Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 1817-1826

ECCOMAS Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

INTEGRATION OF PRINTED SENSORS FOR THE FUNCTIONALIZATION OF COMPOSITE COMPONENTS

INGO WIRTH*, MARC REBILLAT†, FRÉDÉRIC LETELLIER†, MARIO KOHL*, JAN CONEN*, MARC-OLIVER BECKER*, TIM RUSCH*

*Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM)
Wiener Strasse 12, 28359 Bremen, Germany
ingo.wirth@ifam.fraunhofer.de, www.ifam.fraunhofer.de/printing

†Laboratoire Procédés et Ingénierie en Mécanique et Matériaux
- ENSAM/CNRS/CNAM -
151 Bd de l'Hôpital, 75013 Paris, France

Abstract. This paper presents the research activities in the framework of the European MORPHO H2020 project regarding the integration of sensors in composite parts using printing technologies. Printed sensors reported here are able to detect impacts on the host composite structure and to measure temperatures. For temperature measurements thermocouples type T (Cu-CuNi) were used. These type T thermocouples consist of Cu and CuNi materials, which are joined together to form a junction. When the temperature in the junction changes, a small voltage is generated by the thermocouple. This voltage can be measured and can be related to the temperature. For impact detection, printed piezoelectric sensors were implemented in carbon fiber reinforced composite materials. Piezoelectric sensors are based on piezoelectric materials. A voltage is generated when pressure is applied on the sensor or when a wave is crossing the sensor. These piezoelectric sensors are able to measure and localize an impact by measuring the time difference of the arrival of the signal from different piezoelectric sensors.

Key words: SHM, CFRP, piezoelectric sensor, thermocouples, composite structures, innovative printing technology, MORPHO H2020 project.

1 INTRODUCTION

In aviation industry, there exists an increasing demand for structural health monitoring (SHM) of carbon fiber reinforced composite materials (CFRP), which are needed for aerospace structures because of their unique stiffness to weight ratio. The challenge in such a context is to integrate smart systems in composites for lightweight constructions using different sensors without mechanically changing the structural behavior of the host structures (low weight addition and as small as possible stiffness modification) [1-2]. Innovative

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9952.442433

printing technologies allow the integration of printed sensors in composite parts and components by satisfying these criteria. For this purpose, manufacturing and integration processes of sensors in composite parts using printing technologies are investigated here. In this paper, piezoelectric sensors as well as temperature sensors were deposited directly on composite aeronautics parts representative of the aeronautic industry using screen printing and Aerosol Jet® printing technologies. As an architecture network, printed individual sensors can be connected to an overall system [3-4].

The great advantage of printing technologies is the possibility to deposit customized sensor structures directly on planar and non-planar surfaces. The usage of printing technologies results in a great accuracy, reliability, and cost reduction also in a later production process. The development of electrically conductive composites allows the deposition of conductive paths between the sensor structures on the part and finally a connection to the power supply unit. This allows for the realization of a complete sensor structure with low added weight and low influence on the host structure. The sensor technology platform itself offers a broad range of variations of piezoelectric sensor candidate architectures into manufacturing process. The printed sensor network consists of several connected piezoelectric sensors, which build a dynamical load and displacement sensitive element. To detect, localize, classify and quantify damage to CFRP parts, composite aeronautic structural elements may be monitored using data from such printed sensors [5]. This innovative sensor technology can thus be used for SHM by providing a complete and continuous observation of the whole system in the aircraft, but also in any other application area having similar requirements [6].

2 PIEZOELECTRIC SENSORS FOR IMPACT DETECTION

For impact detection piezoelectric sensors were printed on CFRP parts provided by SAFRAN in the framework of the MORPHO H2020 project. These sensors have a 3-layer structure, which consist of a bottom electrode (BE), the piezoelectric layer, and a top electrode (TE). For the electrodes silver conductive paste ESL 1901-SB was used. This silver paste is a silver-filled, flexible resin material designed for use as an electrical conductor. For the piezoelectric layers lacquer from ALGRA AG was used.

2.1 Sensor integration process using screen printing technology

Using screen printing, the silver paste is deposited on a screen and then spread by a flood bar passing over it. This flooding step fills the mesh openings of the screen with paste. In the following printing step, a squeegee overcomes the screen pressure to apply the paste onto CFRP test samples. While printing the viscosity of the paste is reduced by velocity and force of the squeegee. This thixotropic behavior of the paste is necessary for a good printability. Using this process in a first step silver bottom electrodes were printed on the test samples. After printing the silver structures were dried, before the piezoelectric paste was deposited on another screen and then also transferred by a flood bar passing over it. The following process was similar as previously described for the silver paste. After printing the piezo structures were dried, too. In a final step, the silver paste was used again to print the top electrode.

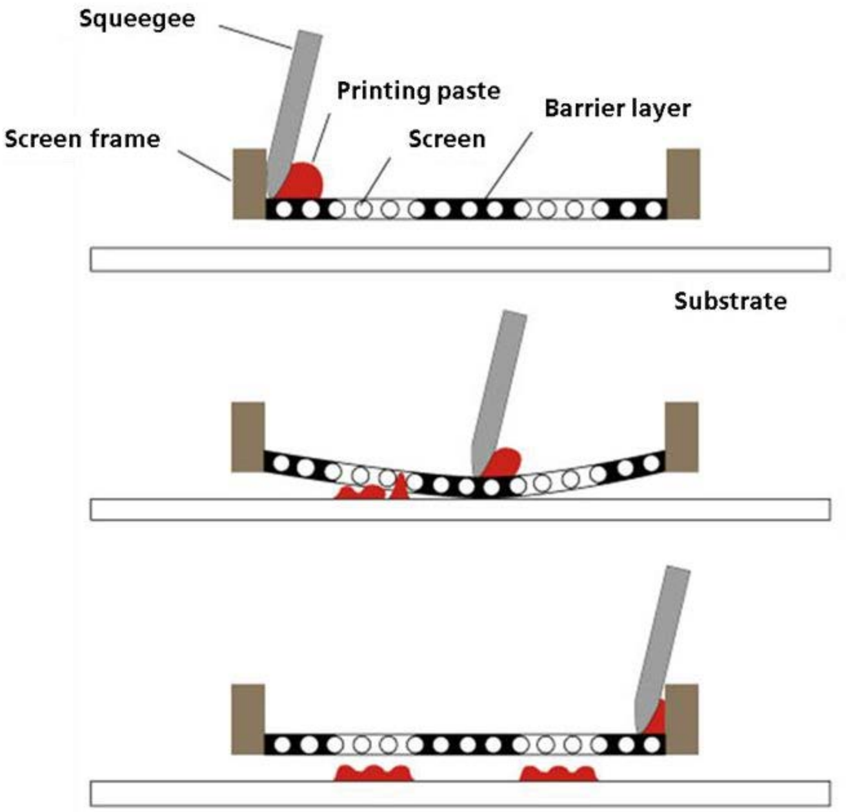

Figure 1: Schematic diagram of the screen-printing process

For each piezoelectric sensor three screens will be used with structure and interspace width of minimum 100 µm. Multilayer printing can be performed with accuracies in the range of 2 - 20 µm. Figure 1 shows a schematic diagram of the screen printing process.

All powder-filled screen-printing pastes consist of a binder system, elemental or pre-alloyed powders and further additives. Particle sizes of the used powders were in the range of 1 - 30 µm. Homogenization of the pastes was performed by a three roll mill. Screening of the right powders and the composition of the ingredients are some of the parameters, which can be varied to achieve optimized results [7-8].

2.2 Polarization of printed piezoelectric sensor structures

After printing, the piezoelectric layers are unpolarized. There is no overall piezoelectric effect because all dipoles in the piezoelectric layers are randomly oriented. For orientation and therefore polarization of the dipoles in the printed sensor structures, they were placed in an electromagnetic field [9]. This process was executed at voltages of $U = 400$ V and temperatures of $T = 100$ °C for $t = 30$ min (Figure 2).

Figure 2: Polarization of PZT sensors on CFRP test samples

Investigation of the printed piezoelectric sensors result in d = 135 µm for the piezoelectric layer thickness. Figure 3 shows such a layer thickness measurement using a Keyence VHX digital microscope. The height of the printed structure was measured along the blue line.

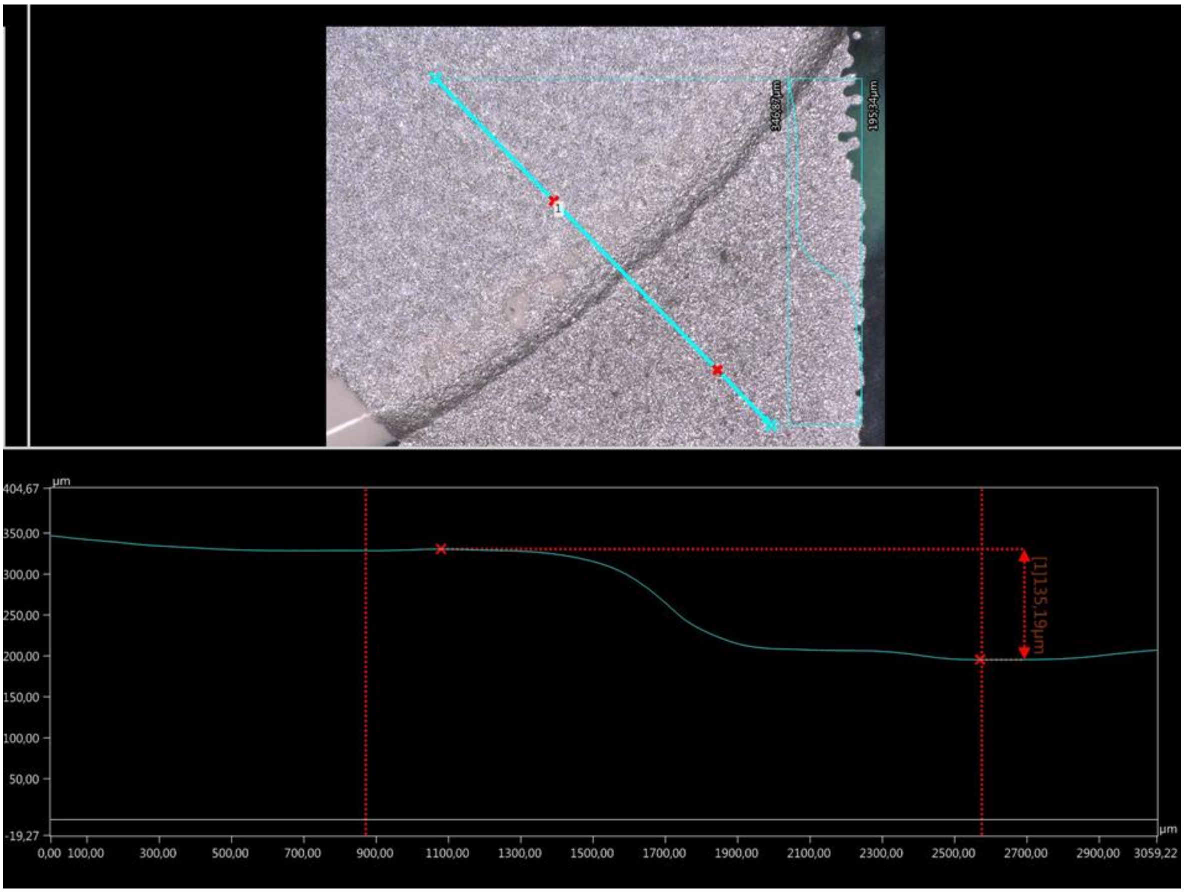

Figure 3: Investigation of layer thickness of piezoelectric layer using a Keyence VHX digital microscope

2.3 Electromechanical characterization of the printed piezoelectric sensors

After polarization, the piezoelectric sensors were characterized electrically regarding the repeatability of the printing process. Impedance measurements were performed using a HIOKI 6330 LCR-meter between 100~Hz and 100~kHz on five different piezoelectric elements printed with the same process parameters on the same composite substrate. Obtained results show that printed piezoelectric sensors were electrically capacitive, as expected, with very similar impedance measurements (Figure 4). Furthermore, the static capacities of all printed piezoelectric sensors were similar and in the range of $\simeq 2$ nF which ensures their compatibility with standard laboratory equipment.

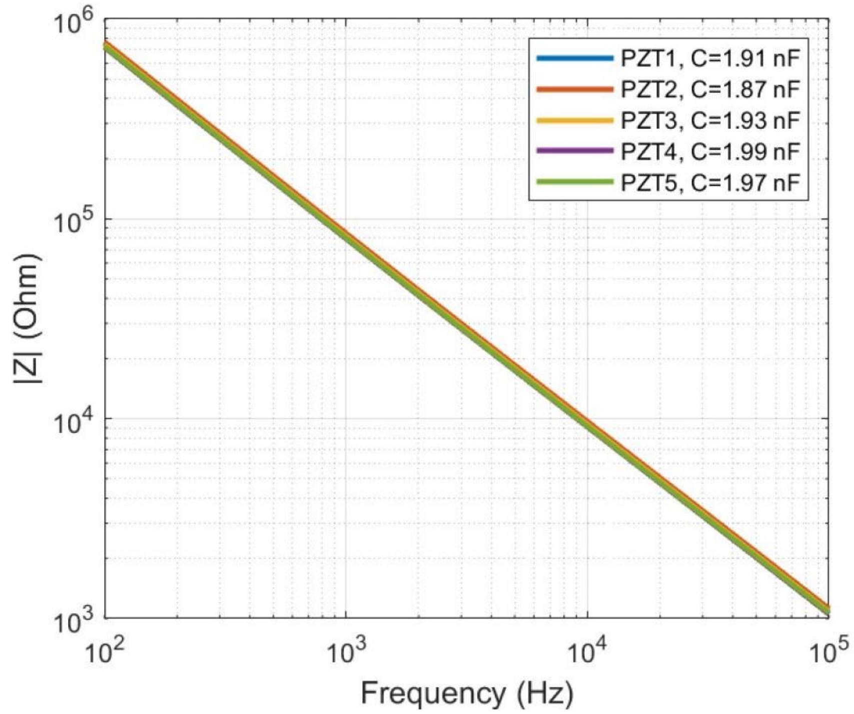

Figure 4: Variation of the modulus of the impedances with frequency measured for 5 similar printed piezoelectric elements. A good repeatability of printed piezoelectric sensors process can be observed.

The second test that has been carried out is related to the electromechanical sensitivity of the printed piezoelectric elements. When an impact occurs on the host structure, it generates propagating waves within the structure, that will produce a dynamical pulse on the sensors and thus result in a measurable voltage. Sensor signals as a result of an impact detection with marbles are shown to be as large U = 2 V (Figure 5). Using a hammer sensor signals up to U = 6 V can be achieved. It can thus be concluded that these sensors work successfully for impact detection.

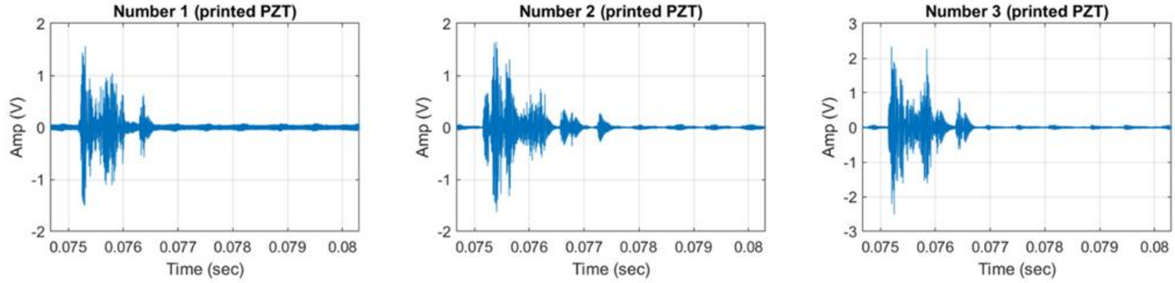

Figure 5: PZT sensor signals / impact detection on CFRP test samples

Impacts can be detected and localized by measuring the time difference of the arrival of the signal from different printed piezoelectric sensors. Figure 6 shows a possible arrangement of piezoelectric sensors for local impact detection of a glass fiber composite (GFK) sample. An experimental campaign is currently underway in order to demonstrate the feasibility of such an approach. However, given the amplitudes of the recorded signals, there is no doubt that it will be successful.

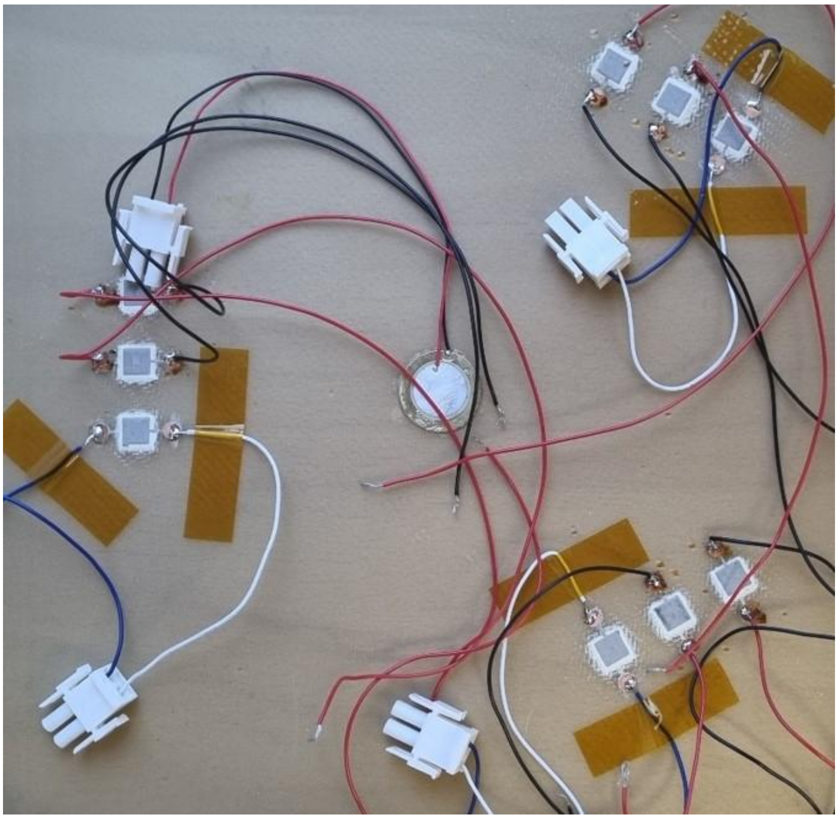

Figure 6: Piezoelectric sensors on GFK sample

3 PRINTED THERMOCOUPLES FOR TEMPERATURE MEASUREMENTS

3.1 Integration process using Aerosol Jet Printing technology

Aerosol Jet® Printing process was used to integrate temperature sensors in CFRP test samples. It allows a high-resolution deposition of nanoscaled suspensions using aerodynamic focusing. To achieve this, the Aerosol Jet® system consists of two modules: A module for aerosol generation from liquid and colloidal suspensions and a module for aerosol focusing and droplet deposition in the printhead. The aerosol is generated using a pneumatic nebulizer. After generation, the aerosol stream is focused using a flow guidance deposition head which forms a co-axial flow between the aerosol stream and a sheath gas stream (Figure 7). For the sheath gas stream, nitrogen is used, because it is a relatively cheap inert gas. Due to the co-axial flow, the sheath gas stream prevents contact of the aerosol stream with the inner cladding of the printhead nozzle. In the printhead, the aerosol stream, which consists of many single droplets in the femtoliter range, is focused down to as small as a tenth of the nozzle diameter [10-13].

Using a nozzle diameter of 200 µm, Cu and CuNi nanoscaled inks were applied to integrated Cu/CuNi-thermocouples on CFRP test samples. The aerosol was deposited on the CFRP test samples by moving the printing module relative to the substrate surface.

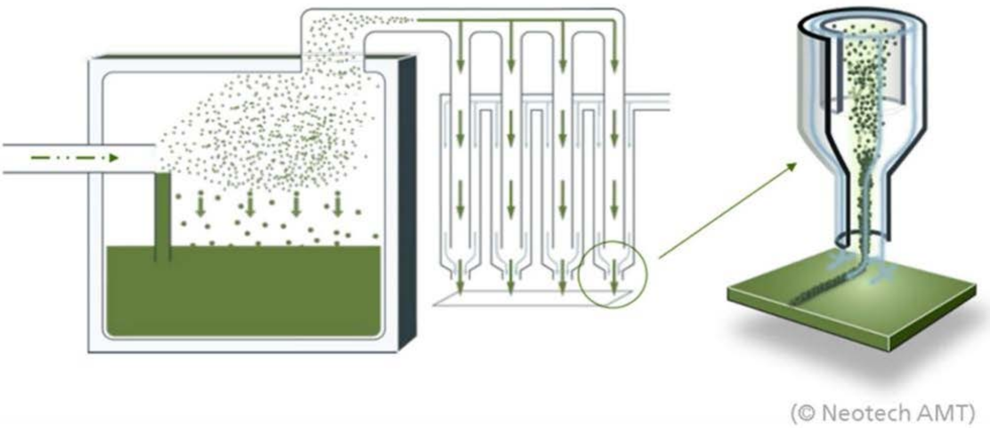

Figure 7: Aerosol Jet® printing process

For application of Cu/CuNi-thermocouples on the CFRP test samples CuNi nanoparticle ink was used. This ink was developed at IFAM and contains nanoparticles in diethylene glycol (DEG) [14-15]. Cu ink with nanoparticles is commercially available from NovaCentrix. Electrically conductive tracks were applied using commercial available Ag ink from Advanced Nano Products (ANP).

Temperature sensors (Cu/CuNi-thermocouples) were printed on CFRP test samples using Cu and CuNi nanoparticle inks (Figure 8). Sensors could be embedded using a lacquer coating, which was sprayed on the surface.

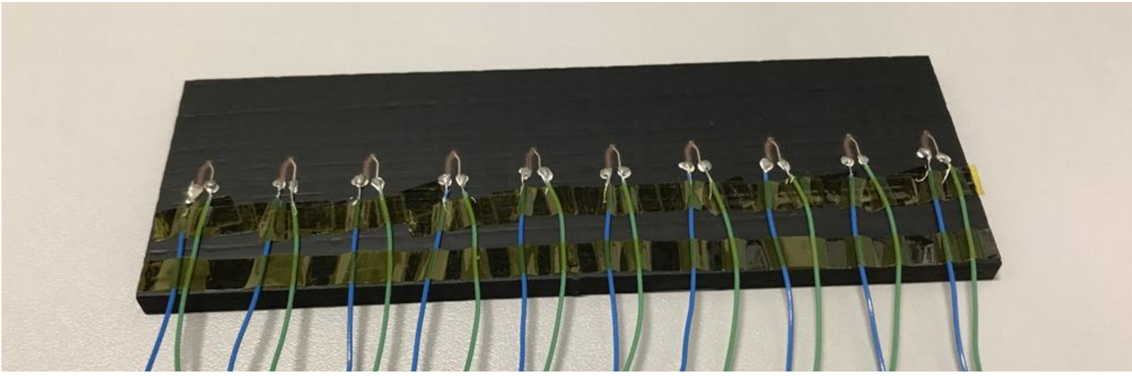

Figure 8: Printed temperature sensors (Cu/CuNi-thermocouples) on CFRP test samples

3.2 Photonic sintering of printed temperature sensor structures

After printing, temperature sensor structures were sintered using a photonic sintering process. This sintering process allows a selective sintering of metallic nanoparticles. Therefore, sintering on temperature sensitive substrates is also possible. The sintering process expulses the solvent and ink additives. Furthermore, photonic sintering process is a fast, scalable and embeddable process.

3.3 Characterization

Printed thermocouples were put in a temperature controlled oven with an additional type K reference thermocouple. Temperature ramps from T = 10 °C to 80 °C and then from T = 80 °C to 10 °C were measured. Results are shown in Figure 9. It can be seen from this figure, that printed Cu/CuNi-thermocouples work fine as typical type T thermoelements without any additional calibration.

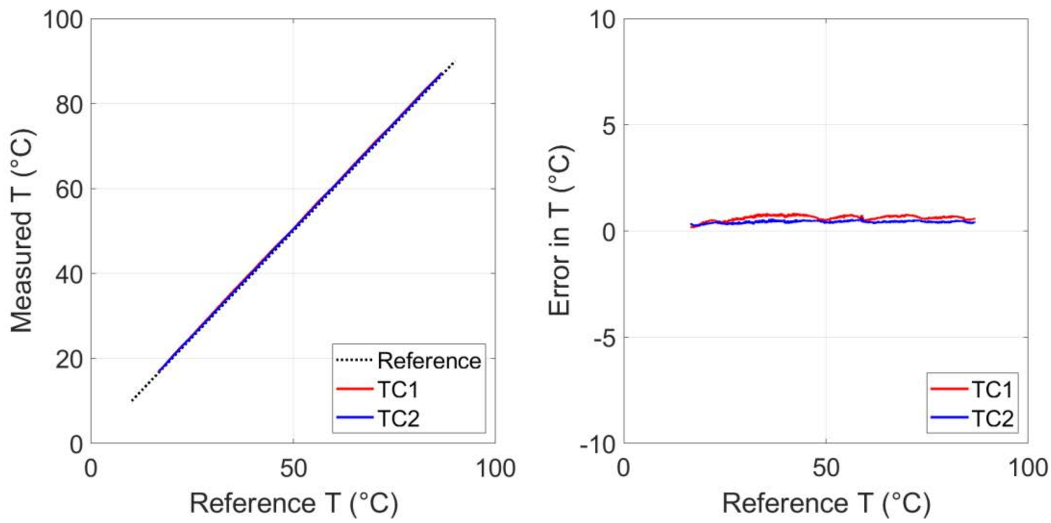

Figure 9: Printed temperature sensors (Cu/CuNi-thermocouples) temperature measurements in comparison with a reference type K thermocouple.

4 CONCLUSIONS

Printed piezoelectric sensors have a variety of potential uses in aeronautics. These sensors can be used to detect and monitor structural deformation, damage, or fatigue in aircrafts, helping to ensure the safety and reliability of the aircraft. Furthermore, it can be used to monitor the vibration of aircraft engines, providing early warning of potential issues and helping to prevent costly engine failures. Even printed piezoelectric sensors can be used in the surface control of aircraft such as flaps, ailerons and elevators for impact detection. Printed temperature sensors are able to monitor temperature changes even in inaccessible places in engines [16]. Overall, the use of printed piezoelectric sensors in aeronautics can help to improve the safety, efficiency, and performance of aircrafts.

5 ACKNOWLEDGEMENTS

The research leading to these results is part of the MORPHO (Manufacturing, Overhaul, Repair for Prognosis Health Overreach) project and has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101006854. MORPHO aims to support the development of intelligent aerospace parts with cognitive capabilities and to optimize their manufacturing and life cycle management.

REFERENCES

[1] H. Hua, Z. Zhang, H. Feng, "Research Status and Method of Aviation Sensor Performance Evaluation", *Journal of Physics: Conference Series* (2021) 1769 012050

[2] Y. Hai, C. Li, Y.Q. Shang, "Research status and development trend of aviation sensor performance evaluation", *Metrology & Measurement Technology* (2020) 40, 2, 1-6.

[3] J.B. Xu, G.P. Liang, J.S. Xu, "Application progress of wireless sensor network technology in aviation field", *Industrial Control Computer* (2018) 31, 1, 75-77.

[4] J.S. Wang, X.Z. Chi, "Development and trend of special sensors", *Measurement Technology* (2019) 39, 4, 57-63.

[5] N. Yue, A. Broer, W. Briand, M. Rèbillat, T. Loutas et D. Zarouchas, "Assessing stiffness degradation of stiffened composite panels in post-buckling compression-compression fatigue using guides waves", *Composite Structures* (2022) 293, 115751.

[6] R. Yang, Y. Rui, M.Y. Xu, et al., "Optimization of Aviation Wireless Sensor Network based on Discrete Cuckoo Search Algorithm", *Materials Science and Engineering* (2020) 926, 1, 021-025.

[7] N. Zavanelli, W.H. Yeo, "Advances in Screen Printing of Conductive Nanomaterials for Stretchable Electronics", *ACS Omega* (2021) 6, 9344-9351.

[8] D.E. Riemer, “The Theoretical Fundamentals of the Screen Printing Process”, *Microelectronics International* (1989).

[9] S.J. Kim, C.Y. Kang, J.W. Choi, D.Y. Kim, M.Y, Sung, H.J. Kim, S.J. Yoon, “Properties of piezoelectric actuator on silicon membrane, prepared by screen printing method”, *Materials Chemistry and Physics* (2005) 90, 2-3, 401-404.

[10] V. Zöllmer, M. Müller, M. Renn, M. Busse, I. Wirth, D. Godlinski, M. Kardos, “Printing with aerosols”, European Coating Journal 7-8 (2006) 46-50.

[11] I. Grunwald, E. Groth, I. Wirth, J. Schumacher, M. Maiwald, V. Zoellmer, M. Busse, “Surface biofunctionalization and production of miniaturized sensor structures using aerosol printing technologies”, Biofabrication 2 (2010) 014106/014101–014106/014111.

[12] V. Zöllmer, E. Pál, M. Maiwald, C. Werner, D. Godlinski, D. Lehmhus, I. Wirth, M. Busse, “Functional materials for printed sensor structures”, 1st Joint International Symposium on System-Integrated Intelligence (2012) New Challenges for Product and Production Engineering.

[13] M. Maiwald, C.Werner, V. Zöllmer, M. Busse, “INKtelligent printing® for sensor application”, Sensors Review (2010) 30, 19-23.

[14] E. Pál, R. Kun, C. Schulze, V. Zöllmer, D. Lehmhus, M. Bäumer, M. Busse, “Composition-dependent sintering behaviour of chemically synthesised CuNi nanoparticles and their application in aerosol printing for preparation of conductive microstructures”, *Colloid Polym. Sci.* (2012).

[15] E. Pal, V. Zöllmer, D. Lehmhus, M. Busse, “Synthesis of Cu0.55Ni0.44Mn0.01 alloy nanoparticles by solution combustion method and their application in aerosol printing”, Colloids and Surfaces A: Physicochem. Eng. Aspects (2011) 384, 661-667.

[16] R. Gorges, W. Bisgrove, R. Curtis, J. Carter, J. W. George, J. Ritchie, I. Wirth, V. Zöllmer, T. Rusch, “Integration of Printed Sensors in Plain Engine Bearings”, Proceedings of the ASME 2018 Internal Combustion Engine Division Fall Technical Conference (2018).