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CAPTURING POLYCRYSTAL PLASTICITY AND INTERGRANULAR CRACKS WITH A NOVEL DIC METHOD

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Abstract. The aim of this paper is to validate a novel DIC method which allows to capture kinematic fields of potentially cracked polycrystalline aggregates. A key feature of the method introduced is that intergranular and intragranular effects can be considered explicitly in the data processing. In this paper, we mainly focus on the validation procedure, which was performed on numerical examples associated to cracked polycrystalline aggregates.

1 Introduction

Surface displacement field measurements of materials subjected to various loadings (e.g. mechanical loading or thermal loading) are an important task for experimentalists conducting research in the field of solid mechanics. Aside from the widely used strain gauge technique, various full-field non-contact optical monitoring methods [1], including both interferometric techniques and non-interferometric techniques, have been developed and applied for this purpose.

In recent years, we have witnessed an increasing number of spectacular developments in optical full-field measurement techniques [2]. The interferometric techniques involve delicate procedures which are not always suited for experiments in conventional testing laboratories. Conversely, the Digital Image Correlation (DIC) method widely considered as a representative non-interferometric optical technique, has been widely accepted and commonly used as a powerful and flexible tool for the surfacic strain measurement in the field of experimental solid mechanics [3, 4, 5].

Crystal plasticity is usually used as the constitutive model to describe the response of crystal grains. The objective of single crystal plasticity is to introduce knowledge of dislocation theory into plasticity of a continuum of solids [6]. In material science, crystal plasticity is now classically used to describe the single crystal mechanical response involving its slip system activity. One major interest of micromechanics of heterogeneous polycrystalline materials is to access local mechanical fields in a given microstructure associated to surfacic strain fields that can be measured [7, 8, 9], in order to contribute to a better understanding of the microstructure dependence of yield behaviour during the mechanical loading at granular scales, and to assess local stress fields in view of developing physically based damage models.

In this paper, a new method is proposed to perform the local strain field measurements relying on DIC algorithms, with a specific treatment of intergranular and intragranular discontinuities. The objective of this paper is to present and to validate this novel processing method, which allows us henceforth to evaluate the material behaviour at both a micro and macro scales.

2 Numerical Validation

2.1 Numerical example generation

In order to validate the proposed methodology on heterogeneous strain fields, it was chosen to use computer-generated speckle cracked images associated to a completely known strain field.

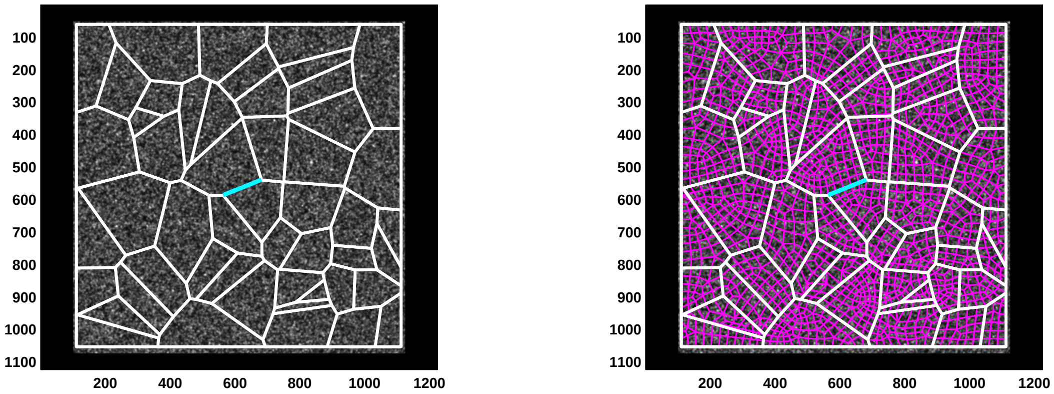
The strain field was obtained by direct crystal plasticity Finite Element (FE) analysis for a given crystal plasticity law [10] and for a given set of boundary conditions and grain orientations. For this numerical study, a realistic aggregates of 50 grains was generated by using a classical Voronoï tessellation, the chosen material behaviour obeys to the Méric-Cailletaud model, described in [10]. The simulation of experimental tensile test was performed using the finite element package Aster with a mesh of 11300 quadratic triangular elements in a bi-dimensional framework under a plane strain assumption [11].

The aim of this FE computation is to provide realistic kinematic fields associated to equilibrated stress fields. Afterwords, the simulated displacement field was then introduced in the virtual image generation procedure, as described in [4], to mimic the acquisition of the series of speckle images by a digital visible camera. It was chosen not to introduce any image distortion in the synthetic images.

2.2 Spatial discretization of the synthetic image

In order to determine precisely the local strain field, particular care should be given on the meshing. With a known microstructure (Figure 1a), where the crack is indicated using a cyan color line, the spatial discretization is performed using an unstructured mesh in order to represent the grain boundaries of the material (Figure 1b).

In this unstructured mesh (Figure 1b), the smallest mesh unit is called "element",



(a) Microstructure for synthetic image

(b) Unstructured mesh

Figure 1: Microstructure with unstructured mesh. Initial crack is indicated using a cyan line.

which is the equivalent of the Correlation Zone (CZ) for classical DIC technique. Each element is constituted by a set of pixels within a polygon. The elements' boundaries are determined accurately and retained in order to apply specific adjacency condition with other elements. Knowing the grain boundaries for the material, with this microstructural discretization method, no element belongs to more than one grain. Therefore, this is a suitable computational mesh for dealing with discrete structure problem (polycrystalline metallic materials, etc.).

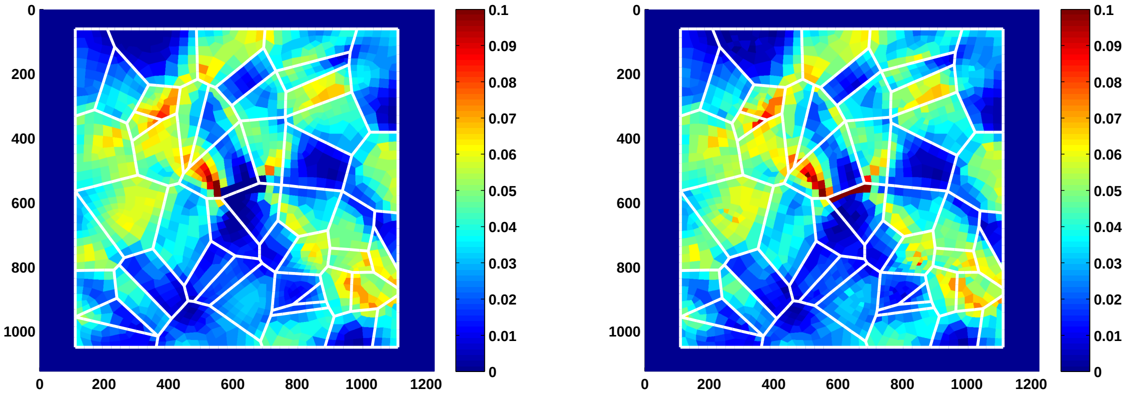
3 Numerical Results

Once the computational mesh is obtained, we introduce the different kinematic continuity constraints in order to describe the mechanical features of material at the different physical scale.

The first solution is to impose no continuity constraints at all between elements (see Figure 2b, where the displacement field is continuous only inside element). The second possibility is to impose normal and tangential continuity on the boundaries of all elements belonging to a given grain. The displacement field is thus continuous within each grain but possibly discontinuous between two adjacent grains (see Figure 2c). The third possibility proposed here is to enforce the normal and tangential continuity of the displacement field at the boundaries of all elements, except the ones corresponding to the crack (see Figure 2d).

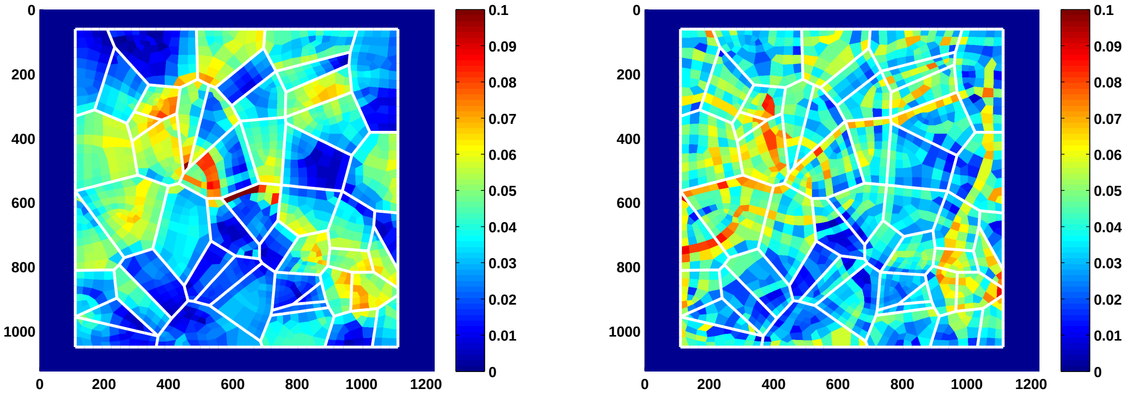
Figure 2 shows the equivalent strain field maps in the Von Mises sense for the cracked polycrystalline aggregates.

The Finite-Element reference computations which are performed with the cracked aggregate up to 2% macroscopic strain is represented in Figure 2a. And Figure 2b, 2c, and



(a) Simulation Aster

(b) Intra-element continuity



(c) Intra-granular continuity

(d) Inter-granular continuity

Figure 2: Equivalent Von Mises strain fields for the cracked polycrystal aggregates

2d show equivalent Von Mises strain fields obtained with the method introduced with the three different continuity levels. In the DIC computation, the kinematic shape function is bi-linear. The mesh is made of 1513 elements distributed in the 50 grains.

The less constrained situation corresponds to no continuity condition except inside each element (Figure 2b), which corresponds to classical local DIC approaches [4, 12], and the displacement fields are described by $1513 \times 4 \times 2 = 12104$ Degrees Of Freedom (DOFs). In this circumstance, the computation is suitable for describing the intragranular behaviour of the polycrystalline aggregates, but it is very sensible to the noise (the noise sensitivity is not discussed in the present paper).

The most constrained situation is associated with the intergranular continuity, which is very similar to the global DIC approaches proposed in [5, 13], except that the continuity of the displacement field is enforced in the real space and not in the isoparametric space of the reference element. This leads to much constrained displacement fields compared to the above mentioned global approaches. For our study, the kinematic fields are described using only 170 DOFs. Figure 2d shows that this set is too small to represent accurately the displacement fields. In this case, the continuity conditions should be restrained in order to improve the accuracy of the measurements.

The intermediate situation consists of intragranular continuity (Figure 2c) which corresponds to 1372 DOFs. It is thus more robust with respect to image noise. This situation is particularly suited to describe intragranular strain heterogeneities and intergranular discontinuities (such as grain boundary slip).

4 Concluding Comments

The comparison of strain fields calculated by DIC and obtained by FE simulation is conclusive to validate our methodology. Furthermore, this method will be validated numerically on the noisy images before applying to experimental visible images collected during a tensile test on a polycrystalline aluminum sample, which could process the full-field kinematic data grain per grain in order to establish the relationship between local strain fields and microstructure at grain scale.

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