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Localized strain field measurement on laminography data with mechanical regularization

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A B S T R A C T

For an in-depth understanding of the failure of structural materials the study of deformation mechanisms in the material bulk is fundamental. *In situ* synchrotron computed laminography provides 3D images of sheet samples and digital volume correlation yields the displacement and strain fields between each step of experimental loading by using the natural contrast of the material. Difficulties arise from the lack of data, which is intrinsic to laminography and leads to several artifacts, and the little absorption contrast in the 3D image texture of the studied aluminum alloy. To lower the uncertainty level and to have a better mechanical admissibility of the measured displacement field, a regularized digital volume correlation procedure is introduced and applied to measure localized displacement and strain fields.

1. Introduction

Thin sheet structures are widely used in the transportation industry but their failure behavior is not always well understood. The three stages of ductile fracture, namely, void nucleation, growth and coalescence, are established but bulk data are still needed to assess the interaction between damage and strain localization at low levels of triaxiality, as shown in Fig. 1. Thanks to the development of 3D imaging and full-field measurement techniques, quantitative data can be obtained to address these issues. Synchrotron X-ray computed laminography (akin to tomography) allows 3D imaging to be performed at the micrometer scale for sheet like samples at the cost of additional noise due to the lack of information [1–4].

The volumes that are naturally contrasted can be used in digital volume correlation (DVC) analyses to measure 3D displacement and strain fields in the bulk. DVC is an extension of 2D digital image correlation [5] to 3D situations [5,6]. The first implementations of DVC have consisted of registering small interrogation volumes (or subvolumes) to determine their mean rigid body translations [7]. Local rotations have been added later on [8]. The warping of the interrogation volume has also been introduced in DVC codes [9]. All these approaches are referred to as local, since each analysis is local (i.e., at the scale of the interrogation volume) and no kinematic constraint is prescribed between neighboring subvolumes.

Global approaches to DVC have been introduced thereafter [10]. Contrary to local approaches, the displacement field is defined over the whole region of interest. In particular, in many instances, its continuity is enforced *a priori*. For example, the kinematics associated with finite element discretizations have been considered [10]. If cracks are to be analyzed, enriched kinematics have also been implemented to account for displacement discontinuities [11,12]. One further step is to regularize the correlation problem by requiring the measured displacement field to satisfy mechanical constraints such as the equilibrium [13,14]. In particular, in areas where the image texture is not sufficiently contrasted, mechanics is utilized to extrapolate the displacement field. If this type of information is not available, then the displacement measurement in these areas would not be possible. This issue is particularly important in 3D imaging as no artificial texture (e.g., secondary particles) can be added without altering the behavior of the studied material.

The aim of the present study is to evaluate the potential of these regularized approaches in the case of little absorption contrast in the 3D images in addition to the fact that complex kinematic fields are sought (i.e., strain localization). The main challenge is related to the fact that if the regularization is too strong, it may smear out the localized region. Conversely, if the regularization is too weak, the DVC calculations may not converge. One additional question is related to the impact of noise induced by laminography. It was

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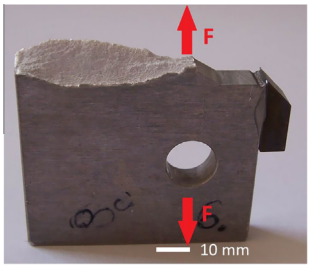

Fig. 1. Illustration of typical ductile fracture path of aluminum alloy sheet loaded in opening mode.

shown that the measurement uncertainty achieved by C8-DVC (i.e., global approach to DVC using 8-noded cubes) reaches levels [4] that are significantly higher than those achieved by analyzing tomographic data [15,16]. The latter are themselves higher than what is usually observed when dealing with standard 2D images [5,6].

The paper is organized as follows. The experiment analyzed herein is introduced in Section 2. It deals with the analysis via laminography of a notched sample made of aluminum alloy. Section 3 summarizes the regularized DVC approach to be used to measure displacement fields of the reconstructed volumes. The proposed regularization combines different functionals, which requires scaling to be performed. Associated with a given choice of normalizing displacement fields, new length scales are obtained. Strain resolutions are first determined in Section 4.1. A scaling strategy is proposed to get an almost unique tendency for different trial displacement fields. For the measured displacement field it is possible to determine strain data (Section 4.2). The cumulative total strain fields are shown and the effect of regularization length is assessed in terms of capturing localized strain fields.

2. Experiment

2.1. Laminography

Synchrotron radiation computed tomography (CT) is a 3D non-destructive technique for objects extended in one direction and thin in the other two directions. By inclining the specimen with an angle $\theta < 90$ degrees with respect to the beam direction, a region of interest that expands along two directions can be scanned [1], see Fig. 2. This technique is referred to as synchrotron radiation computed laminography (CL). A filtered-backprojection algorithm is then used to reconstruct the 3D volume [1,2].

The 3D images utilized herein were obtained at beamline ID19 of the European Synchrotron Radiation Facility (Grenoble, France) with a monochromatic beam of 25 keV, with a 65-degree rotation axis inclination angle and 1500 projections. The reconstructed volumes have a size of $2040 \times 2040 \times 2040$ voxels, with a voxel size of 0.7 μm. More details on the experimental configuration and on

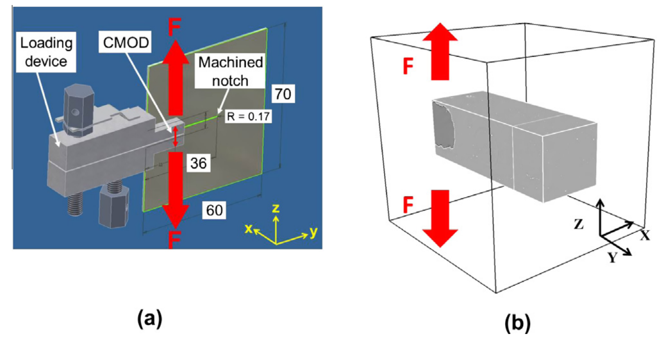

Fig. 3. (a) Schematic view of the analyzed test [4]. The *x*-axis lies along the thickness of the plate, the *y*-axis corresponds to the main propagation direction, and the *z*-axis is aligned with the load direction. (b) The scanned volume is sketched as a cube delineated in black. The region of interest is a parallelipedic volume away from the notch, which can be seen as a dark region for small *y*. It is a gray volume limited by white lines for large *y*.

analyses of the reconstructed volumes themselves can be found in Ref. [17].

2.2. Material and experimental setup

The material used for this study is a commercial Al–Cu aluminum alloy (AA 2198) in T8 condition. The geometry of the flat and notched specimen is schematically shown in Fig. 3(a). The 1-mm thick sample (60-mm in width and 70-mm in height) has a notch that has been machined by EDM leading to a radius of 0.17 mm. The loading consists of opening the notch mouth with a displacement controlled by 2-screw device. Stepwise loading has been applied between each laminography scan. An anti-buckling device, which is not shown, has been mounted around the specimen, leaving a window close to the notch to scan the volume close to the notch. From the scanned region, the region of interest for DVC analyses is chosen to be away from the notch root (Fig. 3(b)).

For the analyzed region of interest, the amount of information is quite low, as shown in the histogram of gray level in Fig. 4(a) and and in the volume with enhanced contrast from Fig. 4(b). Further, the inclusion volume fraction is of 0.3–0.4%. The presence of ring and reconstruction artifacts can be noticed in Fig. 4(b) and makes DVC difficult because it has to be based on the true microstructure and not on artifactual features. It is interesting to assess the development of strains and in particular the strain pattern in such type of experiment and its impact on the final damage change. To address this issue, there is a need for reliable kinematic measurements (i.e., displacement and strain fields) in the presence of very poor textures (Fig. 4). Once such data are available, the next question to answer is linked with the detection of damage. These two points are solved by resorting to global and regularized digital

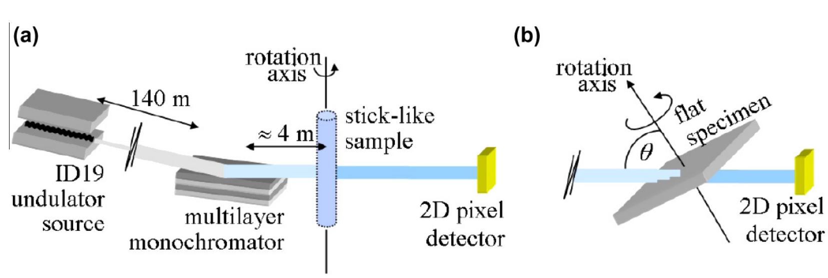

Fig. 2. Schematic view of the CT (a) and CL (b) setup with the ESRF parallel beamline (after [4]).