Abstract

Structural Health Monitoring (SHM) systems play a vital role in safeguarding space exploration, as spacecraft and structures are routinely subjected to detrimental stresses and strains during operation. Conventional strain gauges are widely used in SHM to detect and assess localized strain behaviors in structures. However, fabrication of those strain gauges typically involves complex, multistep processes; they are limited by low sensitivity (Gauge factor, GF ~ 2) and modest strain resolution. These substate-supported strain gauges exhibit limited structural conformity. Although composite-ink-based strain gauges have been explored to overcome these limitations, challenges related to ink formulation, printability, substrate adhesion, and reliance on time and energy-intensive thermal curing remain unresolved. Moreover, footprint-specific resistance tunable strain gauges tailored to diverse SHM requirements are rarely reported in the literature.

This dissertation presents a simplified, single-step fabrication process for high-performing strain gauges using state-of-the-art additive manufacturing technique- Direct Ink Writing (DIW). The results demonstrated that DIW is a robust and scalable method for strain-gauge fabrication, capable of processing inks with diverse rheologies and chemistries. A series of composite inks was formulated by modifying a commercially available silver ink (CB028) with ethyl cellulose (EC) and polyolefin (PO) additives. Ink printability was optimized through rheological analysis-amplitude sweep, viscoelastic recovery, viscosity measurements, frequency sweep, and tack tests. A viscoelastic window approach was introduced to predict and assess the adhesion of formulated inks. Those analysis determined that formulation containing 90%CB028_5% EC_5% PO provided optimal printability and enhanced elasticity and adhesion compared to base ink CB028. Electromechanical testing using a three-point bending configuration revealed piezoresistive responses with gauge factors as high as 106 and stable performance over more than 1000 strain cycles.

The implementation of a near infrared (NIR) laser curing significantly reduced post-processing time from approximately 1 h to nearly 1 min. Systematic analysis of the laser curing process identified optimal parameters—namely a laser power of 0.8 W, a scan speed of 7.5 mm/s, and a single scan pass—which yielded electrical resistance values comparable to those obtained from benchmark oven-cured samples. Moreover, laser-cured strain gauges exhibited greater changes in electrical resistance at identical strain levels, indicating enhanced strain sensitivity compared to their oven-cured counterparts. To tune the electrical resistance, a commercial silver ink (HPS-FG57B) was blended with carbon black ink (SC1502), then printed at varying print speeds on a compact footprint (3.6 mm x 7 mm), with a target resistance of 1000 Ω. Ink containing 46.19 wt% Ag and 1.7 wt% CB, printed at a speed of 10 mm/s, yielded a resistance of 1043.10 ± 61.28 Ω. The resulting strain gauge showed a gauge factor up to 55 and stability over 1000 strain cycles. Substrate-free, conformal strain gauges were successfully printed directly onto G-10/FR4 structural materials. Electrically reliable and mechanically robust interconnections were achieved by printing a solderable silver ink onto the contact pads, with interfacial resistance quantified using the transmission line method (TLM). The measured interfacial resistance between the solderable ink and the composite inks remained below 1 $\mu\Omega\cdot cm^2$, indicating negligible contact resistance.

In summary, this work presents a practical, scalable framework for fabricating highly sensitive, stable, resistance-tunable, and conformal strain gauges via direct ink writing and composite ink formulations. The approach offers a promising pathway toward next-generation structural health-monitoring systems for aerospace and other demanding engineering environments.