, this quantity of PEDOT ensures a conductivity of 0.05 S/cm for the polymer. Additional testing, which is beyond the scope of this article, has shown that this conductivity level will guarantee that the flexible electronic board operates correctly.

FE Analysis

The FE study consisted of several analyses that have been summarized below:

- CAD model of the demonstrator geometry using MSC/APEX, PTC/CREO Parametric.
- FE model construction (MSC/APEX)
- FE analysis (MSC/Apex, MSC/NASTRAN [3], Ansys Mechanical 2020 R2 [4])
- Modal analysis
- Mechanical load analysis
- Thermal load analysis
- Heat flow and transient thermal analysis

The purpose of the analyses is to determine the critical stresses and strain gradients resulting from the movement of the flexible board, and then to make design recommendations.

In addition, the thermal loads were considered to understand how they affect the demonstrator’s criticality, and then a heat flux study was conducted to discover the board’s transient and critical temperatures.

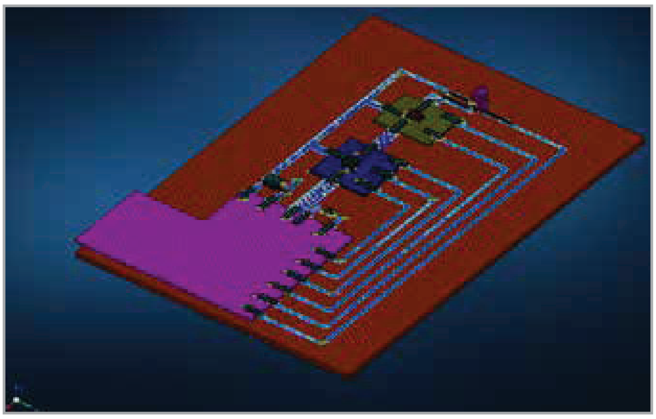


Fig. 2 – FE Model of the demonstrator

Model description

The demonstrator was modelled using Hexahedral for the 3D elements (8 nodes) and Quad Element for the 2D element (4 nodes). The average element size is approximately 1mm. The properties of the materials used are summarized in the Table 2.

A “mesh independent tie” was used in the FEM to model the interactions between the electronic components and the substrate. This allowed the connections between the 2D and 3D elements, as well as between all the 3D elements to be modeled. As already mentioned, the FE model was created using both 2D and 3D elements. Initially two different configurations were evaluated to understand the influence of the “mesh independent tie”, after which the second configuration, consisting predominantly of 3D elements, was chosen because it was more accurate and did not require excessive computing time.

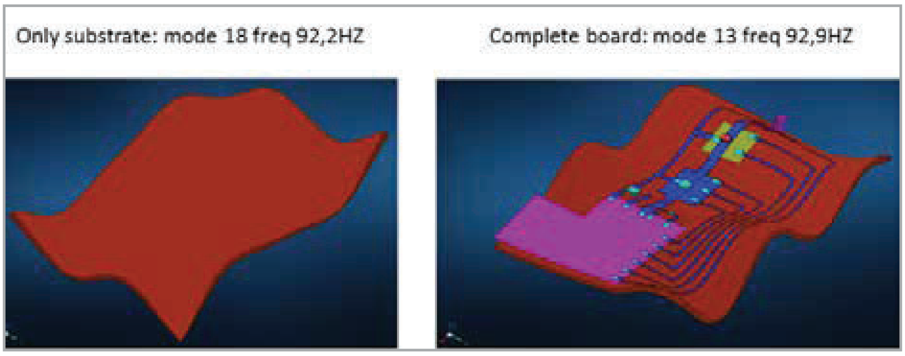
Results and comments

FE results: mechanical

The mechanical analysis was performed by imposing a fixed displacement on the board to determine in which areas the high gradient occurred when the substrate moved.

Modal analysis

The first analysis was a modal analysis to understand the frequency of the modes. This was a “free-free” dynamic analysis, i.e. without any constraints. A first comparison showed the difference between the case of the substrate only and the case of the entire electronic



Only substrate: mode 18 freq 92,2HZ

Complete board: mode 13 freq 92,9HZ

Fig. 3 – Comparison of similar frequency modes

board. Comparable frequencies showed a comparable oscillation, however the rigid board of the accelerometer, of the pressure sensor, and of the microcontroller all determine the shape of the oscillations.

Imposed fixed displacement

To understand the behavior of the board and its components, two cases of imposed fixed displacement were analyzed; one in which the displacement was imposed downward by 98.9 mm, and the second case in which the displacement was imposed upward. In both analyses, one short edge (the side near the temperature sensor) was constrained in all degrees of freedom while the opposite side had the imposed displacement. The results show that the stress gradients are most relevant in the areas close to the temperature sensor (see Fig. 4), and the Von Mises stress values are similar: σ_{vm} of 71.5MPa and 73.5MPa for the displacement imposed downward and upward, respectively.

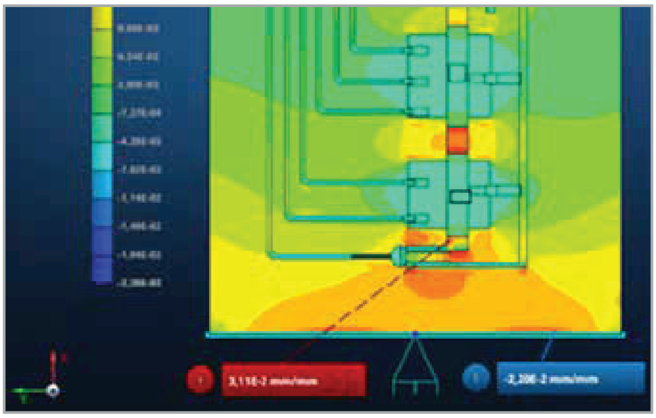


Fig. 4 – ε_{xx}=0.0311 at the downward imposed displacement

A greater difference is seen in the longitudinal strain maps where the higher value of ε_{xx}=0.0311 is found in the area of the temperature sensor at the PEGDA/PEDOT connections for the displacement imposed downward. The case with the upward displacement shows a maximum longitudinal strain ε_{xx}=0.0222 in the lower part of the substrate below the temperature sensor. The values shown in both these cases are below the critical values for the respective materials.

Component with Max σ_{vm}	Max σ_{vm} (MPa) (ΔT = 175 °C)	Max σ_{vm} (MPa) (ΔT = 100 °C)	Max σ_{vm} (MPa) (ΔT = 50 °C)	Material	σ_y (MPa)	σ_{ut} (MPa)
Copper connectors	1800	1030	516 (a)	Copper	100	200
Sensors	257	147	73.4 (b)	Silicon	N/A	62
Connector plate	229	131	65.4 (c)	Copper	100	200
Sensor board	38.8	22.2	11.1 (d)	Polyamide	50	80
Connectors	2.31	1.32	0.661 (e)	PEGDA\PEDOT	1.75	2
Substrate	1.40	0.8	0.4 (f)	TPU Desmopan	12	25.7

Table 3: Von Mises stresses from the thermal expansion analysis, and the mechanical properties.

Mechanical load

This case involved applying an external load of 1MPa (20Kgf) to one short edge of the board while the opposite edge was fixed in all degrees of freedom in a similar manner to that used in the case of the imposed fixed displacement. The Von Mises stresses show higher values at the copper connectors of the temperature sensor and photodiode with values of 466MPa and 541MPa, respectively. The rigid sensor boards also have some critical stress values with a maximum σ_{vm}= 42.1MPa at the short edge of the microcontroller's rigid board near the edge of the substrate and connections. The PEGDA/PEDOT connections showed elevated values of σ_{vm}= 5.19MPa at the larger connection between the micro-controller and the accelerometer board. The substrate also showed critical values of σ_{vm}= 3.93MPa in the same area and, similarly, the longitudinal strains were in the substrate showing a maximum value of ε_{xx}=0.294 near the side of the accelerometer board facing the microcontroller.

Thermal load

An analysis was performed by applying a thermal load to assess the deformation produced by a thermal step. The thermal load was applied to the entire model with boundary conditions at the four sides of the substrate. In particular, there were three cases of thermal load: ΔT=50°C, ΔT=100°C, ΔT=150°C. Table 3 shows that for ΔT=100°C and ΔT=150°C, all components showed criticalities while for ΔT=50°C only the connectors at the temperature and chip sensors had high Von Mises stress values, i.e.: σ_{vm}= 516MPa at the temperature sensor connectors and σ_{vm}= 73.4MPa at the

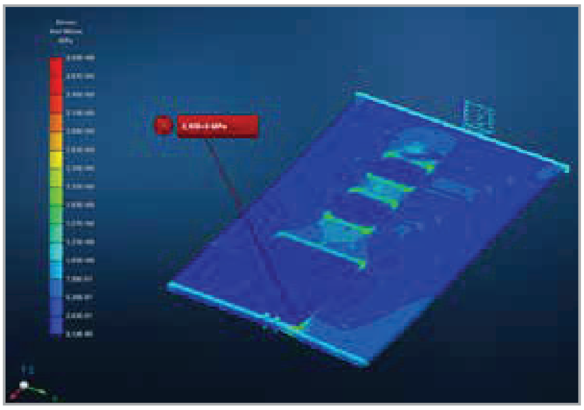


Fig. 5 – Imposed load: Von Mises stresses at the substrate, σ_{vm}= 3.93

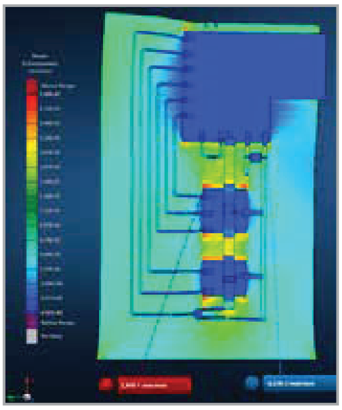


Fig. 6 – Imposed load: longitudinal strain ε_{xx} =0.294

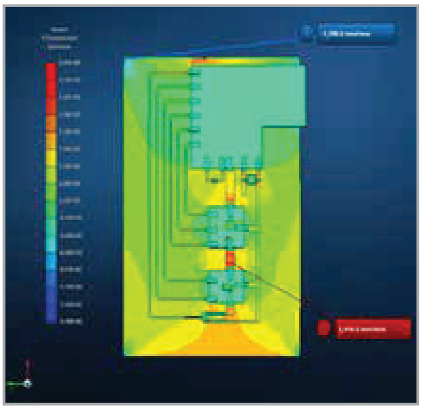
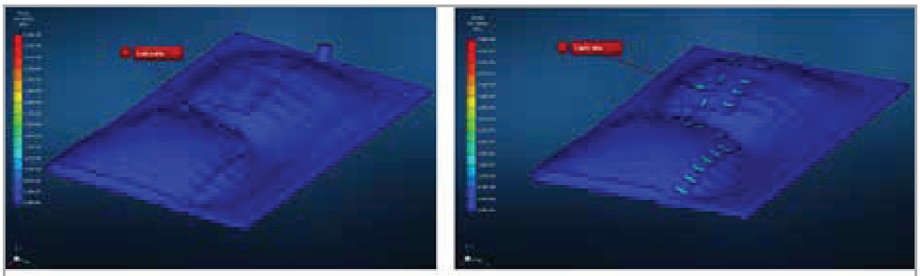
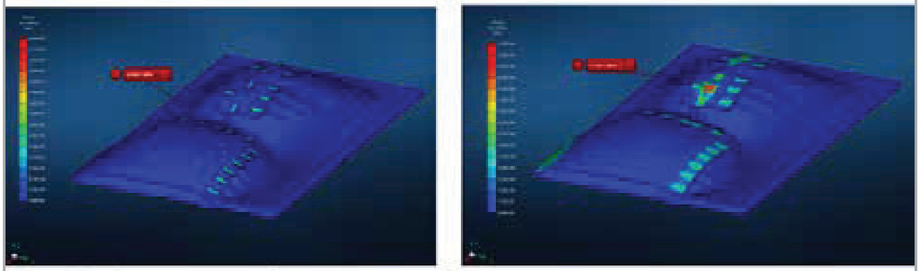


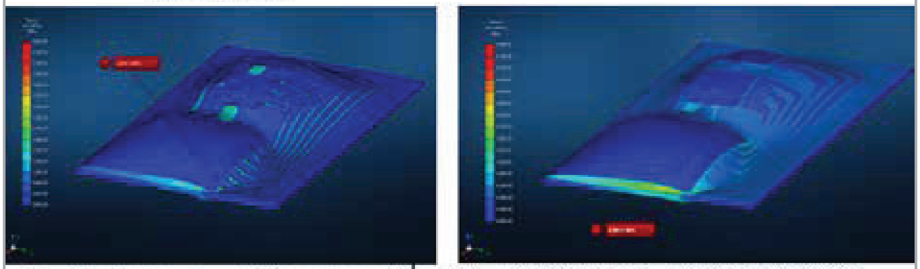
Fig. 7 – Longitudinal deformation ε_{xx}= 0.0215



a) Maximum σ_{vm} at the photodiode b) Maximum σ_{vm} at the accelerometer's chip sensor.



c) Maximum σ_{vm} at the copper connectors. d) Maximum σ_{vm} at the sensor board.



e) Maximum σ_{vm} at the connectors f) Maximum σ_{vm} at the substrate

Fig. 8 – Maximum von Mises stresses at the connections with the different components (a – f)

center of the chip sensors. Observing the longitudinal strain, the substrate also showed high values which can be explained by the fact that the different materials (i.e. substrate and rigid board) joined have different thermal properties. The PEGDA/PEDOT connectors showed $\varepsilon_{xx} = 0.0276$ in the area at the connections with the microcontroller board near the substrate edge.

One other area in the longitudinal strain map that shows criticalities is at the corner of the substrate near the microcontroller board, which is effectively the cause of the $\varepsilon_{xx} = 0.017$ strain due to the different material properties of the microcontroller board and the substrate.

Another case was evaluated using $\Delta T=50°C$ along with an imposed downward displacement of 20mm. In this case, the short edge was fixed while the other edge had the imposed displacement. This analysis confirmed the critical areas at the PEGDA/PEDOT connectors and substrate with $\varepsilon_{xx}=0.0241$ and $\varepsilon_{xx}=0.0215$, respectively. However, the stresses at the electrically conductive connectors ($\sigma_{vm}=0.18MPa$) and at the substrate ($\sigma_{vm}=0.0572MPa$) were not critical.

FE results: thermal

The thermal analysis was conducted for two single electronic components, namely the photodiode and the accelerometer, to evaluate the difference between a component mounted directly on the substrate and one mounted on a conventional electronic board.

Heat flux in the photodiode

An initial analysis was performed by applying a thermal load to the lower part of the substrate. This load started at room temperature and increased to 200°C two seconds later and was maintained at that level for 100s.

This experiment made it possible to determine a relevant transient time of 42s, which is when the photodiode reaches its critical temperature of 85°C (its operating limit). The heat flux analysis revealed that the connectors of the photodiode developed the highest heat flow, equal to 31.895W/mm^2 at 32s.

A second analysis was then performed to simulate the critical conditions for the photodiode. A temperature of 85°C was applied to the component for 5 seconds after which a heat flow analysis was performed to verify its cooling time.

The analysis time was 100s, as in the previous case. The photodiode's transient temperature is shown in Fig. 9 which illustrates that at the end of the analysis the temperature was still above 40°C.

Heat flow in the accelerometer

Similarly to the previous case, a thermal flow analysis was performed to discover the cooling time of the accelerometer and

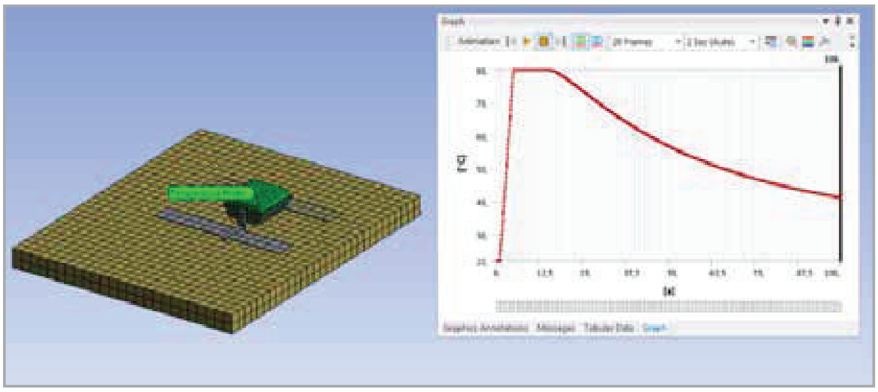


Fig. 9 – Transient temperature of the photodiode

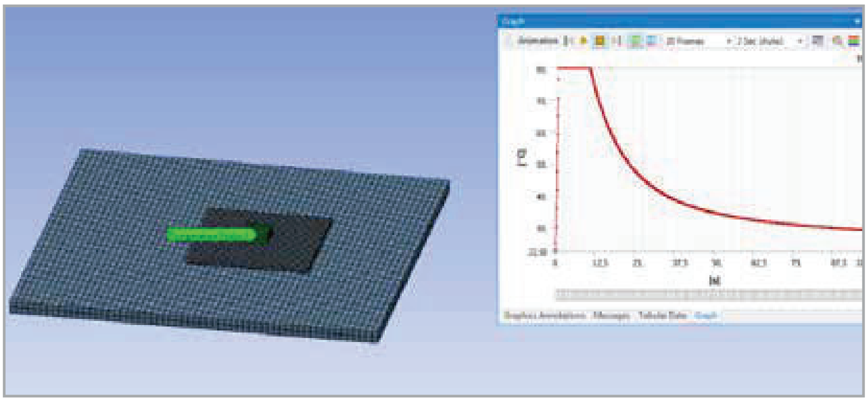


Fig. 10 – Transient temperature of the accelerometer (chip).

to understand the transient temperature from an initial critical temperature of 85°C that persists for about 10 seconds. The total simulation time was 100s. As shown in Fig. 10, the transient flow is much quicker than in the photodiode's with a steep initial gradient while the temperature reaches almost 30°C at the end of the simulation.

Comments

The mechanical analysis for an imposed displacement showed that high longitudinal strain values ($\varepsilon_{xx}=0.0311$) occurred at the PEGDA/PEDOT connectors between the temperature and pressure sensors, and in the substrate ($\varepsilon_{xx}=0.0222$) below the temperature sensor. A load imposed in the in-plane direction resulted in critical stress values in the substrate of $\sigma_{vm}=3.93$MPa at the corner of the microcontroller board near the substrate's edge, and a critical longitudinal strain ($\varepsilon_{xx}=0.294$) in the substrate near the rigid accelerometer board.

A thermal expansion analysis at different thermal loads showed that for $\Delta T=100$°C and $\Delta T=150$°C, several components had critical values while for a lower thermal load of $\Delta T=50$°C only the connectors showed high Von Mises stress values. The critical areas in this case are at the connectors between the pressure sensor and the accelerometer and the area at the corner of the rigid microcontroller board, close to the substrate board. A possible improvement could be to increase the length of the rigid microcontroller board to avoid the high stresses. The connector area, on the other hand, can be improved by modifying the dimensions of the actual connectors or by varying the thickness of the respective board and its elastic modules since it is this difference that is responsible for the deformation in this zone.

References

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[2] Stefano Romano, Sviluppo di nuovi materiali polimerici elettricamente conduttivi per stampanti 3D stereolitografiche, Tesi di Laurea magistrale, Politecnico di Torino, Marzo 2018. (Development of new electrically conductive polymer materials for stereolithographic 3D printers, Master's degree thesis, Politecnico di Torino, March 2018)
[3] MSC Nastran 2018 documentation.
[4] Ansys Mechanical User Guide 2020 R2.

A further comparison between the board-mounted sensors and the sensor mounted directly on the substrate showed a faster transient cooling time for the board-mounted sensors (accelerometer).

The FE analysis, therefore, showed that design improvements are possible, while the modelling process simultaneously demonstrated its ability to evaluate a re-design; greater accuracy can be realized once a compromise is found with computing time.

Conclusions

The study presented here demonstrated the feasibility of the flexible electronic board by evaluating its material characteristics and its functionality under thermal and mechanical loading. Heat flow and transient analyses revealed the time taken to reach the critical temperature and evaluated the component's behavior at different temperatures.

The FEA established the critical areas in certain conditions; discovered which components may have critical issues while providing suggestions to improve the design; and demonstrated modeling's ability to determine the demonstrator's behavior for the defined loading conditions.
The design modification suggestions included changing the geometry of the board to avoid the formation of critical stress in the areas identified as well as reviewing the material's properties in those areas that may otherwise cause undesirable deformations.

This study also enabled improvements to the modelling process itself to be determined, specifically how FEA's accuracy and reliability can be improved without increasing the computing time, thereby revealing greater potential for an FE approach. From a materials standpoint, feasibility was demonstrated, so this first prototype can provide a starting point for other similar flexible electronic board concepts.

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