MICROMECHANICAL MODELING OF THE COMPETITION BETWEEN TRANSGRANULAR AND INTERGRANULAR DUCTILE FRACTURE

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Abstract
In many metallic alloys used in industrial applications, such as precipitation hardened alloys, competition between transgranular and intergranular ductile fracture is observed experimentally. If the latter prevails, material ductility is strongly reduced, which advocates for a comprehensive modeling of this phenomenon. Based on the mechanical homogenization of porous materials, a micromechanical model for intergranular ductile fracture is proposed and used for microstructure-informed investigation of the competition between trangranular and intergranular ductile failure.

1. Introduction

Void nucleation, growth and coalescence is among the dominant ductile failure modes in metallic alloys and can be transgranular as well as intergranular. In the former, the crack propagates through the grains whereas in the latter, the phenomenon of void growth and coalescence happen at grain boundaries due to intense intergranular plastic flow. A wide class of metallic alloys can experience one fracture mode or the other depending on microstructure and loading conditions; some fractographies even reveal mixed damaging processes. For instance, the failure mode of precipitation-hardened alloys is specially sensitive to the aging treatment that can foster transgranular or intergranular ductile fracture [1]. Irradiated metals in which transmutation produces helium bubbles are also a type of material where competition between ductile damage phenomena happens [2]. Since cases in which dimpled intergranular fracture prevails are associated with reduced elongation compared to transgranular fracture occurences, predicting the dominant damage process is of paramount importance.

Since seminal works on isotropic media (*e.g.* [3]), considerable efforts have been made to model ductile failure through homogenization of the mechanical behavior of porous materials. In the last decade, these results have been extended to single crystals with internal cavities (*e.g.* [4]), but modeling of intergranular ductile fracture is still lacking.

2. Methodology and results

In order to account for the successive stages of void growth and void coalescence, a multi-surface plasticity framework is adopted to model porous grains boundaries. The void growth yield criterion is taken from a recent publication [5] while a new void coalescence yield criterion tailored for intergranular cavities is proposed. Based on these yield criteria, the competition between transgranular and intergranular ductile fracture is first assessed theoretically. On the one hand, it is concluded that, in a polycrystal with a uniform distribution of cavities inside grains and at grain boundaries, transgranular void growth will always be favoured, which is in line with experimental observations. In order for intergranular void growth to prevail, grain boundaries must be significantly weakened, either by precipitate-free zones (see Fig. 1a) or by elongated cavities located at crystal interfaces (see Fig. 1b). On the other hand, it is shown that void coalescence can be favoured at grain boundaries over grain interiors for certain crystal orientation couples.

A complete set of constitutive equations is then proposed for the mechanical behavior of porous grain boundaries, similarly to what has been done for porous grains [6], by adding evolution laws for microstructural parameters in a finite strain setting. These two homogenized models – for porous grains and porous grain boundaries – are used to perform numerical simulations of ductile fracture at the polycrystalline scale.are then implemented in a finite-element code by using standard elements to model grain interiors and boundary element that behave according to the model of intergranular ductile fracture. The effect of microstructure on the competition between transgranular and intergranular fracture is then assessed in details.

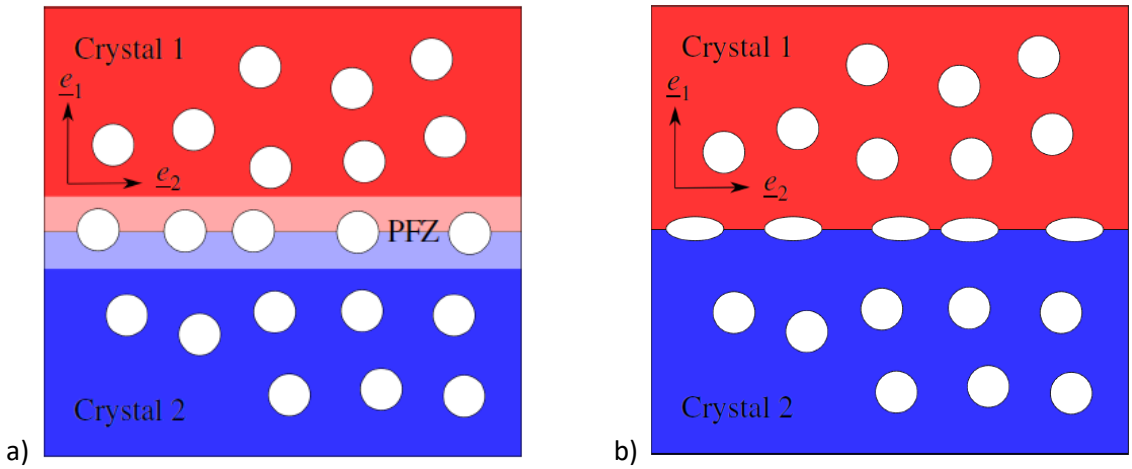

Fig.1 – Case studies of competition between transgranular and intergranular ductile fracture: (a) precipitation-hardened alloy with soft precipitate-free zone (PFZ); (b) elongated cavities at grain boundaries.

3. Conclusion

Using a physical-based micromechanical model for intergranular ductile fracture based on a void growth yield criterion proposed recently in the literature and a void coalescence yield criterion developed in this study, the role of material microstructure in the competition between transgranular and intergranular has been assessed theoretically in a number of case studies. Finite element simulations using this micromechanical model have been set up to assess ductile fracture at the polycrystalline scale, allowing to identify the cases in which intergranular fracture may prevail, which could significantly reduce the occurrence of low-ductility fracture in industrial applications.

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