Distributed Fiber-Optic Thermometry for High-Fidelity Temperature Metrology in Harsh and Thermally Heterogeneous Environments

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Recent advances in distributed optical fiber sensing are enabling transformative approaches for high-resolution temperature metrology in harsh manufacturing environments. In this work, we developed a scalable, high-resolution distributed thermometry platform based on Rayleigh backscattering (RBS)-enabled optical frequency domain reflectometry (OFDR) for real-time spatial thermal mapping during the aluminum casting process. The system utilzed silica optical fibers (UHNA1, Thorlabs) interrogated with a high-speed OFDR platform, enabling high-density thermal metrology with a resolution of approximately 0.65 mm (~1538 points m^{-1}) and acquisition rates up to 62 Hz. The sensing approach was successfully integrated into elevated-temperature casting environments, including the casting of AA356 aluminum in 3D-printed investment shells. Distributed thermal data were acquired throughout the full casting cycle, including shell preheating, molten metal pouring, and subsequent solidification at temperatures approaching 700 °C, showing trends consistent with thermocouple measurements. The platform effectively captured localized thermal gradients, transient heat-transfer phenomena, and the spatio-temporal evolution of temperature during solidification, while the optical fiber remained intact after molten metal pouring and was reusable for subsequent measurements, demonstrating the robustness of the sensing platform in harsh casting environments. Unlike conventional thermocouple-based systems, the distributed fiber-optic approach provided near-continuous thermal measurements along the length of a single optical fiber, significantly improving spatial sensing capability while remaining minimally invasive. The results demonstrate the strong potential of RBS-enabled distributed fiber-optic sensors as robust thermometry platforms for metal casting and other advanced manufacturing applications operating in extreme environments. This work further establishes a foundation for intelligent process monitoring, real-time thermal diagnostics, and digital twin-enabled manufacturing systems, while highlighting the broader applicability of distributed fiber-optic thermometry for next-generation harsh-environment sensing technologies.