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Three-dimensional numerical modeling of ductile fracture mechanisms at the microscale

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ABSTRACT

The present work aims at a better understanding and modeling of ductile fracture during the forming of metallic materials. These materials are formed using series of thermo-mechanical loads where many parameters such as loading type and direction vary, and predictive numerical tools are necessary to understand the occurrence of failure and optimize production costs.

Ductile fracture in metallic materials is the result of voids nucleation, growth, and coalescence mechanisms, leading to a progressive loss of load carrying capacity, until failure [1]. In this work, a micromechanical approach is developed in order to conduct realistic Finite Element (FE) simulations of ductile fracture at the microscale, accounting explicitly for the microstructure of the studied materials. Such simulations require a robust methodology to discretize the microstructure, and then update this discretization during its deformation and progressive failure. Level-Set (LS) functions are used to represent all interfaces [2], and ease the modeling of void linkage events, that are difficult to handle with standard FE methods. This implicit representation of interfaces raises multiple issues. First, discontinuous material behavior at interfaces remains to be modeled. Second, large plastic strains can only be reached using several remeshing operations, which induce an important diffusion of the volume and morphology of the microstructure when the latter is carried only by LS functions. A mesh generation method is developed to mesh interfaces with a conforming FE discretization, hence explicitly representing discontinuities in material behavior. The quality and accuracy of this discretization is maintained during deformation thanks to a mesh adaption algorithm enhanced with a volume conservation constraint [3]. Additionally, real microstructures typically feature a complex morphology that requires a very fine discretization. Using a local error estimator based on LS functions, the discretization is automatically refined where necessary [4]. This error estimator relies on the geometric properties of LS functions, which are maintained during deformation thanks to a new direct LS reinitialization technique [5]. Finally, a computational

fracture mechanics approach and stress-based fracture criteria are proposed to model the nucleation of microscopic voids.

The interest of these numerical developments and micromechanical models is first demonstrated at the scale of representative volume elements with statistically generated microstructures. Then, simulations of real microstructures with measured boundary conditions are addressed. Three-dimensional X-ray images are meshed and displacement fields measured by image correlation are applied at the boundaries of the FE domain in order to conduct simulations in conditions that are as close as possible to what is observed during *in-situ* experiments [6]. Such massive 3D simulations can be achieved thanks to the efficiency of all numerical developments performed in this work, and their implementation in a distributed computing framework. Error measurements accounting for the volume and shape of each void prove the validity of these results, and the interest of this numerical validation framework with respect to standard micromechanical approaches [7].

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