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Experimental Study on Stress Impact during FML Manufacturing on the Functional Conformity of an Embeddable SHM-Sensor-Node †

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Abstract: Experimental studies were conducted to determine if the stresses occurring during the manufacturing process of Fiber Metal Laminates (FML) cause irreversible damage to electronic components. This is especially interesting for electronic systems to be embedded into such FML for later structural health monitoring purposes. Depending on the requirements of the used prepreg material, required temperatures and pressures for manufacturing can be quite high. First studies were conducted on electronic components separately, to validate their functionality after 3.5 h at elevated temperatures and pressures, exceeding manufacturers specifications. The functionality tests were successfully performed afterwards for every tested component, and no malfunctions could be identified. Further experiments will be conducted investigating the influence on a fully functional, programmed electronic system under the same conditions to investigate the influence on memory and soldering joints as well.

Keywords: Structural Health Monitoring; Fiber Metal Laminates; electronics; sensor node; embedded; high temperature

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1. Introduction

In recent years, FMLs have gained a lot of attention in lightweight manufacturing approaches for aeroplanes. The combination of metals and composite materials leads to new materials, uniting the good properties of both types [1]. One of the most prominent examples is the use of Glass Laminate Aluminum Reinforced Epoxy (GLARE) in various parts of the Airbus A380. The manufacturing of FMLs is usually done in an autoclave process at high pressure and temperature conditions. Even though there are approaches on using control techniques to monitor the laminate's properties during the manufacturing process to optimize the curing cycle and reduce the induced stress on the material [2], the most common way is to follow the recommended curing cycle for the prepreg material provided by the manufacturer.

The FML structures, especially those used in safety critical applications as for example an airplane fuselage, need to be inspected for cracks or delaminations inside the material stack not visible for the naked eye regularly, which can be an expensive and time consuming task. One approach to improve this process is to embed sensor nodes for Structural Health Monitoring (SHM) into the material so no large external monitoring systems would be required for inspection.

Different approaches have been made on how to embed electronics into composite materials. Ref. [3] presents an approach where cavities inside the material stack are manufactured to insert the electronic system into after part manufacturing. This is a valid approach for thicker components but not suited for thinner plate dimensions. An assembly space optimized strategy is to directly embed the sensor and even the whole sensor node into the composite layers of the FML material. Investigations in this field are provided by [4–7] for embedding single sensors into fibre composites and by [8,9] for embedding whole sensor nodes. During the embedding process of integrated whole electronic systems into fibre composites or FMLs, the electronic components will face the same conditions regarding pressure and temperature as the surrounding material for one complete curing cycle. This leads to the additional requirement to the electronic components to survive this process functionally unharmed and be ready to work again after cool down. A function verification during the embedding process itself, by supplying the sensor node with a voltage during the autoclave process, is not necessary for embedded sensor nodes that are intended to work as an SHM-system during part life. This paper investigates the ability of commercially available electronic components to survive such a high-temperature laminate curing process.

2. Materials and Methods

During FML manufacturing, the material stack is placed into an autoclave which operates as an oven, vacuum chamber, and pressure chamber at the same time. FMLs can be made using various metal and prepreg combinations and configurations, depending on their intended application. While the metal has basically no effect on the manufacturing conditions inside the autoclave, the prepreg material determines the specifications of the curing cycle to be used. Epoxy-based prepregs make up a comparably large amount of available prepregs. Therefore, a curing cycle suitable for an FML component using such material is reproduced within this investigation.

2.1. Component Preparation

The electronic components used in this study are intended to combine to an SHM sensor node later on. All components chosen have an operating temperature specified inside their data sheets between 105 °C and 125 °C. A maximum short time storing temperature is not directly specified. Therefore, it is crucial to test the components under the expected stresses, which will be inflicted on them during the embedding to ensure the satisfying function after the process. Five specimen of each component are placed onto a stainless-steel handling sheet using heat tolerant adhesive tape. To investigate possible differences in heat transfer into the component package, three pieces of each component are placed face down onto the metal, contacting the adhesive tape with the package-pins and the other two face up, pins in the air. Out of these specimen, two components of each type are additionally placed on the edge of a second smaller strip of 120 µm thick stainless steel to investigate the impact of high pressure acting on the active components as well. This is thought to replicate a pile of fibres being present beneath the component during the curing process and pressing against at one point. Figure 1 shows the schematic and actual arrangement of components for the experiment.

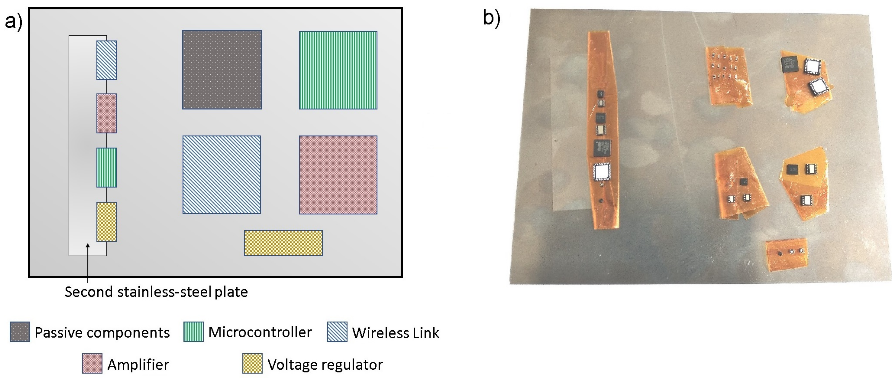

Figure 1. Components fixed on a stainless-steel plate two of each specimen fixed on the edge of another 120 µm thick plate. (**a**) Schematic placement. (**b**) Placement on the plate.

2.2. Emulated Curing Cycle

Listed below in Table 1 are different epoxy based prepregs with their maximum curing conditions to demonstrate the differences in curing based on the used material. The curing temperature and pressure recommendation is given by the manufacturer. During the curing process, the FML component itself should be placed inside a weak vacuum. The heat-up and cool-down rate are recommended by the manufacturer as well. The electronic components will be tested to withstand the maximum recommended curing conditions listed for 2 h to emulate the maximum curing stresses for most of the commercially available epoxy based prepreg materials. This way it can be safely assumed that, for lower curing recommendations, there will be even less stress acting on the electronic components and therefore less influence can be expected.

Table 1. Curing conditions for a selection of epoxy based prepregs by the manufacturer Hexcel®.

Prepreg Name	Curing Temperature	Pressure	Duration (Curing T)
HexPly® 913 [10]	125 °C–160 °C	7 bar	10–60 min
HexPly® 916 [11]	120 °C–130 °C	5 bar	30–60 min
HexPly® 922-1 [12]	165 °C–180 °C	3–5 bar	120 min
HexPly® EH25 [13]	150 °C–180 °C	3–7 bar	120–840 min
HexPly® 8552 [14]	175 °C–185 °C	7 bar	115–125 min

2.3. Pressure Control

The pressure acting on the components is controlled by a combination of a vacuum pump drawing the vacuum through the bottom connector and a pressure controller connected to the laboratory pressure port, shown in Figure 2. For this, the vacuum pump is at first connected via the pressure controller to check if the value reached is acceptable. If not, the vacuum bagging has to be controlled and adjusted. After that, the vacuum pump can be connected directly to the bottom connector and the pressure controller can be connected to the side port and programmed for the desired relative pressure value.

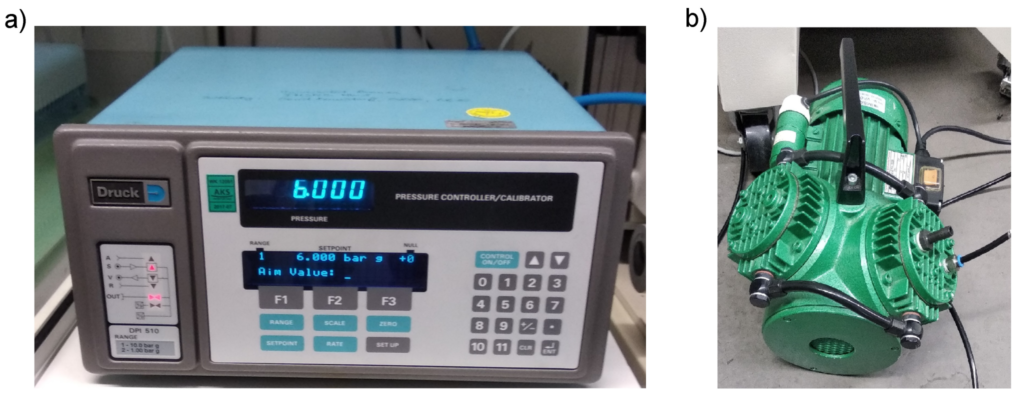

Figure 2. Pressure control equipment. (**a**) Pressure controller. (**b**) Vacuum pump.

Using this pressure chamber inside an oven provides the possibility to expose the electronic components to similar conditions that are present inside an autoclave without actually using one.

2.4. Temperature Proof Pressure Chamber

To insert the prepared components under the right amount of pressure into the oven, a suitable container is needed. Therefore, a small steel box with a gasket to seal it is prepared with two connections: One at the bottom of the box, one at a higher point on the side. The box containing the prepared components can be seen in Figure 3.

Another part of the experimental setup is a small layer of pink-transparent foil. This is a vacuum bagging film for temperatures up to 180 °C, applied to the metal surface of the pressure chamber using adhesive vacuum tape. Through the bottom connection a vacuum can be drawn, while at the same time external pressure can be applied through the side connection.

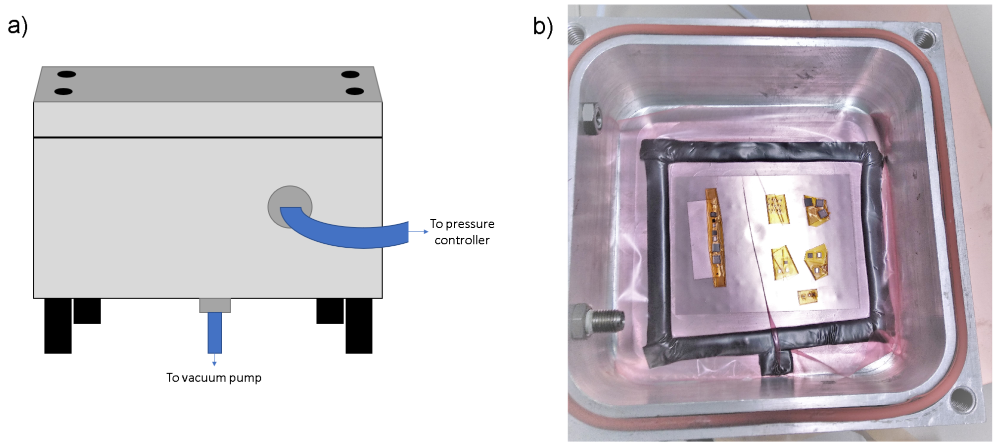

Figure 3. Steel box with gasket, inserted component test-plate and applied vacuum bagging film before insertion into the oven. (**a**) Schematic view of the pressure chamber. (**b**) Photography of the prepared chamber.

3. Results

Since the experiment is carried out without the use of an autoclave, dedicated heat-up and cool-down rates could not be controlled directly. The time it took to heat up and cool down again is measured instead. The measurement point is chosen to be inside the steel-box, next to the components, inside the vacuum bagging to record the actual temperature affecting the items under test. The temperature cycle used in this work is depicted in Figure 4 as the solid green line, as well as the minimum curing cycle recommended for HexPly® 8552, represented by the dashed black line. The components themselves are held within a medium vacuum around 0.15 bar under the vacuum bagging, and a pressure of 7 bar is applied inside the pressure chamber during the whole process.

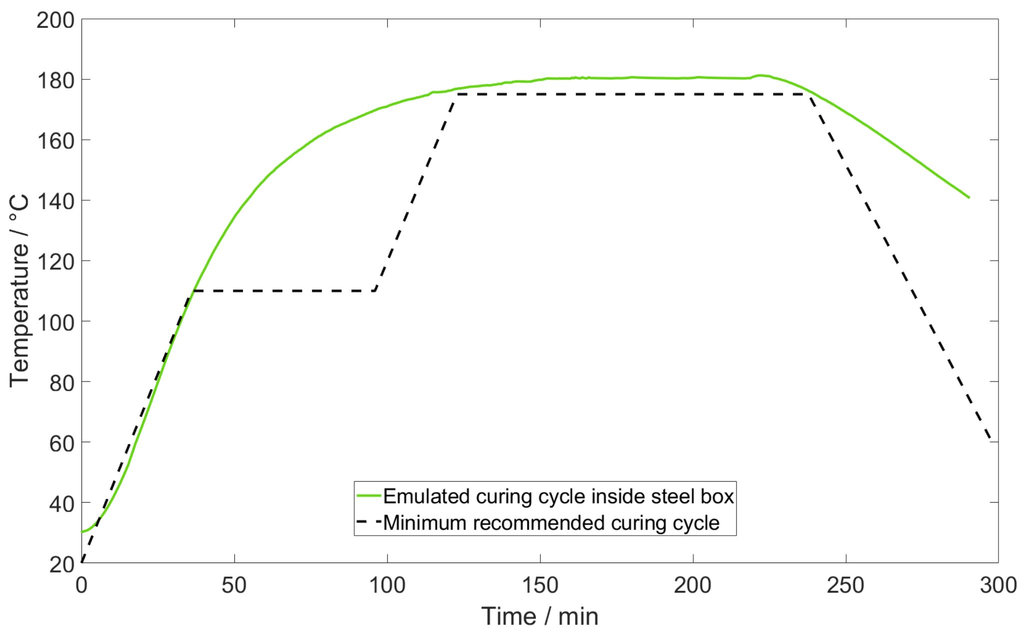

Figure 4. Curing cycle emulated to test electronic components versus recommended curing cycle.

In the recommended curing cycle, the second plateau is specified as minimum 175 °C, maximum 185 °C for at least 115 min. It can be seen that the components are exposed to the elevated temperatures, above their specification for an even longer duration than following the recommended curing cycle. The first 110 °C plateau is not held for 60 min but the steel box is further heated up instead to be able to reach the maximum temperature of 180 °C within the recommended time frame. After 190 min within the oven at an oven-temperature of 180 °C and a cool down phase down to 95 °C, corresponding 140 °C inside the steel box, the additional pressure as well as the vacuum is removed and the box is put onto a heat tolerant surface to cool down to room temperature overnight. The components are then extracted and the passive ones are measured directly, and the active components are soldered to PCBs for functionality tests. Table 2 shows the results for the measurements of the passive components before and after the experiment. It is noticeable that in case of the resistors under test, the changes in measured resistance were negligible, the changes in capacitance for the tested capacitors increase accordingly to the value of the component, but the changes are relatively small. The capacitance values measured are still within the specified range for the components.

For the active components, the differences after the experiment could not be measured directly with a significant value. The components were soldered onto PCBs to test their functionality. Inside the following list, the component types and tested functionalities for each type are listed:

- Voltage regulator: Boot process, output voltage stability over full input range
- Microcontroller: Boot process, programmability, Pin-output High/Low, ADC, I2C
- Wireless Link: Boot process, I2C, wireless readout, memory read/write
- Amplifier: Boot process, amplification at G = 20

With Analog-to-Digital Converter (ADC) functionality for measurement purposes, the Inter-Integrated Circuit (I2C) bus was used for communication on the PCB and the gain was chosen just to test the general functionality of the amplifier. The tested functions could still be executed sufficiently by every tested specimen after the experiment. Therefore, it is safe to say that all tested components survived the process and would thereby survive an embedding procedure for epoxy based prepreg FMLs with the highest temperature and pressure requirements available.

Table 2. Measurement values for tested passive components before and after the experiment as well as the percentual difference.

Passive Component	Before Experiment	After Experiment	Difference
Resistor 0402 0.1% 2 kΩ	2.003 kΩ	2.003 kΩ	0%
Resistor 0402 0.1% 2 kΩ	2.003 kΩ	2.003 kΩ	0%
Resistor 0402 0.1% 2 kΩ	2.003 kΩ	2.003 kΩ	0%
Resistor 0402 1.0% 64.9 Ω	65.6 Ω	65.4 Ω	−0.3%
Resistor 0402 1.0% 64.9 Ω	65.3 Ω	65.4 Ω	+0.2%
Resistor 0402 1.0% 64.9 Ω	65.4 Ω	65.7 Ω	+0.5%
Capacitor 0402 X7R 100 nF	93.3 nF	95.9 nF	+2.8%
Capacitor 0402 X7R 100 nF	92.6 nF	95.1 nF	+2.7%
Capacitor 0402 X7R 100 nF	94.7 nF	98.1 nF	+3.6%
Capacitor 0402 X7R 1 µF	892 nF	961 nF	+7.7%
Capacitor 0402 X7R 1 µF	827 nF	943 nF	+14.0%
Capacitor 0402 X7R 1 µF	864 nF	933 nF	+8.0%
Capacitor 0402 X7R 0.47 µF	409.8 nF	417.8 nF	+2.0%
Capacitor 0402 X7R 0.47 µF	417.2 nF	427.7 nF	+2.5%
Capacitor 0402 X7R 0.47 µF	407.4 nF	416.0 nF	+2.1%

4. Discussion and Conclusions

The aim of this work was to investigate the possibility to embed commercially available standard components within FMLs cured at up to 180 °C while regaining their full functionality after cool down. All investigated functionalities of the active components were still available and sufficiently executed and the values for passive components only changed in a negligible amount. For the high precision resistors tested, there could not even a slight difference be noticed. The results of this work clearly show that it is possible for components exposed to the comparably harsh environmental conditions that occur during FML part manufacturing to survive this process unharmed, at least in the short term. To investigate possible effects of those extraordinary conditions on the lifetime of the component, further experiments would need to be conducted.

Possible effects on the Flash and EEPROM memories programmed before this kind of test have not been performed yet. Upcoming work will investigate the influence of embedding on memory stability in an experiment where several soldered, fully functional PCBs will be tested by the same procedure as the components before. Furthermore, it is planned to increase the duration of the executed experiment as well as the tested temperature to identify the maximum possible curing conditions that embedded SHM sensor nodes can endure and probably identify a curing cycle that is not suited for commercially available electronic components anymore.

This work shows that it is generally possible to integrate commercially available components into composite materials cured using pressure and increased temperatures of up to 180 °C without component malfunctions. As the temperature exceeding manufacturers specifications in combination with increased pressure is expected to induce detrimental effects at some point, further investigations in this direction will be conducted.

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References

1. Moussavi-Torshizi, S.E.; Dariushi, S.; Sadighi, M.; Safarpour, P. A study on tensile properties of a novel fiber/metal laminates. *Mater. Sci. Eng. A* **2010**, *A527*, 4920–4925. [CrossRef]
2. Prussak, R.; Stefaniak, D.; Kappel, E.; Hühne, C.; Sinapius, M. Smart cure cycles for fiber metal laminates using embedded fiber Bragg grating sensors. *Compos. Struct.* **2019**, *203*, 252–260. [CrossRef]
3. Jang, T.S.; Oh, D.S.; Kim, J.K.; Kang, K.I.; Cha, W.H.; Rhee, S.W. Development of multi-functional composite structures with embedded electronics for space application. *Acta Astronaut.* **2011**, *68*, 240–252. [CrossRef]
4. Salas, M.; Hübner, M.; Borysov, M.; Koerdt, M.; Rennoch, M.; Herrmann, A.S.; Lang, W. Measuring Material Moisture in Fiber Reinforced Polymers by Integrated Sensors. *IEEE Sensors J.* **2018**, *18*, 3836–3843. [CrossRef]
5. Hübner, M.; Koerdt, M.; Hardi, E.; Herrmann, A.S.; Lang, W. Embedding Miniaturized Flexible Sensors for Online Monitoring of Fibre Composite Production. In Proceedings of the ECCM18—18th European Conference on Composite Materials, Athens, Greece, 25–28 June 2018.

6. Arellano, M.T.; Crouzeix, L.; Collombet, F.; Douchin, B.; Grunevald, Y.H. Mechanical Characterization of an Alternative Technique to Embed Sensors in Composite Structures: The Monitoring Patch. *Appl. Compos. Mater.* **2012**, *19*, 379–391. [CrossRef]
7. Geng, X.; Jiang, M.; Gao, L.; Wang, Q.; Jia, Y.; Sui, Q.; Jia, L.; Li, D. Sensing characteristics of FBG sensor embedded in CFRP laminate. *Measurement* **2017**, *98*, 199–204. [CrossRef]
8. Berkemeyer, F.; Lang, W. Rotor Blade Temperature Monitoring with Material Integrated Wireless Sensor Tags. In Proceedings of the IEEE 2020 Conference-Sensor and Measurement Science International, Dubrovnik, Croatia, 25–28 May 2020.
9. Klein, L. Sensor Systems for FRP Lightweight Structures: Automotive Features Based on Serial Sensor Products. *Sensors* **2019**, *19*, 3088. [CrossRef] [PubMed]
10. Hexcel Corporation. HexPly 913. 2020. Available online: https://www.hexcel.com/user_area/content_media/raw/HexPly_913_eu_DataSheet.pdf (accessed on 25 August 2021).
11. Hexcel Corporation. HexPly 916. 2020. Available online: https://www.hexcel.com/user_area/content_media/raw/HexPly_916_eu_DataSheet.pdf (accessed on 25 August 2021).
12. Hexcel Corporation. HexPly 922-1. 2020. Available online: https://www.hexcel.com/user_area/content_media/raw/HexPly_9221_eu_DataSheet(1).pdf (accessed on 25 August 2021).
13. Hexcel Corporation. HexPly EH25. 2020. Available online: https://www.hexcel.com/user_area/content_media/raw/HexPly_EH25_eu_DataSheet.pdf (accessed on 25 August 2021).
14. Hexcel Corporation. HexPly 8552. 2020. Available online: https://www.hexcel.com/user_area/content_media/raw/HexPly_8552_eu_DataSheet.pdf (accessed on 25 August 2021).