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Experimental setup for fully coupled kinematic and thermal measurements at the microstructure scale of an AISI 316L steel

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ABSTRACT

In polycrystalline metallic materials, above a certain threshold, mechanical deformations induce plastic strains at the grain scale. The development of plasticity also triggers a thermal dissipation due to local mechanical irreversibilities. These phenomena conduct to a heterogeneous state of deformation and temperature which has never been simultaneously observed at the micrometric scale. In this paper, an original experimental setup is presented in order to obtain fully coupled measurements. The objective is to get at the same time strain and temperature fields in the same zone at the microstructure scale of an AISI 316L austenitic stainless steel specimen during a tensile test. The fully coupled measurements underscore the relationship between the local plastic and thermal heterogeneities during the first stages of the deformation until a more general plastic state of the specimen. These results may also be used to perform energy balances at the micrometric scale.

1. Introduction

Many isotropic metallic materials are made of an aggregate of grains having a distribution of crystallographic orientations without any outstanding texture effect. During the first stages of an applied mechanical loading, according to their orientation with respect to the loading axis, some grains are submitted to a more important deformation than others, leading to local heterogeneous plasticity. By increasing the loading, the plastic yielding tends to spread over the sample and a more homogeneous state is generally observed as far as the number of grains submitted to plasticity is concerned [1,2].

Since the pioneering work of Farren and Taylor [3,4], it is also well known that this plastic deformation is accompanied by a heat dissipation conducting to temperature variations during the loading of the specimen. These historical experiments, carried out on mild steels, aluminium and copper, consisted in monotonic tensile and torsion tests during which either thermocouples or a calorimeter was used to evaluate the mean value of the heat generated during cold working and thus to realize energy balances at the scale of the specimen.

Similar quasi-static experiments have been renewed more recently using the same type of calorimetric approach [5,6]. However, as calorimeters remain awkward to handle, thermal measurements have later been obtained by infrared thermography (IRT) [7]. Moreover the higher recording frequency provided by this technique enables the establishment of energy balances for specimens submitted to dynamic phenomena [8,9]. In most of these studies, thermal fields are averaged over the whole sample in order to evaluate mean thermal sources.

However, dissipation and strain fields in a polycristal are not homogeneous. A way to account for this is to perform full-field measurements. Hence, such experimental studies have been developed since a few years. For instance, thermal fields grabbed by IRT were studied to investigate local instabilities like Portevin-Le Chatelier effect [10] and kinematic fields were obtained through digital image correlation (DIC) to analyse localization phenomena like necking or Lüders bands [11]. In order to underscore the link between thermal and kinematic behaviours, couplings of IRT and DIC measurements were attempted either on both sides of the sample [12,13] or on separate samples [14]. These results were exploited to perform energy balances at the scale of specimens submitted to instable and local phenomena.

Nevertheless, some particular cases require the realization of such energy balances at the grain scale. For example, in the case of incoming plasticity or fatigue, plastic strains can be very small and heterogeneous. Performing thermomechanical measurements on a metallic sample at this scale could indeed be useful, as it would give information on the behaviour of a representative elementary volume (REV) of a polycristal.

The objective of this study is thus to focus on the REV scale and to measure, on the same surface area and at the same time, thermal

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emissions and strain fields. For that purpose, an original fully coupled thermal and kinematic measurement technique is proposed. To our knowledge, such a technique has never been developed nor presented before.

The outline of this article is therefore the following. The full-field measurements methods are first presented, namely infrared thermography (IRT) for temperature measurements and digital image correlation for strain field measurements. Next, since performing fully coupled measurements at a micrometric scale is a very delicate task, the difficulties to overcome and the precautions to take are developed. Finally, thermal and kinematic coupled information obtained during a uniaxial tensile test on AISI 316L austenitic stainless steel are presented and discussed.

2. Experimental setup

The aim of this section is to present, on the one hand the original setup developed for the fully coupled measurements and, on the other hand, the difficulties to overcome as well as the necessary precautions to take.

2.1. Infrared thermography and temperature field measurements

Any point of an object at a temperature greater than 0 K emits an infrared radiation invisible to the naked eye, which can be related to its temperature; infrared cameras are based on this principle. Historically, infrared detectors were developed for military purposes during the second half of last century. In the early 60s, cameras dedicated to civil applications only disposed of a single infrared detector and a complete scan of the surface was necessary to get a temperature field. As a consequence, recording frequencies were very low and measurements could suffer from thermal drift. In the 80s, focal plane array (FPA) cameras became widespread; made of an array of detectors, they allow higher recording frequencies. The thermal radiation received by the infrared detectors generates an electric signal which is converted into an image corresponding to a map of thermal emissions and whose unit is the "digital level".

The camera used in this work is a Cedip Jade; its infrared sensitive part is a FPA of 320 × 240 InSb detectors, cooled down at 77 K by a rotary Stirling and working in the spectral range from 3 to 5 μm. Its maximum recording frequency in full frame is 170 Hz and the dynamic range of digital levels is 14 bits. This camera is used with a high magnification lens known as G1 since the spatial resolution matches the size of one detector, namely 30 μm × 30 μm; this leads to a 9.6 mm × 7.2 mm observation zone. Nevertheless, such a lens induces optical distortions especially on the borders of the image, narrowing the working area to a central square of 5 mm × 5 mm.

The conversion of digital levels into temperatures needs two crucial steps: the calibration of the detector array and the determination of the emissivity of the sample's surface. Moreover, in order to perform accurate quantitative infrared thermography, in addition to these two steps, some precautions must be taken.

On the one hand, the calibration law, which gives a link between temperatures and thermal emissions, has to be established by exposing the detector array of the camera in front of an extended blackbody at different controlled temperatures. However each detector possesses its own behaviour which is even different each time the camera is switched on; this is a particular drawback of FPA cameras. Thus, in a standard use, the response of each detector is corrected by a gain and an offset in order to be closer to the array's mean response: this is the Non Uniformity Correction (NUC) procedure. Despite such a correction, if a detector's response is still too far from the mean value, its response is replaced by one of the closest detector among those following the mean response or by an average made over several ones: this is the Bad Pixel Replacement (BPR) procedure. In many general applications, such corrections (NUC and BPR) are systematically applied. The NUC and BPR procedures tend to make the response of the detectors array uniform, which is an important disadvantage if one expects to observe small heterogeneities at a local scale or to calculate gradients or Laplacians present in the heat equation over several thermal images [15]. Nonetheless the standard NUC and BPR procedures can be bypassed by the determination of a calibration law made for each detector [16]. In this configuration, the unique mean calibration law is replaced by a set of 76,800 calibration laws. In Fig. 1, the calibration curves obtained for all the detectors are plotted in order to emphasize the heterogeneity of their response. One can notice a similar trend for all the curves except for two outstanding ones (at the top and at the bottom of Fig. 1) corresponding to defective pixels. Such pixels will not be taken into account during the data processing. Moreover, as the calibration is influenced by many parameters (distance to the object, lens used, working temperature, integration time, frame rate ...), a new calibration is necessary for each test configuration [17] but also each time the camera is switched on.

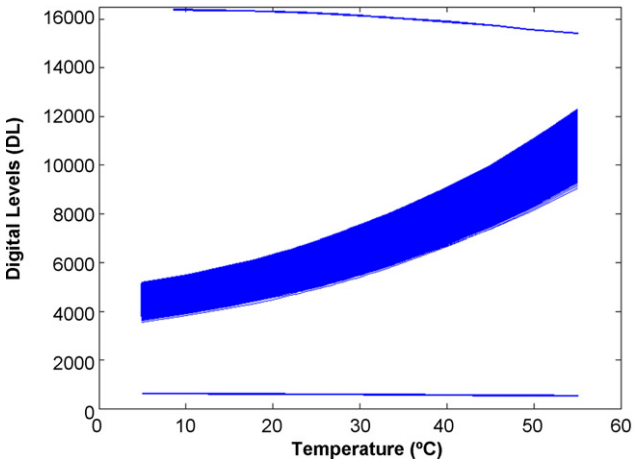

Fig. 1. Cluster of curves obtained during the calibration of the 76,800 detectors of the array. The outstanding curves at top and bottom correspond to defective detectors.

On the other hand, the emissivity of the object has to be determined. This can be realized through a classically used method consisting in a comparison between the radiation of the object and the one of an extended blackbody, both being at the same temperature [18].

At last, for a better accuracy, the camera is turned on more than 4 h before beginning any measurements including calibration in order to get rid of thermal drift. The working place around the camera is protected from any reflections of the environment thanks to black tissue. Every element close to the camera is also covered by black tissue or painted with high emissivity black paint in order to dispose of any residual reflection.

2.2. Digital image correlation and strain field measurements

Images of the sample are grabbed during the tests thanks to a CCD camera Jai CV-M4+. This camera is made of a matrix of 1368 × 1024 detectors, whose size is 6.45 μm × 6.45 μm. It is sensitive to visible wavelengths from 0.38 to 1 μm and delivers 10 bits greyscale images. A Tamron 23FM50SP 50 mm lens associated to extension tubes allows a high magnification and a spatial reso-