

## In-situ investigation of the early stages of ductile damage (void nucleation) in Cu–Al alloys

### 1. Background and state of the art

Ductile fracture in metallic materials results from plasticity-assisted cavitation damage, which is generally described in three stages: void nucleation, growth, and coalescence [1]. While the mechanisms governing void growth and coalescence are now well established and widely modelled, those associated with void nucleation remain insufficiently understood and difficult to quantify in a predictive manner, particularly at microscopic and atomic scales. In this context, void nucleation is generally attributed to the progressive accumulation of crystallographic defects induced by plastic deformation, in particular through dislocation activity and vacancy formation, which constitute the earliest forms of localized damage potentially leading to loss of cohesion.

These microscopic mechanisms of defect localization raise, at even smaller scales, several open questions. Interfacial decohesion is generally considered to proceed through two successive steps. The first corresponds to the formation of a nascent crack or an initial cavity, while the second is associated with crack propagation along the interface. However, the mechanisms governing the first step remain poorly understood. In situ transmission electron microscopy (TEM) observations suggest either that a matrix/precipitate interface may undergo partial decohesion [2], or that the walls of accommodating dislocation cells located near matrix/precipitate interfaces act as preferential nucleation sites for ductile fracture, rather than the interface itself [3].

The second step raises the question of the high stress levels required for crack propagation, which appear difficult to reconcile with the behaviour of a normally ductile microstructure undergoing plastic deformation. To address this apparent contradiction, alternative mechanisms have been proposed, based on the growth of a pre-existing embryonic cavity. These involve either vacancy absorption or growth mediated by the emission of prismatic dislocation loops [4]. However, existing micromechanical models rely on different assumptions depending on the approach, leading to widely scattered estimates of the critical stresses.

This uncertainty regarding the elementary mechanisms of damage highlights the need for model systems capable of isolating and comparing the different proposed hypotheses. In this context, Cu–Al alloys are particularly relevant systems for studying void nucleation. Depending on composition, they offer access to contrasted microstructures: two-phase states containing a matrix and intermetallic precipitates, suitable for studying interfacial decohesion, as well as concentrated solid solutions that may exhibit, under deformation, atomic rearrangements or structural transformations associated with electronic stability rules of the Hume–Rothery type, still debated in the literature. These different microstructures provide an ideal framework for investigating the influence of chemistry and microstructure on the early stages of ductile damage.

### 2. Objectives and approach

In this perspective, two complementary multi-scale experimental approaches will be implemented.

In-situ high-resolution transmission electron microscopy (HR-TEM) tensile tests will be performed in order to directly observe local deformation mechanisms and the earliest stages of fracture in model alloys. The associated strain field mapping will be analysed to identify the crystallographic defects involved, as well as possible phase transformations or structural evolutions (Figure 1a). A coupling with atomistic modelling of fracture would then be possible.

In parallel, interrupted tensile tests will be combined with three-dimensional characterization using Plasma-FIB tomography (Figure 1b). This approach will enable quantification of the evolution of damage in the bulk, in particular the formation and spatial distribution of voids. The 3D reconstructions may be

Complemented by 3D EBSD analyses in order to correlate damage development with both the initial and deformed microstructures.

The combination of these multi-scale approaches will make it possible to link local nucleation mechanisms, microstructural evolution, and macroscopic damage response. This study will improve the understanding of the earliest stages of ductile fracture in metallic alloys, with the aim of supporting more robust predictive models and ultimately contributing to the design of more damage-resistant alloys.

**Keywords:** Plasticity, ductile fracture, multi-scale approach, in-situ mechanical testing, 3D tomography, TEM.

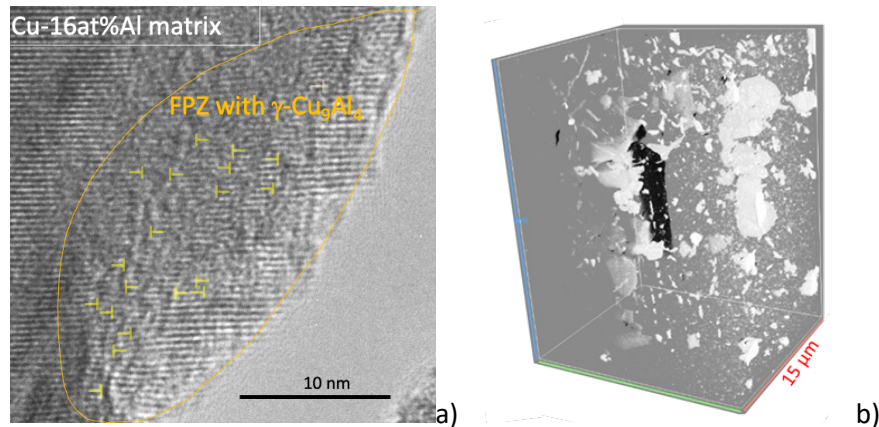


Figure 1: **a)** Fracture process zone (FPZ) in a Cu–16 at.% Al alloy observed by in situ HRTEM with a (111) edge-on orientation, showing the formation of nanograins at the fracture surface. A highly dislocated interface can be observed. **b)** 3D characterization by Plasma-FIB tomography of a deformed Al-4 wt% Cu alloy; dark regions correspond to ductile damage voids.

### Candidate profile

The ideal candidate will have a background in mechanical metallurgy, materials mechanics, or solid-state physics. A strong interest in experimental work is essential to successfully carry out this project. Skills in atomistic simulations would also be appreciated, in order to facilitate interactions with the theoretical component developed within the associated ANR project.

### Host laboratory

The PhD will be carried out at PIMM laboratory (Procédés et Ingénierie en Mécanique et Matériaux, ENSAM/CNRS/CNAM) in Paris, with regular stays at the Paris-Saclay area for experimental campaigns.

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