Time-resolved diffraction during laser–material interaction: operando studies under extreme thermal conditions

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High-power laser–material interaction enables access to extreme thermodynamic conditions, characterized by rapid heating and cooling (up to 10^5–10^6 K/s), steep thermal gradients, and highly transient phase transformations. These conditions, routinely encountered in laser-based additive manufacturing processes, provide a well-controlled platform to study non-equilibrium materials behaviour using diffraction.

In this contribution, operando diffraction experiments performed at synchrotron and neutron facilities are presented, with the aim of linking transient thermal conditions to phase formation, solidification pathways, and strain evolution. High-speed synchrotron X-ray diffraction enables time-resolved tracking of phase transformations during rapid solidification, revealing deviations from equilibrium pathways, the formation of metastable phases, and transitions in solidification modes governed by local thermal gradients and interface velocities [1-2]. At the same time, the evolution of diffraction peaks provides access to transient lattice strain and temperature fields within the process zone, enabling a quantitative description of the thermomechanical boundary conditions.

These diffraction-based measurements are increasingly combined with complementary sensing approaches and modelling. Acoustic emission and related in situ sensors provide indirect but high-temporal-resolution information on process dynamics, while operando diffraction serves as a reference to relate these signals to underlying microstructural mechanisms [3]. In parallel, diffraction-derived data are used to validate and constrain thermal and thermomechanical simulations, enabling a more consistent description of the process conditions.

Complementary neutron diffraction experiments extend these investigations to bulk samples, enabling the measurement of transient lattice strains and residual stress evolution under realistic processing conditions. The development of dedicated sample environments compatible with large-scale facilities allows operando diffraction across multiple length scales and penetration depths [4]. Taken together, these results illustrate how recent advances in instrumentation, sample environments, and data correlation approaches enable diffraction-based studies of materials under extreme, non-equilibrium conditions.

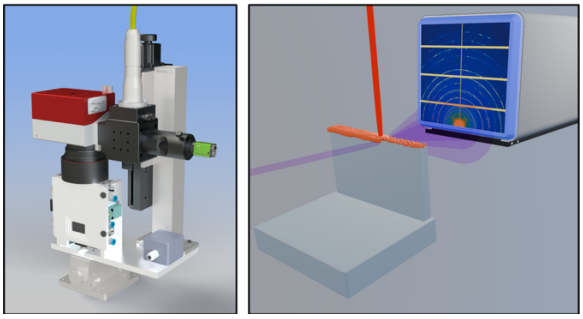


Figure 1. *Miniaturized laser additive manufacturing device and corresponding diffraction geometry*

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