INL/MIS-22-68169-Revision-0

Additive Manufactured Strain Gauges for Structural Health Monitoring

July 2022

Changing the World's Energy Future

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http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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Introduction

Monitoring strain within the hostile conditions of nuclear reactors are of interest for the measurement of deformation and vibrations of fuel elements and structural components during reactor power cycles (***Figure 1a***). Traditionally, resistive strain gauges (RSG) have been used since they are well-established and allow for the active measurement of strain at strategic locations on a component [1]. RSGs, however, are confined to wired interconnections and require non-trivial attachment strategies (e.g., welding, epoxy, etc.) that can not only affect the underlying component, but also cause variable sensing performance. The successful deployment of reliable strain gauges in reactor conditions stands to benefit from improved sensor design and manufacturing that allow for its application within the wide nuclear test space (i.e., environment, sample geometry, materials compatibility) necessary for the qualification and demonstration of next-generation reactor designs and materials scheduled within the next decade.

Methodology

The interdigitated (IDE) capacitive strain gauge (CSG) is a viable sensor design since it has been shown to have a low profile, low hysteresis, high strain sensitivity, and wireless sensing integration capabilities [2, 3] that would benefit nuclear sensing applications. The current inability to purchase CSGs drives the need for direct write additive manufacturing (AM) technologies to quickly fabricate IDE CSGs and offset the geometry and materials limitations of traditional fabrication techniques. In recent years, AM has demonstrated the ability to fabricate sensors that can overcome the high temperature environments (i.e., above 300 °C conditions; [4]) and non-planar, geometric challenges (i.e., cylindrical geometries; [5]) that are commonly found in nuclear reactors. In addition to allowing the deposition of up to a sub-micron feature size, the flexibility of AM allows for it to be compatible with tailorable, nuclear-relevant ink materials [6] making it an ideal tool for the rapid prototyping of

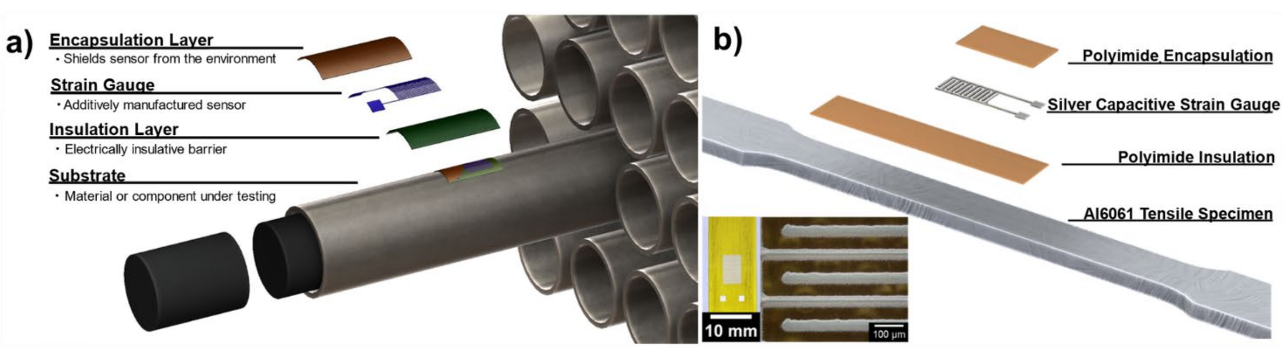

Figure 1. Schematic of interdigitated capacitive strain gauge on a a) fuel pin and b) aluminum alloy 6061 tensile specimen presently studied; future direction will aim towards using materials less susceptible to degradation and damage from nuclear environments.

miniaturized strain gauges for in-pile applications [7].

Objectives

The objective of this initial work aims to:

1) <u>Qualify sensor design and manufacturing</u>: demonstrate and optimize the AM process to fabricate IDE CSGs that are reproducible (i.e., similar gauge factor across multiple samples) and predictable (i.e., correlates to analytical models) in performance.
2) <u>Compare strain sensor technologies</u>: compare the performance of the printed IDE CSGs against commercially available bondable free-filament resistive strain gauges (RSG). Bondable free-filament RSGs are an ideal candidate sensor for comparison as they are relatively cheap, have a small profile, and are useful for high temperature strain measurements on small substrates under laboratory conditions [8].

The mechanical and thermal performance of the strain gauges are qualified in moderate temperatures from 20 °C - 300 °C using standardized testing procedures to simulate the temperatures found in existing light water reactors. The results from this work will lead towards the development of AM fabricated in-pile strain gauges designed for high-temperatures (i.e., 300 °C - 950 °C) and additional environmental factors found in Generation IV reactor designs.

Current Status

The AM IDE CSGs were initially fabricated and tested at Boise State University with polyimide insulation/encapsulation and silver electrodes on a flat Al6061 substrate (***Figure 1b***). In its current state, the CSGs are not ready for nuclear applications, however this work demonstrated that the AM strain gauges, when compared to bondable high temperature RSGs, had promising performance for elevated temperature applications. The AM IDE CSGs closely followed analytical models and exhibited

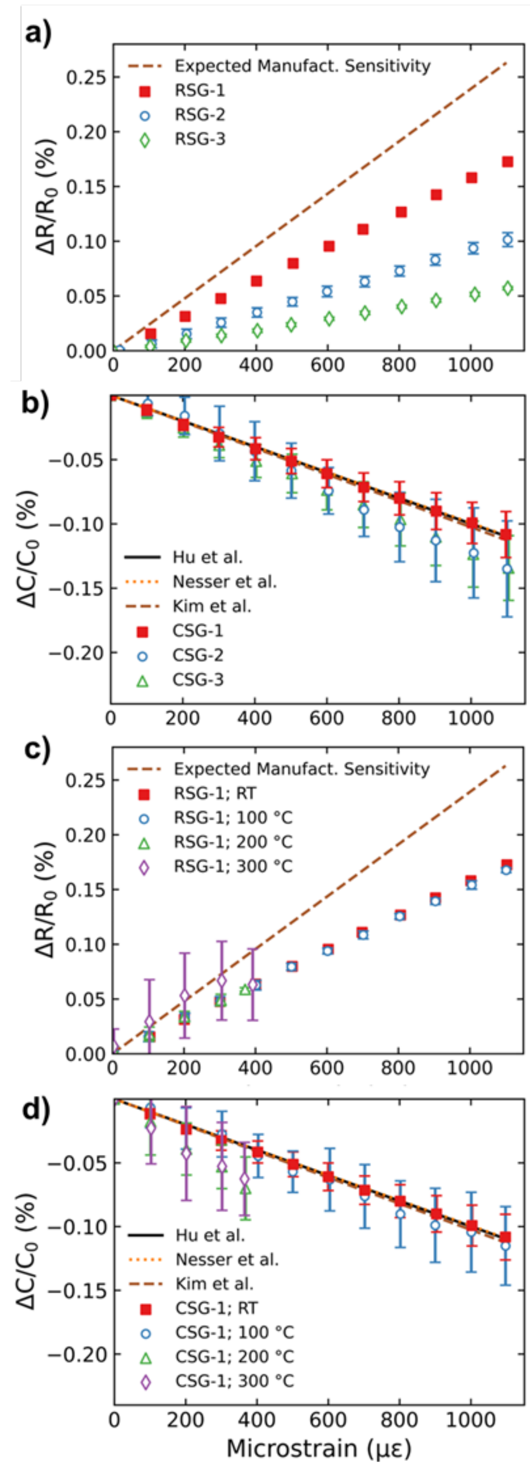

Figure 2. Testing results of the commercial resistive strain gauges at a) RT and c) elevated temperature and printed strain gauges at b) RT and d) elevated temperature

similar strain sensitivities (i.e., gauge factor) across multiple fabricated sensors (***Figure 2***). The IDE CSG in this work also filled a current lack of understanding of IDE CSG tested at elevated temperatures (i.e., above 100 °C) on metallic substrates and in low strain environments (i.e., ≈1000 με) that are prototypic of nuclear applications. Having a reproducible and predictable strain sensing performance are two factors that are important when deploying the strain gauges in costly, time-consuming experiments (e.g., test reactor facilities).

Path Forward

The application of AM sensors for harsh environments requires a careful selection of materials and improved strategies in both packaging and heterogenous integration. Presently, efforts are being made to investigate the fabrication of IDE CSG that are made of only metal and ceramic constituent layers (***Figure 1***) that are less susceptible to damage and degradation. This is supported by Idaho National Laboratory's current capability to develop and optimize AM ink materials that are application specific for the printed device. The AM IDE CSGs will also continue to be exposed to separate effects testing (i.e., mechanical strain, temperature, vibration, etc.) and used to support nuclear programs where current RSG technologies are not applicable due to size constraints. Although not currently within the scope, it is recognized that the successful deployment of CSGs also requires significant improvements in signal processing and data acquisition to allow for a stable long-term CSG measurements with intrinsic balancing, error compensations, and minimal circuit drifting.

Conclusion

In this work, AM was used to fabricate low-profile IDE CSGs that is reproducible and predictable in strain sensing performance. These efforts support other U.S. Department of Energy Office of Nuclear Energy programs, such as the Advanced Reactors Technologies and Advanced Materials and Manufacturing Technologies programs through implementation of advanced manufacturing techniques in sensor fabrication. These sensors enable data acquisition for improved material testing and validating modeling and simulation efforts to support the development, testing, and qualification of new nuclear materials.

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