ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 18 (2018) 630–644

Available online at www.sciencedirect.com

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journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Determination of coupled mechanical and thermal fields using 2D digital image correlation and infrared thermography: Numerical procedures and results

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ARTICLE INFO

Article history:
Received 5 May 2017
Accepted 8 October 2017
Available online

Keywords:
Digital image correlation (DIC)
Infrared thermography (IRT)
Coupled thermo-mechanical fields
Aluminum multicrystal

ABSTRACT

The objective of the work is to develop numerical method for determining coupled thermo-mechanical fields based on experimental data obtained from two cameras working in the visible and infrared mode. The sequence of images recorded by the first camera is used to determine the displacement field on the sample surface using the 2D digital image correlation (DIC) method. The resulting field from DIC analysis in a form of a set of discrete points with the corresponding in-plane displacement vector is used as the input for the next step of analysis, where the coupled temperature field is computed. This paper provides a detailed description of the numerical procedures, that allow, to obtain coupled thermal and mechanical fields together with the specification of experimental data needed for calculations. The presented approach was tested on an experimental data obtained during uniaxial tension of the multicrystalline aluminum. The developed numerical routine has been implemented in dedicated software, which can be used for the testing of materials on both a macro and micro scales.

1. Introduction

Deformation processes usually proceed in a localized way when considered in both macro and micro scales. Thus, in order to obtain the complete view of the mechanical behavior of the tested material, the field methods of measurement of mechanical quantities should be applied. One of these is the digital image correlation (DIC) method, which for many years has found its application in experimental mechanics as a method for displacement and strain measurements [1,2]. The origin of DIC is the speckle photography technique, which was first published in the early 1980s [3]. From that moment on, the continuous development and improvement of this method has begun. The basic theory and numerical procedures of the DIC were given in [4]. Sutton et al. proposed an improvement of iterative method which reduce computation time in DIC analysis [5]. The next important step in the development of the

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https://doi.org/10.1016/j.acme.2017.10.005
1644-9665/

List of symbols

$\mathbf{x} = (x, y)$ Eulerian coordinate system
$\mathbf{X} = (X, Y)$ Lagrangian coordinate system
$\mathbf{u} = (u_x, u_y)$ in-plane displacement vector
$\mathbf{F}$ deformation gradient
$\mathbf{R}$ rotation matrix
$\mathbf{U}$ stretch tensor
$\mathbf{E}$ Lagrangian strain tensor
α rigid rotation angle
t time
$\mathbf{f}$ reference image gray-level intensity vector
g current image gray-level intensity vector
c correlation coefficient
ϵ emissivity of the specimen's surface
T temperature

DIC method was application of Newton–Raphson technique as an alternative to the coarse-fine search technique used in calculation of subset deformation [6]. The authors of work [7] gave an extensive review of correlation criteria and algorithms that are mostly used and well established in DIC analysis. Reliability-guided DIC which can be applied for calculation of deformation of objects with complex shapes was given in [8]. Finally the concept (FE)-based global digital image correlation and its comparison to standard subset-based DIC was discussed in [9].

On the other hand, plastic deformation is an irreversible process accompanied by dissipation of energy in form of heat. Therefore, many authors use the infrared thermography (IRT) in order to study thermal effects during deformation process. The main advantage of IRT, is the real time non-contact measurement of temperature distribution on the specimen's surface. In the literature different aspects of thermal effects accompanying the deformation process were analyzed. The paper [10] presents the experimental and theoretical study on stored and dissipated energy evolution and their influence on formulation of isotropic and kinematic hardening law. The propagation of the Lüders band based on thermal data was investigated in [11]. Thermo-mechanical coupling during tension test for austenitic steel was analyzed by the author in [12]. In [13] the IRT was used to study the fatigue in metals taking into account the occurrence of intrinsic dissipation. The analysis of the temperature field was used for determination of the strain localization during static [14] and quasi-static [15] tensile loading. Finally in [16] the experimental method based on IRT and visible imaging was developed for analyzing the energy storage rate distribution in the area of strain localization.

Nevertheless, one of the drawbacks of IRT applied for testing of materials, is the inability to assign the measured temperature of the sample surface to its material point. An infrared camera is directed at the fixed area of space and does not follow the deformation of the sample (Eulerian description of motion). However, in the solid mechanics, a convenient way is to use the Lagrangian description of motion, which allows one to track the change of mechanical fields in time at the material point level. There are many works in the literature in which both techniques are used in order to study thermo-mechanical effects during the deformation process of a wide class of the materials. The localized necking of steel was studied in [17], a notched titanium rolled sheets was experimentally and numerically analyzed in [18] and the coarse-grained aluminum multicrystal was studied during load-unload tensile test in [19].

Usually, the mechanical and thermal fields are determined on opposite sides of the specimen and the obtained results are presented in different coordinate systems [20,16]. This approach allows for the qualitative analysis of obtained results only and is not sufficient in many cases. Nevertheless, there are some papers in which authors determine the coupled mechanical and thermal fields [21,22]. In this case the same area of the specimen is observe simultaneously by two cameras (visible range and InfraRed), using especially designed experimental setup. Then, the displacement field obtained by using separate software is used for tracking the temperature field during deformation. Following the direction of that research, in this paper the algorithm of a traditional DIC 2D method is proposed together with a numerical procedure that extends its ability for coupling the thermal field. The detailed descriptions of the correlation and coupling procedures are presented. The procedures are implemented in the dedicated ThermoCorr software developed by the authors [23]. The software allows for: determination of the displacement field using DIC 2D algorithm, the space and time coupling procedure and carry out the analysis of obtained results. Due to the fact that the obtained data are fully coupled, any further calculation can be made in order to get distributions of other quantities, i.e. plastic work, energy dissipated as heat, etc. This gives the possibility to study the mechanisms of dissipation and energy storage during a deformation process. This paper is organized as follows. In Section 1 a short introduction is presented. Section 2.1 includes the description of experimental data registered simultaneously by two cameras working in visible and infrared mode. This section gives also the basic information about the structure of the input data used for calculation. In Section 2.2 the fundamental concepts of the 2D DIC is presented. Section 3 contains the detailed description of the temperature field determination. The space and time coupling procedure of displacement and temperature fields are shown in Section 4. In Section 5 the methods of determination of strain and rigid rotation are presented. Then, the implementation of presented procedures is shortly described in Section 6. The experimental procedure and results obtained using the developed software for the analysis of uniaxial tension of multicrystalline aluminum are presented in Sections 7 and 8, respectively. Finally, a summary and conclusions are given in Section 9.

2. Numerical procedures

2.1. Data acquisition

The estimation of coupled thermo-mechanical fields requires two independent sequences of data obtained during the