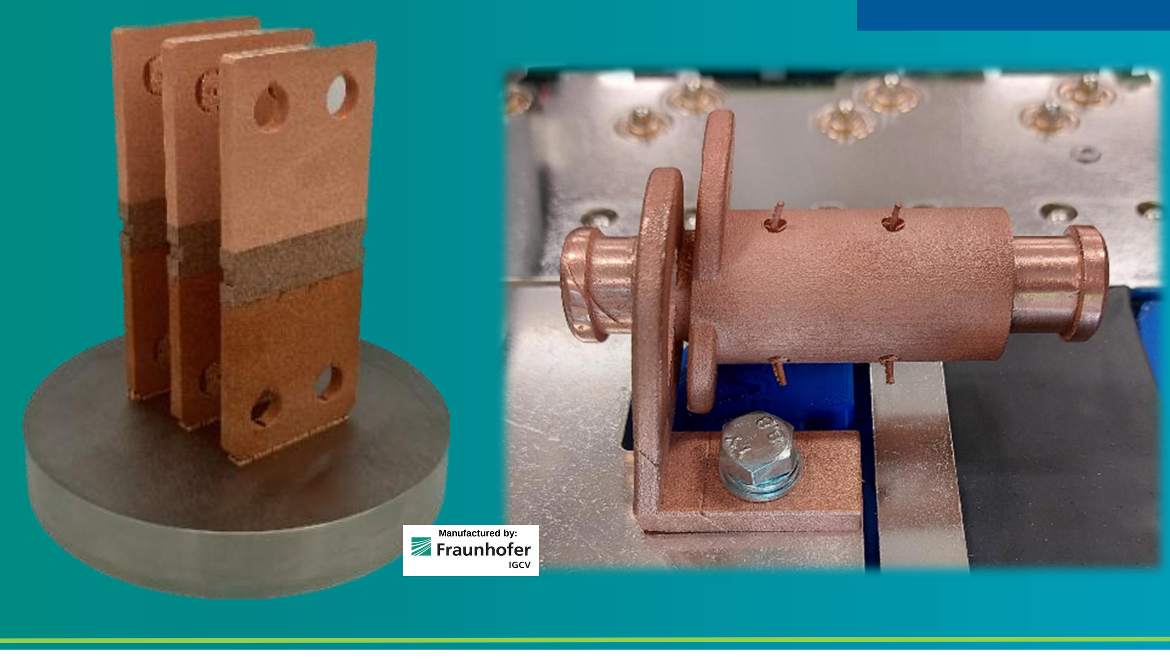

Stefan Karanovic[a], Erwin Reisinger[a], Martin Niederwieser[a], Andreas Klug[a]

[a] AVL List GmbH, Hans-List-Platz 1, 8020 Graz, Austria
Email of corresponding author: Stefan.Karanovic@avl.com

Advanced Current Measurement Sensor Enabled by Multi-Material Additive Manufacturing

Motivation and State of the Art

Metal Additive Manufacturing (AM) has advanced significantly, transforming from prototyping to a crucial industrial manufacturing technology. AM offers new possibilities, including advanced functional materials, complex geometries, and novel material combinations. This innovation potential is particularly relevant for current measurement devices, which face limitations with conventional manufacturing methods. The electrification in mobility drives the demand for precise current measurement devices across various applications. Modern mobility systems, such as electric vehicles, aerospace, and maritime applications, need accurate current measurement under varying conditions.

Current sensors, or shunts, operate based on Ohm's Law, using known resistance and measuring voltage drop to calculate current (as shown in Fig 1). Traditional shunts do not not meet the dynamic requirements of these applications. AM of multi-materials enables the creation of advanced current sensors with complex geometries and tailored properties.

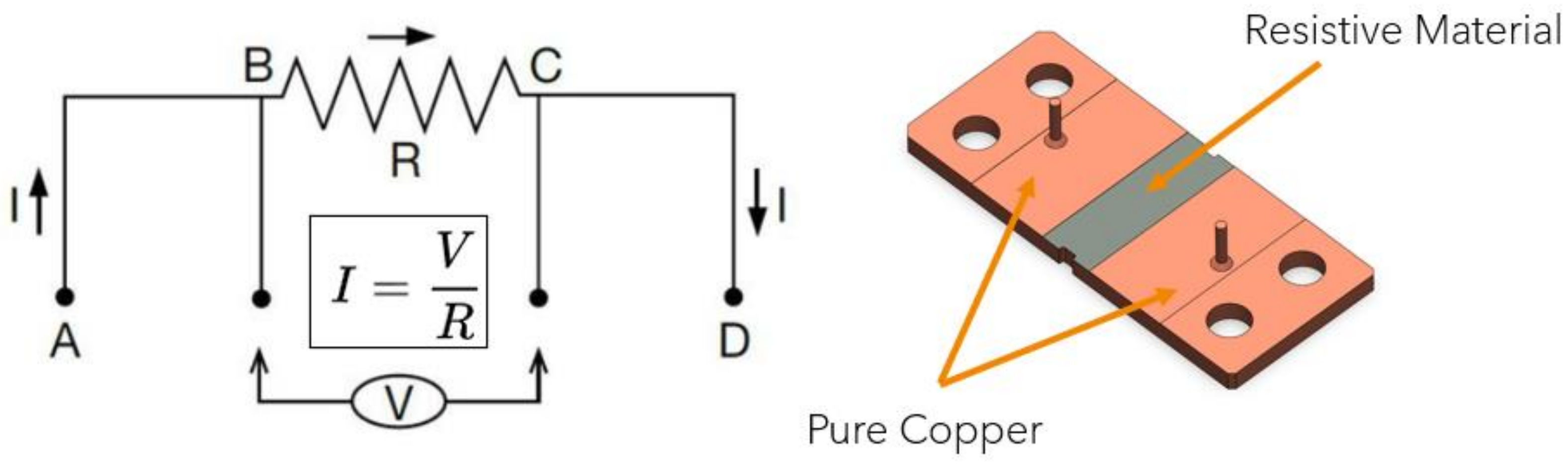

Fig.1: State of the Art: concept of resistive current measurement (left), conventional sensor design (right)

Concept

Conventional current sensor designs face significant challenges due to manufacturing constraints, primarily thermal effects and magnetic interference. Conventional shunt sensors heat up during operation, altering their resistance and affecting measurement accuracy, which necessitates complex temperature compensation mechanisms. Additionally, magnetic fields generated by the current can interfere with the sensor's bandwidth and accuracy, leading to measurement errors.

To address these issues, two innovative solutions are proposed: the **coaxial shunt design** and the **Mobius shunt design**. Both designs guide the current in opposite directions to nearly eliminate the resulting magnetic fields, enhancing sensor accuracy and bandwidth (also due to lower self inductance). The **coaxial design** integrates cooling within the sensor's core, minimizing thermal drift and reducing the need for temperature error compensation. The **Mobius shunt** leverages the unique properties of a Mobius strip to achieve nearly complete magnetic field elimination.

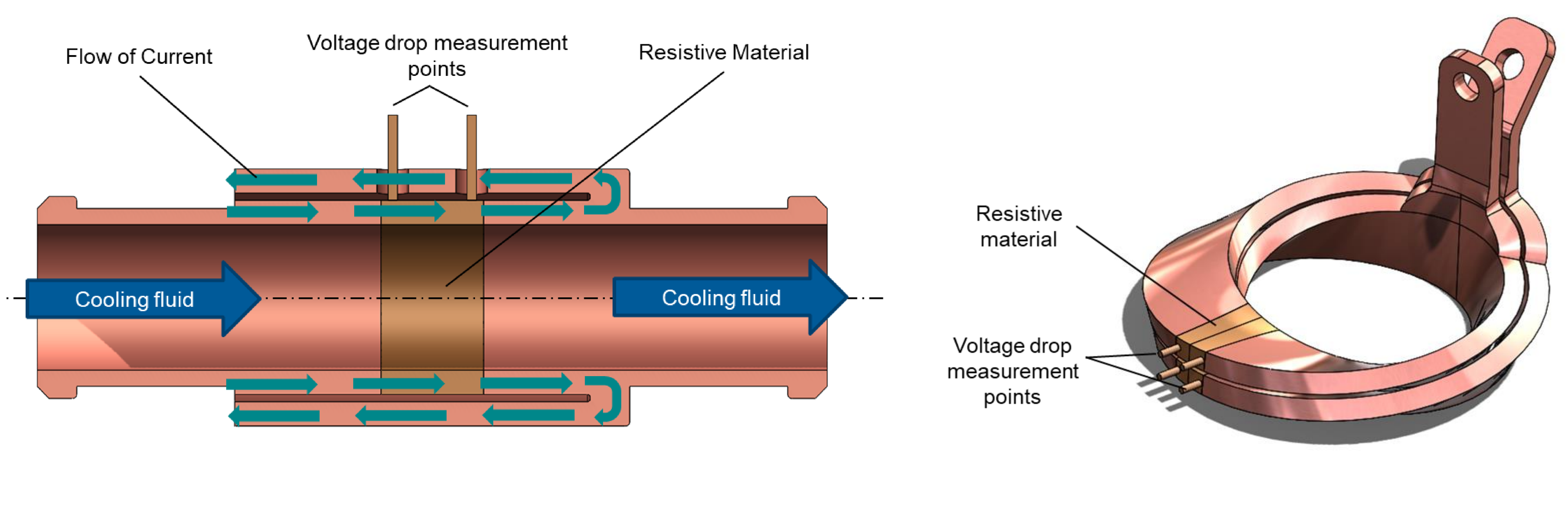

Fig.2: Cross section of coaxial shunt design (left) and the Mobius shunt design (right)

Abstract

Additive Manufacturing (AM) is increasingly integral to the evolution modern sensor systems, enabling completely new possibilities including novel material combinations, advanced functional materials and complex part geometries. AM of multi-materials enables the creation of advanced current sensors (shunts) with complex geometries. This approach allows for tailored material properties, producing sensors that withstand high currents, bandwidths, and temperature variations. The evaluations demonstrate promising results, with metal printing techniques achieving sufficient electrical conductivity and exceptional bandwidth.
The study details the sensor design, manufacturing process, and functionality. Numerical and experimental evaluations under varying current loads demonstrate the potential across sectors such as mobility and power generation.

Results & Discussion

The results of the conventional shunt sensor design replicated using multi-material AM have shown nearly identical electrical parameters to those of conventionally manufactured sensors. Experimental results demonstrate a linear dependence of the material resistance over temperature, providing a basis reference and proof of concept that the electrical parameters are comparable. This successful replication validates the feasibility of using AM for producing current sensors with reliable performance.

Further, the Coaxial shunt design has been realized and experimentally evaluated in terms of bandwidth. Conventional shunt designs typically have a bandwidth limit of approximately 5-10 kHz, beyond which the error rate increases significantly. The proposed shunt designs indicate that, the bandwidth limit could be extended up to approximately 350 kHz. This substantial improvement highlights the potential of AM in enhancing sensor performance.

Overall, the results are highly promising and indicate that these innovative designs have great potential as highly accurate current sensors for a range of industrial applications, particularly in sectors such as mobility and power generation.

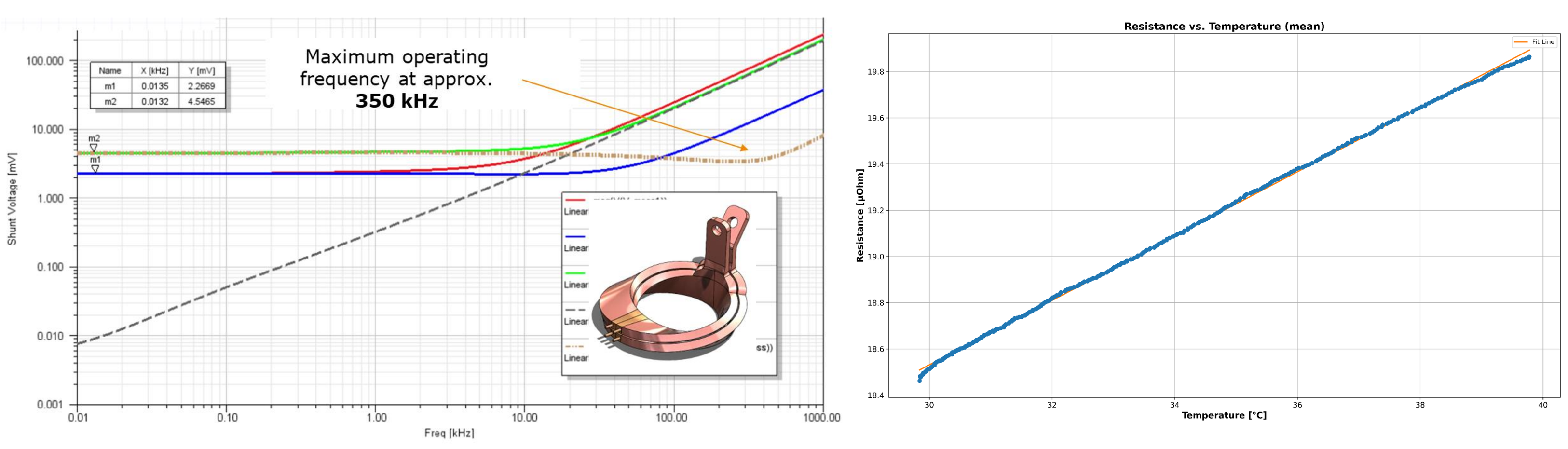

Fig.3: Simulation results showcasing bandwidth limits of the Mobius design (left), linear dependence of resistance over temperature of additively manufactured pure copper (right)

Acknowledgements

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