Abstract

This dissertation investigates the possibility of developing a comprehensive, multiscale modelling framework tailored for the Powder Bed Fusion with Electron Beam (PBF-EB) process. The work aims to identify and link together physical phenomena occurring at different spatial and temporal scales of the process, ranging from the micrometric scale up to the final component scale, to provide a fully integrated approach that joins experimental data and simulation, to enable finer process monitoring, prediction, and optimisation.

A conceptual multiscale framework is proposed to connect micro-, meso-, macro, and machine-scale models, linking data and simulations across scales through consistent data-passing strategies. Within this framework, the attention has been on the implementation two modelling approaches: data-driven models at the process scale and Crystal Plasticity Finite Element Method (CPFEM) models at the microscale. Together, they address critical challenges in process stability, energy efficiency, and material characterization.

Regarding the process scale, the process stability and efficiency were tackled. For this reason, an unsupervised anomaly detection framework based on a generative Long Short-Term Memory (LSTM) autoencoder was developed using multivariate sensor data acquired directly from an Arcam A2X system. The model identifies and quantifies anomalous patterns without labelled data, enabling the prediction of build failures several hours before their occurrence. This represents the first anomaly detection system specifically designed for the PBF-EB process and demonstrates high potential for real-time process control in industrial applications. A second data-driven model was implemented to predict energy consumption and melting time from layer-wise geometrical features and electron beam trajectories. These results allowed to disprove the common idea of geometry-independent energy consumption in the PBF-EB, since they instead highlight a strong correlation between the complexity and energy consumption. Jointly, this approach offers new insights for enhancing process optimisation, efficiency and sustainability.

Moving to the microscale, a CPFEM model of Ti-6Al-4V produced by PBF-EB was developed. A synthetic microstructures generation procedure was implemented to accurately reproduce α-β morphology and texture of lamellar microstructures resulting from the PBF-EB process through the integration of Electron Backscattered

Diffraction (EBSD) and optical data. Simulations across 20 statistically representative volume elements successfully reproduced experimental tensile behaviour with an error below 1 %, capturing the anisotropic response and local strain–stress localization mechanisms due to the two distinct phases. These results confirm the capability of CPFEM to act as a virtual material laboratory for investigating process–structure–property relationships in additively manufactured alloys.

All the presented models and frameworks, act as a foundation for an integrated multiscale modelling approach for the PBF-EB that combines physics-based and data-driven approaches. Such synergistic approach is the key for understanding complex phenomena interactions across scales and establishing a basis for future developments toward a fully coupled simulation environment, capable of supporting and enhancing the industrial adoption of PBF-EB process.