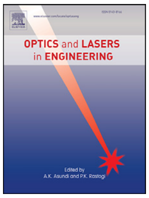
Optics and Lasers in Engineering 112 (2019) 182–195

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Review

Investigations of the thermomechanical behavior of a coarse-grained aluminum multicrystal using Constrained full-field measurements methods

L. Li[a,*], F. Latourte[b], J.-M. Muracciole[a,c], L. Waltz[a,c], L. Sabatier[a,d], B. Wattrisse[a,c]

[a] *LMGC, Univ. Montpellier, CNRS, Montpellier, France*
[b] *EDF R&D, MMC Department, Moret-sur-Loing, France*
[c] *Laboratoire de Micromécanique et d'Intégrité des Structures (MIST), IRSN-CNRS-Université de Montpellier, Montpellier, France*
[d] *Aix Marseille Univ, CNRS, Centrale Marseille, LMA UMR 7031, Marseille, France*

ARTICLE INFO

Keywords:
Digital image correlation (DIC)
Constrained DIC
InfraRed Thermography (IRT)
Constrained IRT
EBSD analysis
Displacement and strain mapping
Crystal plasticity

ABSTRACT

With the intention of achieving an experimental grain scale energy balance at finite strain and at the grain scale, a mechanical test on a coarse-grained aluminium is presented in this paper using two complementary imaging techniques based on visible and infrared light. Specific image processing methods referred to as Constrained Digital Image Correlation (Constrained DIC) and Constrained InfraRed Thermography (Constrained IRT) are applied to investigate the thermomechanical behavior at the microstructural scale. Constrained DIC is used to obtain displacement and strain fields during the test, while Constrained IRT provides an estimate of temperature and heat source fields induced by the mechanical loading. The proposed "constrained" methods allow to enforce an adjustable level of constraints on a measured field (displacement or temperature) without referring to a specific finite-element description. In that manner, it is possible to decouple the measurement model and the interpretation model while keeping regularizing constraints (such as continuity of the fields). In this paper, we mainly focus on the **kinematic** analysis of the experimental test. Electron Backscatter Diffraction (EBSD) is also used in this case to experimentally characterize the microstucture of a 3 mm thick specimen with centimetric grain size.

1. Introduction

Polycrystalline metals usually possess a microstructure composed of an aggregation of crystalline grains with varying size, morphology and orientation. During a macroscopic tensile loading, the diversity of grain orientations and the intrinsic anisotropy of crystal plasticity leads to strong heterogeneities in the material plastic response, and consequently to an inhomogeneous thermal distribution due to thermomechanical effects.

Recently, heterogeneous phenomena on mechanical and thermal fields have been studied in metallic materials at the granular scale [1–6]. All these works have shown the variety of micromechanical modelling issues that can be addressed using classical DIC (Digital Image Correlation) & IRT (InfraRed Thermography) method. Hereafter, a "Constrained" surface DIC or IRT method is proposed to enrich the kinematic or thermal transformation of neighbouring elements (or grains) by imposing continuity (or discontinuity) conditions on the displacement (or the displacement gradient component) or on the temperature (or the temperature gradient).

Performing strain field and heat source measurements ultimately allows to access to the evolution of the mechanical and calorimetric energies involved in the transformation. This assessment contributes to a better knowledge of the local thermomechanical signature of the material deformation mechanisms.

As mentioned, two data processing methods (Constrained DIC [7,8] and Constrained IRT [9]) are required to perform kinematic and thermal measurements that are both needed to conduct a local energy balance within each grain during a mechanically-loaded test. In the light of this general objective, we mainly focus in this paper on the **kinematic** aspect of the aforementioned general methodology.

First, the principle of Constrained DIC method will be introduced. Then, the numerical validation of Constrained DIC method will be performed on numerical example associated to cracked polycrystalline aggregates. Afterwards, this novel method will be applied to real experimental images.

In fact, surface displacement field measurements of materials subjected to various loadings (*e.g.* mechanical loading or thermal loading) are an important task for experimentalists addressing challenges in the field of solid mechanics.

In recent years, an increasing number of spectacular developments in optical full-field measurement techniques has been witnessed [10], including both interferometric techniques and non-interferometric techniques. However, the interferometric techniques involve delicate proce-

---

[*] Corresponding author.
E-mail address: li.li@univ-montp2.fr (L. Li).

https://doi.org/10.1016/j.optlaseng.2018.08.003
Received 30 December 2017; Received in revised form 20 July 2018; Accepted 8 August 2018

dures which are not always easily transferable to conventional testing laboratories. Consequently, the Digital Image Correlation (DIC) method widely considered as a representative non-interferometric optical technique, has been largely accepted and commonly used as a powerful and flexible tool for surface displacement and strain measurement in the experimental solid mechanics field [2,4,6,11–14].

These measurements are particularly valuable in the sense that they allow the interpretation of complex tests at different scales and that they are naturally adapted to scale transitions. For these reasons, they have been largely used to characterise the deformation mechanisms or to propose and validate micromechanical models or scale transition laws.

From a microstructural viewpoint, polycrystalline materials are a discrete structure that are composed of jointed grains with varying sizes and orientations. The characterisation and measurement of grain structures is of great interest to Materials Scientists because they are directly related to the physical properties of matter [15,16].

Our objective here is the understanding of the relationship between the microstructural parameters and the mechanical behaviour of the heterogeneous materials at the macroscopic scale, in particular at the granular length scale [17–19].

Using the classical local approaches, the material microstructure is not accounted for in the kinematic computation:

- Firstly, the introduced subsets (for DIC) are independently defined from the microstructure
- Secondly, as the transformation of neighbouring subsets are separately processed, so subsets may overlap.

This is an inherent disadvantage of these local methods when dealing with heterogeneous structure problems.

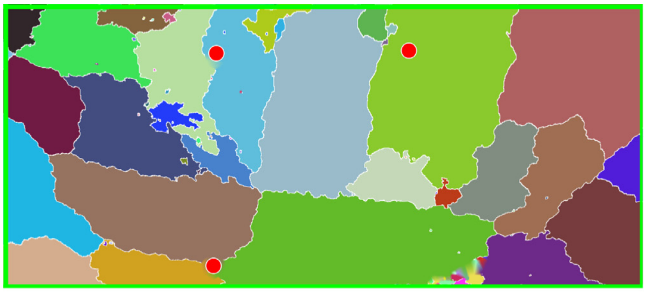
Nevertheless, classical local DIC methods have been widely used to highlight the heterogeneity in kinematic fields [2,6,12,20], in a large range of situations dealing for instance, with the fracture mechanics (intergranular or intragranular) problems.

2. Principle of constrained DIC method

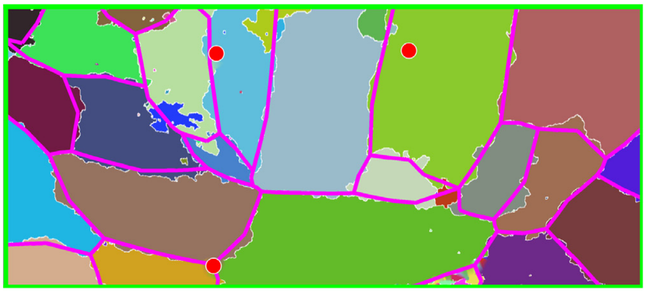
Global DIC methods were proposed to determine the displacement and strain fields on the whole image. These methods propose to parametrize the kinematic fields using a limited set of degrees of freedom which tends to regularize the DIC problem. These methods were firstly introduced to impose the continuity of measured displacement on a finite-element mesh [21,22] or using B-splines [23,24]. Gobal DIC methods were afterwards extended to allow some discontinuities in the displacement fields to account for crack development [25,26].

The Constrained DIC method proposed here corresponds to an alternative to global DIC methods. It relies on a mesh that respects the material microstructure and it introduces shape functions that are expressed in the real space and not on the associated reference element (as in classical finite elements). The shape functions can be any kind (we generally use linear, bi-linear, quadratic, bi-quadratic polynomial functions), and the shape function choice is independent of the shape of the element. The most significant difference with global (finite-element based) DIC methods relies in the fact that the level of restriction between two adjacent elements can be modified by choosing the number (and the location) of points where to enforce the continuity conditions on the element boundary. It is also interesting to note that the proposed method allows to handle in the same framework classical local DIC methods (which corresponds to a regular rectangular mesh with no continuity condition between each elements) to global finite-element based methods on regular meshes (by imposing continuity conditions on the ends of each element boundary).

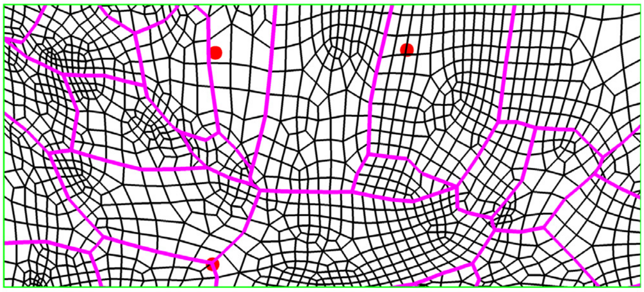
As classical DIC approaches (whether local or global), the proposed method also relies on the Brightness Conservation equation [27] motivating the use of a pattern recognition algorithm for the detection of changes in the grey level distribution of targeted surface during loading. Indeed, the main steps of Constrained DIC method are the following:



(a) Microstructure of a polycrystalline metallic material analysed by EBSD



(b) Grain boundaries extraction



(c) Unstructured mesh for this polycrystalline material

Fig. 1. Spatial description of the geometry of a polycrystalline aggregation. The grain boundaries are in magenta and the element contours are in black. And the three red dots are for spatial matching procedure [6]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Spatial discretization of the geometry
  Through an EBSD analysis, a two-dimensional array of data associated with the microstructure is provided by microscopic devise [28,29]. Afterwards, this microstructural map (Fig. 1a) can be used to perform a spatial discretization (Finite Element type) in order to respect as much as possible the real microstructure. The obtained mesh is used for subsequent processing of the kinematic response.
  In order to optimize the meshing procedure, the real grain boundaries (white contours in Fig. 1a) are simplified and polygonized so as to keep the large grains and regroup the smallest ones, as shown in Fig. 1b in magenta. By construction, the level of microstructural simplification has to be adjusted depending on the spatial resolution associated with the kinematic and/or thermal measurement. The introduced uncertainty during the grain boundary extraction operation is not quantified, which is supposed to be negligible in this paper.
  Afterwards, an unstructured mesh is carefully applied on the “simplified” geometry (representing the microstructure) within each grain in order to keep the representation of physical grain boundaries, as shown in Fig. 1c. Inside each grain, the smallest mesh unit is called an “element”, which is equivalent of the correlation subset for classical DIC methods. The element contours are accurately determined.