Microstructure Based Constitutive Modelling of Metastable 3D Printed Materials Strained at Extremely Low Temperatures

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Stainless steels are widely used at extremely low temperatures due to their excellent properties, including high ductility. However, they exhibit metastable behaviour when strained beyond the yield point. The aim of the present work is to observe and analyse the evolution of the material microstructure – particularly the fcc-to-bcc phase transformation [1] – during plastic deformation and fracture in AISI 304 and 316L stainless steels at extremely low temperatures (77 K and 4.2 K). The study focuses on phenomena such as intermittent plastic flow, diffusionless martensitic transformation, and the development of micro-damage and fracture [2,3] in metastable materials manufactured using additive techniques.

The unique cryogenic experiments were conducted using an in-house testing system equipped for both uniaxial and multiaxial loading. The specimens were mounted in a vacuum-insulated cryostat integrated with a dedicated testing machine. To ensure the required temperature, the coolant was transferred from a dewar to the cryostat via a specialized transfer line. The fracture surfaces were examined in detail using magnetometric methods (Feritscope), scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and X-ray diffraction with synchrotron radiation. The X-ray diffraction studies revealed, among other findings, that the fcc-to-bcc phase transformation extensively accompanies macrocrack propagation. Moreover, the resulting α′ martensite undergoes intensive twinning to achieve a good lattice fit with the austenitic matrix. The secondary phase nucleates at the intersections of shear bands – i.e., at the crossings of ε-martensite plates or twin lamellae – and subsequently undergoes growth and coalescence.

An extended multiscale constitutive model describing the plastic strain induced fcc-bcc phase transformation will be presented. The model accounts for a multiphase material consisting of an austenitic matrix and Eshelby-type ellipsoidal inclusions corresponding to both martensitic variants, ε and α′. Furthermore, based on in-house experimental data, a phase transformation tensor will be incorporated into the constitutive framework, taking into account both volumetric and shear components.

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