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X-ray Computed Tomography for Pores Evolutions Under Thermo-mechanical Loading : In Situ Characterization at Nano and Micro Scale

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Pores inside a material often significantly affect the properties of the bulk part. Such pores can originate from elaboration (casting pores, unmelt during additive manufacturing…) or from processing (e.g. damage nucleation during rolling). Subsequent thermo-mechanical treatments may induce some evolution either toward growth (e.g. opening mechanical state) or towards healing (e.g. hot rolling). Most of the models describing pores evolution kinetics are based on simple geometric assumptions (spherical or ellipsoidal shape), involve a single physical phenomenon (diffusion, plasticity, grain boundary sliding…) and/or are valid in a limited range of the mechanical parameters (triaxiality range, Lode parameter). There is a lack of experimental observations of pores evolution with pores of complex shapes submitted to a wide range of stress states representative of a bulk behavior.
Nowadays, X-ray computed tomography enable the acquisition of 3D images within a few minutes at micro scale (micro-CT) using an X-ray lab source and within a few seconds at micro and nano scales (micro-CT and nano-CT) using a synchrotron source [1]. These acquisition times are compatible with in situ thermo-mechanical tests. Some representative examples of in situ characterization of pore evolution under thermo-mechanical loading using lab source and synchrotron source micro-CT and synchrotron source nano-CT will be presented.

At micro-scale, mechanical tests representative of hot rolling conditions are conducted on an as cast aluminum alloy [2,3]. Digital volume correlation approach dedicated to large deformation [4] gives access to the stress states and enables to assess the validity of mechanical models for pore closure. Closure kinetics of branched pores are analyzed. Figure 1 presents a sequence of 3D rendering of a cylindrical sample submitted to high temperature compression (higher than 400°C) and imaged using synchrotron micro-CT (pores are highlighted in blue).

At nano-scale, the transition from diffusion driven growth mechanism to plasticity driven growth mechanism is investigated on a model aluminum copper alloy with copper rich spherical nodules during high temperature tensile tests (Figure 2). Experiments and models show a good agreement in this case where pores present simple shapes [5]. When tests are conducted on a fine grain magnesium alloys in the superplastic regime, the effect of the various physical phenomena responsible for the deformation (diffusion, plasticity, grain boundary sliding…) is clearly visible on the morphology of the pores and on their kinetics of evolution [6]. The classification of pores evolution enlightens the coexistence of the various mechanisms.

When characterization spatio-temporal constraints are relaxed, lab source CT is a widespread and easy access relevant tool. An example from geoscience: the densification of polar firn [7] illustrates the capabilities and the limitations of the lab micro-CT. The respective contributions of diffusion process and viscoplastic deformation on the pore closure are estimated thanks to a decoupling strategy. The activity of diffusion and dislocation glides mechanisms are also captured by local pores curvature analysis.

As a perspective, the expected potential of X-ray tomography within the next few years is discussed. The outcome of ESRF-EBS upgrade is illustrated by some preliminary experiments performed at ESRF in 2022 [8].

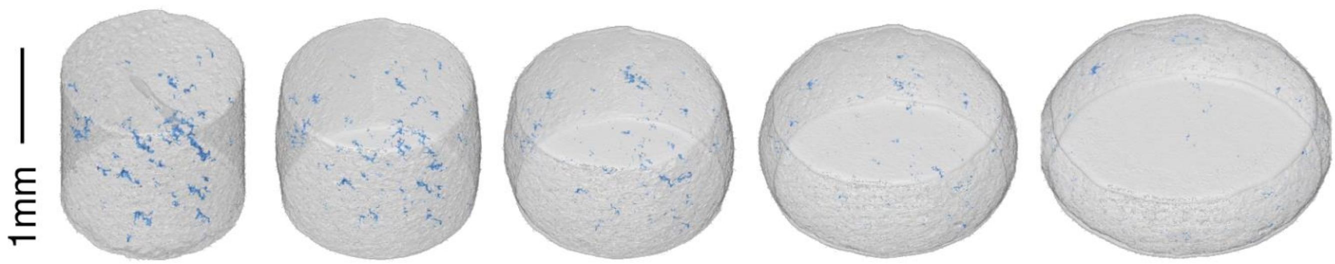

Figure 1. 3D rendering of as-homogenized Al alloy cylinder submitted to high temperature compression. Pores are highlighted in blue.

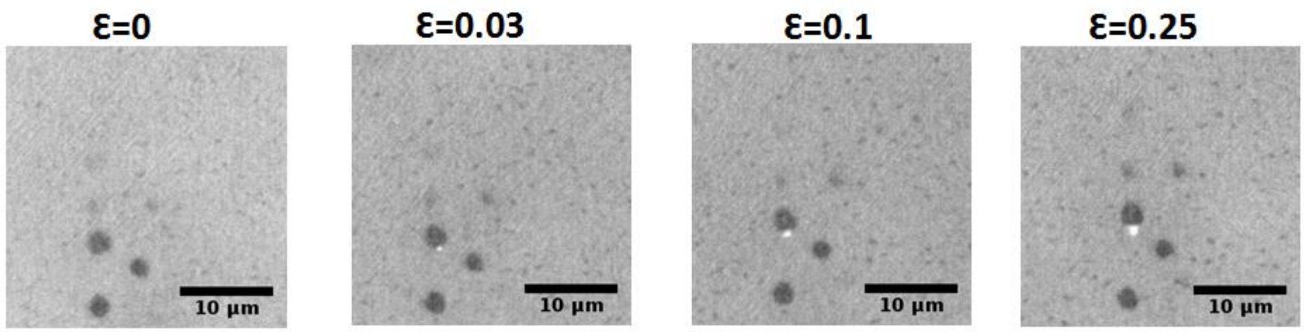

Figure 2. 2D cross sections inside the bulk of a model aluminum copper alloy submitted to high temperature tensile test. Dark gray is copper rich inclusions. Pore is white.

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