Multiscale analysis of the anisotropy induced by defects in LPBF additive manufacturing using coarse graining homogenisation techniques

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Abstract

Additive manufacturing techniques have garnered significant interest in various industrial applications due to their potential for design optimisation, cost reduction, and shortened lead times. Among these techniques, Laser Powder Bed Fusion (LPBF) stands out for its ability to produce components of relatively small size with complex designs and satisfying material properties. Especially, it enables geometries that are unachievable with traditional manufacturing processes (1). These features are also relevant in the nuclear industry and particularly in nuclear fuel assemblies where components needs to provide high performances in restricted spaces (2).
The LPBF process uses a laser to melt and fuse metallic powder particles spread in a powder bed. The component is formed incrementally, as a new layer of powder is added after each pass of the laser. Despite its benefits, this technique also presents a specific defectology characterised by the type and quantity of pores, their spatial distribution and the potential interactions between them. It can be strongly influenced by the numerous manufacturing parameters, including for example the powder characteristics, the laser path and any complex interactions between these factors. In particular, a strong correlation can be observed between the lasing strategy used and the location of defects, revealing signature patterns (3).

The criticality of these voids with respect to the mechanical behaviour of LPBF components has yet to be fully established.

Previous works already showed the detrimental nature of larger voids (4) and highlighted the significant influence of the spatial distribution of defects (5). However, these studies usually focus only on spherical pores and rarely investigate the interaction between different types of voids. Besides, the anisotropy induced by the observed specific patterns remains undercharacterised. These limitations motivate the need for suitable numerical methods that can effectively simulate the behaviour of explicitly modelled complex pore populations. Simulations on images appear as a suitable approach to overcome the complex and significant meshing work usually required. Some authors also discussed scenarios where the defect size approaches the structure scale (6). This is particularly noteworthy for the thin designs

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enabled by LPBF and raises the question of the validity of the scale separation hypothesis in homogenisation. Moreover, since pore populations are highly diverse and the components typically fine, the existence or the appropriate size of a Representative Volume Element (RVE) remains uncertain.

In this work, we study the anisotropy induced by the particular spatial organisation of complex defect populations and investigate the existence of a homogenised RVE for such materials.

We address this question by performing high-fidelity multigrid elastic simulations on synthetic images representing a given distribution of pores (7). Elastic computations are conducted using six independent loading cases to evaluate the elasticity tensor. Coarse graining (CG) techniques are used to perform exact homogenisation of the domain at multiple scales (8). In this approach, the mesoscopic variables are computed from the convolution of microscopic variables with a kernel, while enforcing mechanical conservation laws at both scales. As a result, the method provides homogenised property fields across all elements without the need of a RVE. It is also worth noting that no assumptions are made regarding the material's behaviour. The convolution linearity ensures the elastic results remain independent after the homogenisation. Therefore, the elasticity tensor can be evaluated at multiple mesoscopic scales. The local anisotropy degree of the material is then determined by analysing the number of independent eigenvalues of the elasticity tensor and the corresponding eigenspaces (9).

Therefore, CG techniques allow for establishing correlations between the microscopic defect distributions and the resulting elastic properties at different scales. These findings highlight which defects should be accounted for, depending on the observation scale considered. Furthermore, the analysis of the variability of the homogenised elastic properties at different scales enables conclusions regarding the existence or size of a RVE and its degree of anisotropy. In the absence of a RVE, this method still automatically provides the equivalent heterogeneous material at the macroscopic scale for a given pore population.

Currently, the approach shows promising results in capturing anisotropic behaviours induced by voids at mesoscopic scales for relatively simple cases. Future work will focus on investigating the existence or size of a RVE and applying the same scheme to more complex defect populations. The validity of the scale separation hypothesis should also be examined. This can be achieved by evaluating the homogenised properties on real thin structures under actual loading conditions.

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