Optics and Lasers in Engineering 86 (2016) 264–274

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Infrared thermography coupled with digital image correlation in studying plastic deformation on the mesoscale level

Xiaogang Wang [a,*], Jean-François Witz [b], Ahmed El Bartali [b], Chao Jiang [a]

[a] Sate Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, 410082 Changsha, PR China

[b] LML UMR CNRS 8107, Université Lille Nord de France, Bd. Paul Langevin, 59655 Villeneuve d'Ascq, France

ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form
4 May 2016
Accepted 3 June 2016
Available online 24 June 2016

Keywords:
Infrared thermography
Digital image correlation
Coupled measurement
Oligocrystal
Out-of-plane deformation

ABSTRACT

This paper focuses on a study of plastic deformation on the mesoscale level by infrared thermography coupled with digital image correlation. First, a novel technique for fully-coupled thermal and kinematic measurements was developed, and the common problem of spatial coupling in the multifield measurement was solved successfully using an image registration method. Then the developed technique was applied to investigate the plastic deformation of a pure aluminium oligocrystal specimen in a tensile test. The deformed specimen manifested high strains of type out-of-plane, which were found closely associated with the crystallographic structure. From a metrological point of view, the out-of-plane effect on the thermographic measurement was analyzed, and the pertinent radiometric artifacts were estimated. The source of errors was verified through a correlation analysis between the estimated artifacts and specimen surface profile. Moreover, the out-of-plane effect on the kinematic measurement was investigated, and the relevant errors were analyzed via the correlation residual. The analysis highlighted the role of the microstructure that played in the plastic deformation and showed that grain boundary was crucial in shaping the heterogeneous deformation patterns for aluminium oligocrystals.

1. Introduction

It is known that any metallic material undergoing plastic deformation tends to dissipate a part of strain energy as heat. One of the very interesting issues associated with energy dissipation is that it is usually a very sensitive indicator of the microstructure evolution [1–6]. The idea of using heat release to study the thermomechanical behaviour of materials can date back to the 1930s. By recording the heat development during plastic deformation, Taylor and Quinney [7] were able to quantify the dissipated energy and then to access the latent energy (or stored energy). It demonstrated that a global energy balance in plastic deformation could be experimentally established based on the measurements of heat and deformation. This seminal work was pursued by numerous researchers in a period of nearly a century with substantial improvements on the experimental characterization methods [8–10]. Nevertheless, most of the investigations remain at a macroscopic scale, and some insight on the intrinsic links between energy evolution, heterogeneous deformation pattern and microstructural changes has rarely been reported.

On the aspect of the metrology, now there is a high demand for more detailed information being experimentally accessible, such as the distributions of temperature and strain in a heterogeneous deformation process. Recently, it has become realizable thanks to the development of full-field measurement techniques, e.g., infrared thermography (IRT) for measuring temperature field [11–13] and digital image correlation (DIC) method for accessing displacement and strain fields [14–19]. These techniques have the advantages of non-contact, real-time, full-field measurement and high precision. In the community of mechanics of materials and structures, the IRT and DIC methods have been extensively used for characterizing the material behaviours in terms of temperature, heat sources and strain. In many occasions, the temperature field and strain field are expected to be obtained simultaneously, then an experimental energy balance could be possibly established within a two-dimensional space. For performing such a thermal–kinematic coupled measurement, different technical solutions have been proposed. They can be classified into two groups according to their experimental set-ups: namely single-face measurement [20–26] and two-face measurement [27–32]. The first experimental configuration refers that both IR camera and visible-light camera observe the same face of the specimen. And for the latter layout, each imaging device observes one face of the specimen, thus both faces are being measured. In addition, a special

* Corresponding author.
E-mail address: xgwang@hnu.edu.cn (X. Wang).

http://dx.doi.org/10.1016/j.optlaseng.2016.06.001
0143-8166/

technique called infrared image correlation method has been recently developed. It allows both temperature and strain measurements on the same face of the specimen through a single IR camera [33–35]. In some studies [36,37] that employed only thermal field measurement, some dedicated motion compensation methods were developed for the displacement evaluation. In this work, an original two-face measurement technique is also developed, with a proper solution to the common problem of spatial coupling in the multifield measurement.

On the aspect of the application, the full-field measurements have been extensively applied to the mechanical testing and evaluation of the metallic materials and elastomers [30–32,36,37]. They show particular values in characterizing the heterogeneous deformation process of materials, which can be embodied both in the thermal and kinematic fields [38–41]. Presently, a noteworthy tendency of the current research is the transformation of the observation scale from the conventional macroscale to the mesoscale and even microscale. The research on the microstructure scale now attracts an increasing attention. Such studies can be carried out either via the incorporation with microscopic devices [42,43], or by directly investigating a special kind of specimens with simple structures, e.g., oligocrystal [44,45], bicrystal [46] and single crystal [47–49]. The latter solution can reduce the technical difficulty in the measurement to a certain extent and enables to demonstrate the microstructure-dependent phenomena on a macroscale or mesoscale level. Nevertheless, the studies show that an important surface roughening effect (or out-of-plane deformation) tends to occur on the specimens made of coarse grains, as remarked by [44]. In a quantitative analysis on the deformed bicrystal specimen in [46], one grain was measured being shifted around 150 μm in height with respect to the other grain, leading an abrupt geometrical change at the grain boundary. Such kind of out-of-plane deformation may produce considerable affections on the optical measurements, including both IRT and DIC. This effect, however, was mostly disregarded in the relevant studies, and a necessary metrology analysis was often absent.

In this work, the studied material is a pure aluminium oligocrystal specimen with a single layer of coarse grains. It undergoes plastic deformation in a tensile test, being measured simultaneously by the developed IRT-DIC fully coupled measurement system. The heterogeneous characteristic of the plastic deformation at the grain scale is studied based on the obtained temperature and strain fields. In particular, the out-of-plane deformation and its influence on the optical measurements are analyzed quantitatively.

2. Material and technology

The preparation of the studied material aluminium oligocrystal is first introduced, followed by the presentation of the technical development in this work for performing the thermal–kinematic fully coupled measurement.

2.1. Material preparation

The oligocrystal specimen was prepared by the strain-annealing method [46], from a very pure aluminum (purity 99.99%) plate. The preparation procedure is summarized by the following steps:

1. The specimens cut from the original metal sheet were firstly annealed at 545 °C for 1 h. This first annealing allows removing of the residual stresses resulting from the manufacturing process.
2. Annealed specimens were then stretched by around 3.5% longitudinal strain that corresponds to the “critical strain” value necessary to obtain, after a second annealing of recrystallization, maximum grain size.
3. Stretched specimens were finally annealed at 545 °C for 1 h.

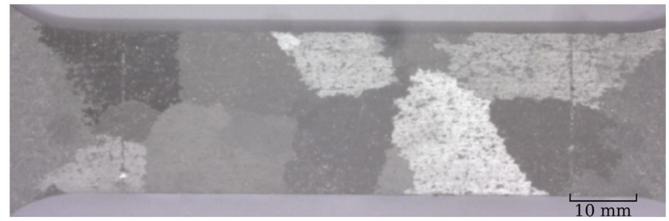

Fig. 1. The surface of a pure aluminium oligocrystal specimen after recrystallization and chemical etching.

The final obtained oligocrystal specimen contains about 10 grains in a single layer. The average diameter of the grains can attain 15 mm, and the thickness of the specimen is 1.5 mm. In order to observe the grain texture of the oligocrystal specimen, a chemical etching is necessary. The chemical etching can form an oxide layer with variable thickness on the material surface that allows distinguishing the grains with the naked eyes. Fig. 1 shows the surface of an oligocrystal specimen after the chemical etching.

Concerning the anticipated two-face measurement, one important issue is the identity of the grain textures appearing on the two faces of the specimen. In other words, the grain boundaries are expected be perpendicular to the specimen surface, which can best ensure a quasi-identical mechanical behaviour manifesting on the two specimen faces on a grain scale (being aware that the specimen is made of a single layer of grains). Fig. 2 shows the grain textures of the two faces of the specimen (face A for kinematic measurement and face B for thermal measurement) and the overlay of the respective grain boundaries extracted.

Fig. 2 exhibits that the overlapping of grain boundaries is satisfactory on a grain scale, in particular for the coarse grains in the center of the specimen. For some small grains, e.g., the ones located in the upper left corner of the specimen, their overlapping effect is less satisfactory. For these particular zones, it should be very attentive when the coupled measurement results are expected to be compared. For most of the grains, we can assure that the grain boundaries are perpendicular to the specimen surface.

2.2. Technical development

In the two-face measurement configuration, each imaging device (IR/visible-light camera) observes one face of the specimen. The main advantage of this experimental set-up is that each technique has the flexibility to choose the surface coating for its own good, without special constraints. It is very important concerning the measurement precision for both techniques, as generally the IRT prefers a uniform coating of very high emissivity, and the DIC measurement, in contrast, requires a speckled coating with strong black-white contrast.

The main problem involved in the two-face coupled measurement is the spatial alignment of images captured on the two different faces of the specimen. First, the IR and visible-light cameras should be able to observe the same zone of the specimen disregarding its thickness. Second, the sensor plane of the camera is difficult to be aligned perfectly parallel to the specimen surface. Thus, the captured images are often projective imagery of the object. In addition to the projection effect, the optical images may also suffer from geometrical distortions owing to the defects of the imaging system. For the purpose of eliminating all the unintended non-matched effects (rigid motion, projection and distortion) in the two-face coupled measurement, a dedicated spatial alignment