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Void-free embedding of optical fibers into high strength metals using thermal spray-based additive manufacturing.

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Abstract

The integration of sensors within critical metallic components represents a transformative step toward real-time structural health monitoring in key industrial sectors such as transportation, energy, and aerospace. The increasing demand for reliability and efficiency in infrastructures like railway networks, hydrogen pipelines, and nuclear facilities—along with the emergence of low-carbon technologies including small modular reactors and hydrogen-fueled engines—necessitates the continuous monitoring of temperature and mechanical deformation within structural materials. Embedding sensors directly inside high-strength metals (e.g., steels, nickel-based superalloys, or titanium alloys) would enable unprecedented insight into component performance under service conditions. However, realizing this capability remains highly challenging due to the extreme thermal environments associated with processing such metals, which makes very difficult the direct embedment of conventional silica-based optical fibers during casting, welding or additive manufacturing (AM) approaches such as powder bed fusion (PBF) or directed energy deposition (DED). To address the limitations of existing methods for embedding optical fibers into high-strength metallic materials, this work introduces a novel technique based on the Thermal Spray (TS) additive manufacturing process. The proposed TS-based method enables to embed a commercial Cu-coated single-mode silica optical fiber within a stainless steel shielding. During TS processing, microdroplets of molten metal are projected onto the fiber surface. Due to their small size and rapid cooling, the resulting temperature increase in the fiber remains acceptable, preventing degradation of optical properties. This approach offers three major advantages over previous embedding strategies. First, it enables to equip existing structures (such as pipelines, railway tracks, or components in nuclear facilities) by allowing the shielded optical fiber to be welded directly onto their surfaces for real-time monitoring. Second, it supports integration into newly manufactured parts produced by conventional AM methods, as the stainless-steel shielding both protects the fiber from high process temperatures and ensures material compatibility with common AM feedstocks. Third, the method is scalable and can be adapted for long fiber lengths, opening the way for large-scale sensing applications. The embedding process is performed using a custom-designed apparatus called the "optical fiber lathe", which keeps the fiber under tension while rotating it to ensure uniform metal deposition. This mechanical setup is critical for achieving strong bonding between the metal and the fiber. The TS process is performed manually and is monitored employing a camera to control the nozzle–fiber distance. After fabrication, the samples are characterized to evaluate the integrity of the optical fiber, the quality of metal adhesion, and the microstructural properties of the stainless-steel shielding. Finally, a lightweight thermo-mechanical model is developed to simulate temperature and stress evolution during deposition. This predictive tool helps interpret experimental observations, supports process optimization, and provides a foundation for scaling the technique toward industrial applications in self-monitoring metallic structures.

Keywords:

Optical fiber sensors Thermal spray Additive Manufacturing