Smart Wall Pipes and ducts (SWaP)

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ABSTRACT

Freedom of design, complex shapes, on demand production are a few of the new possibilities that additive manufacturing is providing for many applications/fields. In particular, the field of thermal management systems is requiring more complex geometries to meet the increasing demands on thermal budgets. However, as systems become more complex so too does the measurement of fluid properties. Here, Smart Wall Pipes and ducts (SWaP) has developed revolutionary components with integrated sensing capabilities, which have been created solely by 3D printing techniques, to measure fundamental fluids properties of circulating fluids where the results are comparable to that of commercially available sensors.

Keywords: Embedded sensors; 3D printed sensors; additive manufacturing

1. INTRODUCTION

Thermal management is becoming ever more important due to increasing application demands in fields such as manufacturing (injection moulds, tooling stamps), automotive (batteries, electric motors), and aerospace (engines, shielding). To meet these demanding thermal requirements, Additive Manufacturing (AM) is being used to create parts with increased complexity to allow for more design freedom and, ultimately, more efficient thermal management. However, as the part complexity increases so too does the measurement of fundamental fluid parameters of thermal management systems. This intersection of part complexity and measurement of fluid parameters for thermal management systems, specifically hydraulic circuits used in cooling systems, is where the project focus of Smart Wall Pipes and ducts (SWaP) lies.

For SWaP, the breakthrough character and aim of the project's initial phase is the combination of advanced manufacturing methods, in the form of Selective Laser Melting (SLM) and AerosolJet Printing (AJP), to create a new generation of smart fluidic elements for cooling systems. These smart fluidic elements are designed with the following attributes:

- Compatibility with existing standard hydraulic circuits.
- Capability to sense fundamental fluidic properties.
- Negligible addition of mass and volume to the cooling system while being a single component part produced at an affordable cost.
- Direct integration in the fluid flow to allow for multiple measurement points of fluid properties in the cooling system.

The major results obtained thus far in SWaP have been quite significant in that the pipe has been successfully produced by SLM with hydraulic and electrical connectors as well as embedded resistive thermal detectors (RTDs) from AJP. The smart fluidic element has been successfully tested in hydraulic circuits for cooling system applications where leak-free integration in a piping system with circulating fluids has been achieved. Temperature measurements from the embedded sensors have been successfully recorded and the results were comparable to that of commercial RTDs, e.g. Pt100. The printed RTDs have shown linear responses, positive resistance-temperature relationships, and reproducibility.

2. STATE OF THE ART

The inspiration of SWaP was derived from the limitations and difficulties of directly measuring fluid properties in a hydraulic circuit of a cooling system with existing methods. Sensing properties such as temperature, pressure, and flow rate of circulating fluids are of utmost importance for the operation and the monitoring of a cooling system. Ideally, these measurements should be performed directly in the fluid flow with sensors directly in contact with the fluid. In practice, this approach cannot always be applied due to hard to reach measurement areas, lack of space, and limitations of total mass to the system.

Current cooling systems at CERN are using sensors located on the outer surface of a pipe as well as integrated to the inner surface of the pipe. The process of sensor integration requires modification of both the sensor and the piping system and extra materials/components, which add mass and volume to the system at a higher risk of leaks due to the use of additional fittings. Finally, the size of the component to be integrated into the piping system limits the number and the position of the sensors that can be used for the cooling system.

To address the shortcomings of integrating electrically connected devices into complex parts, CSEM has recently developed a method to produce a 3D metal part with embedded electrical wires[1], which is opening a new approach to add sensors and actuators to demanding systems. This method relies on SLM, a 3D printing technology to realize complex metal parts. Typical methods to insert sensors on 3D printed metal parts are based on placing the sensor during or after fabrication along with the corresponding electrical connections where the main challenges are typically linked to 1) the temperature of the SLM process, 2) the surface roughness, and 3) the complexity to connect the sensors or to create the sensor connections during the fabrication process.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In SWaP, we propose to combine different AM methods to achieve a generic (as it may be applied to any market) manufacturing technology to produce 3D metal components (here a pipe for hydraulic circuits in a cooling system) with embedded sensors. The process is relying on the combination of 1) SLM to produce the metal parts, embedded wiring, and external electrical connectors, 2) casting of an insulation layer to electrically insulate the substrate, and 3) the deposition of the sensors by AJP.

The advantage to combine these AM technologies together is the freedom of design to allow for the fabrication of complex shapes (such as embedded channels), weight reduction (to reduce material and energy consumption as well as to improve ease of handling or simplification of support structures), and a reduction of assembly steps (lifetime improvement).

AM technologies are also interesting because of the quick turnaround time to produce a component, reducing the time to market for a new component as 3D printers only require a design file and no complex tooling such as moulds. The production does not require highly complex infrastructures, like CMOS and MEMS foundries, meaning it could be used in any country with a minimal infrastructure investment. Even if AM is capable to produce new components in a short time, AM is not suited to achieve high volume and low-cost production but is more aimed at addressing small to mid-scale volumes of complex parts with high added value.

4. PROJECT RESULTS

To create the smart fluidic devices, the fabrication relies on the combination of different advanced manufacturing technologies with the following steps:

- Design of the smart pipe and generation of the printing file.
- Fabrication of the pipe, the electrical wires, electrical connectors, and fluidic interfaces by SLM by locally melting a powder layer with a laser and repeating this process until the part is finished. After complete removal of the un-melted powder, an insulation layer, consisting of a UV curable epoxy, is cast around the electrical wires to hold the wires in position as well as to create an electrical insulation layer on the inside of the cavity where the RTD is printed.
- The pipes are removed from the build platform by wire saw cutting and supporting materials are removed. To reduce the leakage of the fluidic interfaces, the parts are electropolished.
- Finally, after a thermal treatment of the UV curable epoxy, the RTD is deposited by AJP using a silver-based nanoparticle ink. A thermal treatment is performed to sinter the nanoparticles together to provide an electrical connection.

The fabricated pipe with integrated RTD sensor is depicted in **Fig. 1.**

The completed SLM pipe with hydraulic and electrical connectors and embedded sensors was connected to a hydraulic circuit that is used in a test setup for cooling applications and where temperature measurements of the fluid are performed. The aim was to validate SWaP's technology and for comparison purposes to that of the current method. Before the test begins in the hydraulic circuit, the leak rate of the SLM part was determined and the characterization of the embedded temperature sensor, e.g. thermal cycling, was performed

To ensure the tightness of the SLM pipe as well as that of the entire hydraulic circuit, leak tests with helium and carbon dioxide (CO_2) were performed. The hydraulic circuit was first connected to the helium leak detector where air was removed from inside the pipe by vacuum and helium was then dispersed on the outer surface of the hydraulic circuit. The detector measures the flow of helium penetrating the part. Afterwards, the pipe was filled with CO_2, in gas state, at a maximum pressure of 10 bar. A CO_2 sniffer was used to detect any leaks. Both tests resulted in a very low leak rate ($< 2 \times 10^{-10}$mbar·L·s^{-1}) which is within the permissible range for hydraulic circuits.

Thermal cycling tests were performed and concentrated on the printed RTD response under continuous and repeated temperature changes for different ranges. The pipes were placed in a climatic chamber where each cycle was started at a temperature of +5°C, decreased to a temperature of -15°C, and increased again to +5°C, with a ramp rate of 2°C/min. and a total number of ten cycles. During the thermal cycling test, resistance measurements with the AJP patterned sensors were collected with respect to temperature. The results are presented in **Fig. 2.** The resistance of the AJP printed sensor increased with increasing

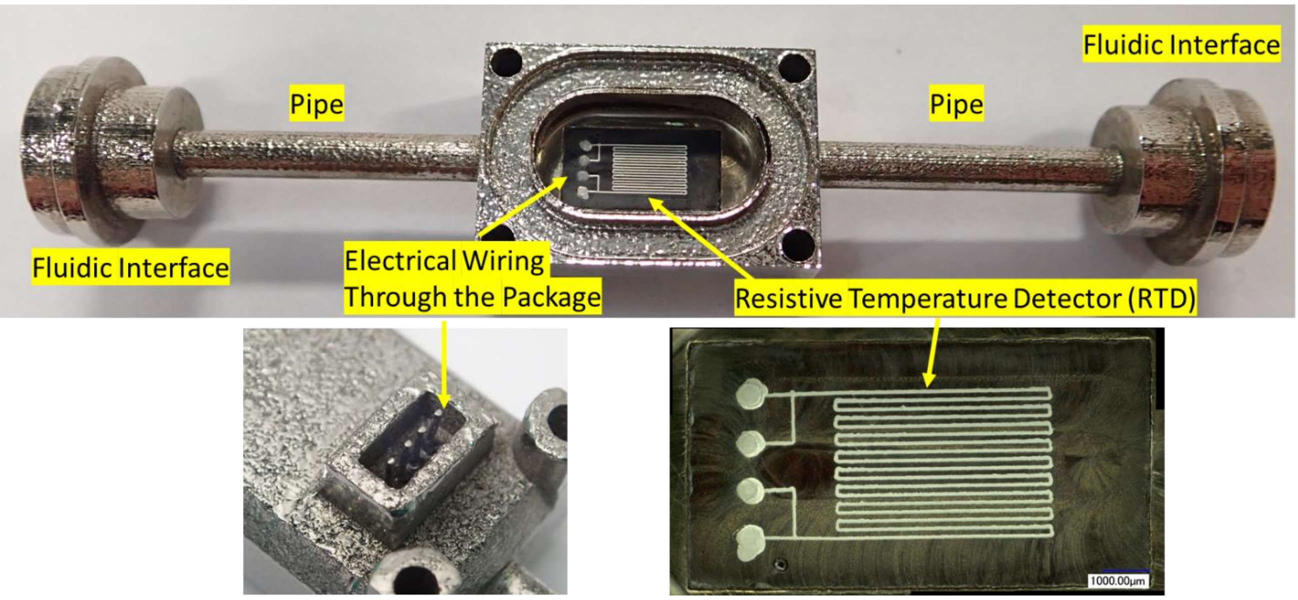

Fig. 1. AM constructed pipe from SLM with AJP patterned RTD embedded.

temperature and near linear behaviour to temperature changes and was repeatable for many of the cycles.

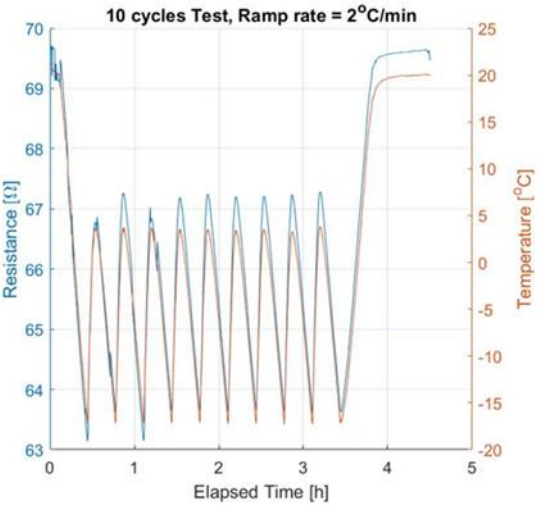

Fig. 2. Thermal cycling results for AJP patterned RTD sensors.

Calibration of the printed RTD sensor was then performed by connecting the pipe to a hydraulic circuit that is used in a test setup for cooling applications. The hydraulic circuit (**Fig. 3.**) was assembled with standard materials (pipe, connectors, fittings, commercial sensors) and consisted of:

- Two temperature sensors attached to the outer surface of the pipe (TS1, TS2).
- Two temperature sensors integrated inside a PEEK tube embedded in a tee union (Probe1, Probe2).
- The pipe (SLM Pipe) with the embedded AJP patterned RTD in the pipe wall.

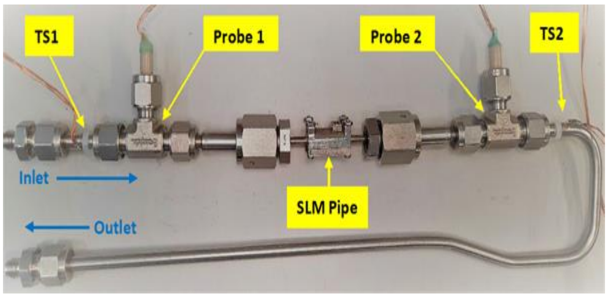

Fig. 3. Hydraulic circuit incorporating SLM pipe with RTD sensors.

The circuit is placed inside the vacuum chamber; the mass flow and the pressure of the coolant, liquid C6F14, were controlled by a flowmeter. Temperature measurements were performed using commercial RTDs at four different points along the hydraulic circuit: 1) before the SLM part, 2) inside the wall of the SLM pipe, 3) after the SLM part, and 4) on the outer surface of piping. Resistance measurements were performed on the AJP patterned RTD sensor for different temperatures to calculate the temperature coefficients of the embedded RTD sensor. Applying the following polynomial equation to the acquired temperature-resistance data:

$$T(R) = a + bR$$
$$a = -405.9, b = 6.169$$

the obtained calibration curve line is shown in **Fig. 4.** with the corresponding Positive Temperature Coefficients (PTCs).

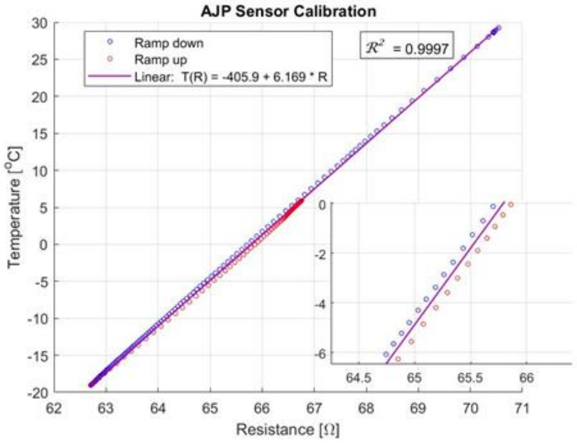

Fig. 4. Hydraulic circuit incorporating SLM pipe with RTD sensors.

The AJP patterned sensor presented a linear behaviour. The common for most of the sensors effect of hysteresis is illustrated for a data area inside the plot. The low hysteresis of the AJP patterned RTDs is an indicator that such sensors provide reliable measurements.

The validity of the calibration curve obtained in **Fig. 4.** was verified by an additional test with the C6F14 coolant where temperature measurements were recorded with the AJP patterned RTD sensor as well as two commercially available RTD sensors (Pt100). The AJP patterned RTD sensor behaviour observed in **Fig. 5.** was near identical to the commercial RTD sensors of Probe1 and Probe2.

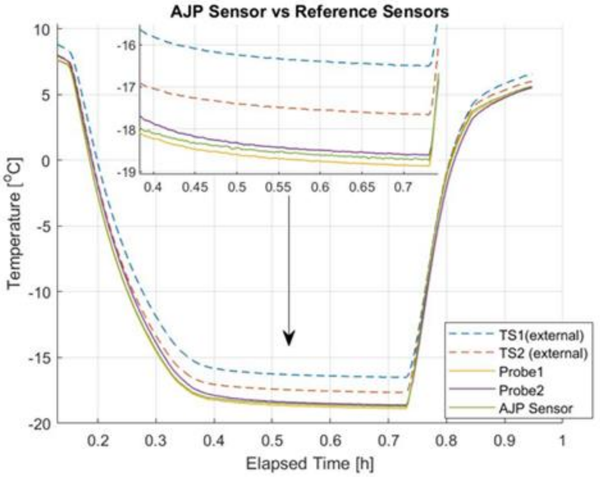

Fig. 5. Comparison of AJP patterned RTD sensor to that of commercially available Pt100 RTD sensors.

The AJP patterned RTD temperature measurement lies between the temperatures measured for Probe1 and Probe2. Considering the position of the different sensors along the hydraulic circuit, the result was sensible. However, an offset between the temperature values taken by the embedded sensors and by the two external sensors was observed. This proves the importance of placing sensors as close as possible to a fluid to have a more accurate monitoring of system conditions.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

At the end of the ATTRACT Phase 1, a TRL of 3 was achieved. To reach a TRL of 5 to 7 in ATTRACT Phase 2, the main steps will be linked to 1) use of more robust and thermally stable electrical insulation layer around the electrical pins, ideally a ceramic based material, 2) a reliability study to determine the operating range and lifetime of the fabricated devices, and 3) extension to additional sensor types, particularly to pressure and flow sensors.

5.2. Project Synergies and Outreach

To reinforce the consortium, the following competencies, through partnerships, will need to be added:

- Development of an insulation material from polymers, ceramics, or composites with coefficient of thermal expansion (CTE) <15ppm, temperature stability > 250°C, and UV curable.
- Simulation and design of pressure and flow sensors compatible with the technology developed in ATTRACT Phase 1.
- Readout electronics for the various sensors.
- Software interface to display the measured flow parameters/values in a practical way.
- 1 or 2 additional use cases for thermal management systems.

The ATTRACT Phase 1 work was dedicated to the technology development with results obtained in the latter part of the project, limiting the possibility to disseminate the results. In ATTRACT Phase 2, we believe that the technology is now capable to produce sensors in various 3D printed parts and that we will be able to generate an important volume of results that can be disseminated through journal papers, conferences, and social networks. Showing additional use cases will also reinforce the capability to disseminate the results.

5.3. Technology application and demonstration cases

SWaP's initial idea was to create new smart fluid measurement possibilities in cooling systems. A key application is to target the cooling systems used in silicon tracker detectors at CERN. All particle detectors are using millions of silicon electronic sensors. These electronics and read-out equipment generate significant heat, which must be reduced to avoid thermal runaway and uncontrolled annealing. Regarding the specifications required on such applications, where the space is limited and the monitoring of the system is of high importance, SWaP's technology contributes to and improves such systems by its ability to design smart, accurate, and small-scale components with embedded sensing capabilities.

Taking advantage of 3D printing technologies, SWaP can find applications in various fields due to the ability to produce on demand products to fit applications individually. The aim is either to improve existing systems or to create new smart sustainable systems while being conscience of industrial and societal challenges. Some example applications are listed below:

- Pipe segments in cooling plants with embedded measurement of refrigerant temperature, pressure, and flow rate.
- Chemical synthesis with multiple reactors.
- Fuel injection systems (monitoring pressure and temperature among multiple injectors, control of fuel pump efficiency).
- Aerospace piping systems (water, fuel, coolant).

5.4. Technology commercialization

The commercialization of the technology would preferentially be performed through a technology transfer with a company current producing thermal management systems.

As other fields are also interested by the capability to produce 3D metal parts with embedded sensors, a start-up could also be envisioned.

5.5. Envisioned risks

Even though AM is currently being used in production, the SWaP technology is consisting of a combination of technologies and materials, therefore the main envisioned risks are:

- Insulation material: the chosen insulation material needs to withstand the pressure and the temperature seen by the pipe without causing leaks. The properties of the insulation material should be maintained during the lifetime of the thermal management system. The envisioned material will be carefully chosen on compatibility with the pipe material, e.g. CTE.
- Sensor sensitivity and range: the current temperature sensors and future pressure and flow sensors should be able to reach targeted specifications in terms of sensitivity and measurement range. Through a combination of simulation and material testing, the mitigation of this risk shall be minimized.

5.6. Liaison with Student Teams and Socio-Economic Study

In the frame of ATTRACT Phase 1, IdeaSquare at CERN has contributed to SWaP by bringing us in contact with a Master of Science (MSc) student team from Aalto University in Finland, in the frame of a “Capstone in Sustainability” course. The student's work concentrated on finding real life applications of SWaP, which are aligned to Sustainable Development Goals (SDGs) and evaluating the societal impact of this technology. After brainstorming and workshops, the team brought several application examples for SWaP's technology and found several relevant company profiles in Finland. These applications included fields such as hydroponics, aquaculture systems, pipe leakage detection devices, and atmospheric gas monitoring.

Our plan for enabling such activities in ATTRACT Phase 2 is based on our collaboration with IdeaSquare that is successfully running the Challenge Based Innovation (CBI) program. Together with the IS and KT group, IdeaSquare could support our participation in such programs by hosting several such activities and workshops. Then, a person that is responsible for this position and who liaises with the student teams, will be allocated by the consortium.

Our impression on socio-economic aspects regarding the management, the process of establishing connections with industry and companies, the resources and the assignments of this project can be provided and discussed by conducting interviews, as a contribution to the study.

6. ACKNOWLEDGEMENT

This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222. CSEM would like to thank the Swiss Confederation for financial support. CERN would like to thank that team at IdeaSquare; Dr. Markus Nordberg, Head of Resources Development, Development and Innovation Unit (IPT-DI) for his support and for the collaboration with the MSc student team from Aalto University. Dr. Pablo Garcia Tello, Section Head of the Development of EU Projects & Initiatives for his advices and guidance in various aspects of SWaP.

7. REFERENCES

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