Damage evolution in classical and additive materials at cryogenic temperatures

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Modern engineering materials, particularly metastable austenitic stainless steels, are produced using a range of methods, from traditional plastic working processes to advanced additive manufacturing technologies such as Laser Powder Bed Fusion (L-PBF). The manufacturing process plays a crucial role in shaping the material's microstructure, thereby determining its mechanical properties and resistance to damage, especially under extreme operating conditions such as cryogenic temperatures. The present study focuses on the kinetics of damage evolution in metastable austenitic stainless steels (grades 304 and 316L) subjected to monotonic tensile loading at room (293 K) and liquid helium temperature (4.2 K). To qualitatively assess the degree of structural degradation, microscopic investigations were conducted using a scanning electron microscope (SEM) equipped with EDS (energy-dispersive spectroscopy) and EBSD (electron backscatter diffraction) detectors. The results indicate that the level of micro-damage observed in L-PBF samples is significantly higher than that in samples produced using traditional manufacturing methods. To quantitatively assess the damage level, multiple unloading tests were conducted at room temperature (293 K) and at liquid helium temperature (4.2 K), during which the unloading secant modulus was determined for each cycle. Based on the effective unloading modulus, the evolution of the damage parameter D – defined as the ratio of the damaged surface area to the total cross-sectional area of the representative volume element (RVE) – was evaluated. Furthermore, the kinetics of damage evolution was identified using the Lemaitre–Chaboche [1] and Bonora [2] damage models. Within the framework of this study, a comparative analysis of the identified damage kinetics for both conventionally manufactured and additively manufactured materials is performed. The results are expected to enable a quantitative assessment of differences in the initial damage state and the evolution of damage, with particular emphasis on the influence of process-induced porosity characteristic of additive manufacturing (3D printing) technologies. A key element of the study is the formulation of a constitutive model for damaged material. The model shall describe the coupling between increasing damage and the plastic strain–induced fcc–bcc phase transformation, which is characteristic of metastable materials operating at cryogenic temperatures. A suitable framework is offered by the Garion–Skoczeń model [3], which accounts for the evolution of anisotropic damage, represented by a Murakami-type damage tensor, in the presence of a secondary phase generated by strain-induced phase transformation. The proposed model aims to provide tools for more accurate lifetime prediction of stainless steel components operating in extreme cryogenic environments, highlighting the significant role of manufacturing technology in the structural safety assessment process.

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