Multiscale Insights into Additive Manufacturing Enabled by Operando X-ray Diffraction and Imaging

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Abstract

Additive manufacturing (AM) of metals is governed by highly transient, multiphysics processes involving rapid melting, solidification, phase transformations, and stress evolution over multiple length and time scales. Understanding and ultimately controlling the resulting process–structure–property relationships remains a major challenge, particularly for complex alloys and multi-material systems. In this context, operando synchrotron X-ray diffraction and imaging have emerged as powerful tools to directly observe and quantify the fundamental mechanisms active during AM. In this contribution, we demonstrate how operando X-ray techniques provide unique insights into solidification pathways, phase evolution, and defect formation during laser powder bed fusion (LPBF). By combining high-speed X-ray diffraction with real-time imaging, it becomes possible to disentangle competing physical phenomena that are otherwise inseparable using post-mortem characterization alone. Examples include the direct identification of solidification modes in austenitic stainless steels, where subtle changes in powder chemistry lead to markedly different phase formation sequences and final microstructures. Operando diffraction reveals how these differences originate during solidification, enabling a direct link between processing conditions, thermodynamic pathways, and crystallographic texture development. The approach is further extended to multi-material AM, where the coexistence of materials with strongly contrasting thermophysical properties introduces

additional complexity. Operando X-ray characterization allows the temporal and spatial separation of distinct cracking mechanisms—such as solidification cracking, liquation cracking, and metal-induced embrittlement—by correlating crack initiation with phase formation and melt pool dynamics in real time. These observations clarify why different cracking mechanisms may dominate under similar processing conditions and highlight the limitations of interpretations based solely on ex situ analyses. Importantly, the operando insights also guide mitigation strategies, showing how process optimization can reduce cracking, and where compositional modifications become unavoidable. Beyond fundamental understanding, operando X-ray methods provide critical experimental input for validating multiphysics and multiscale models of AM. The real-time data on phase evolution, thermal history, and defect formation offer a benchmark for numerical simulations and data-driven approaches, ultimately supporting the rational design of materials, processes, and architectures—including functionally graded materials and metamaterials produced by AM. Overall, operando X-ray diffraction and imaging bridge the gap between processing and performance in additive manufacturing. By revealing the mechanisms that govern microstructure and defect formation as they occur, these techniques play a key role in advancing process control, materials design, and predictive modeling for next-generation additively manufactured components.

Keywords:

Additive Manufacturing X-ray Diffraction X-ray Imaging Multimaterials Cracking Solidifcation Simulations