Investigation of grain-scale surface deformation of a pure aluminium polycrystal through kinematic-thermal full-field coupling measurement

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Abstract This is a study of plastic strain localization, temperature evolution, surface roughening and of the origin of these phenomena in polycrystals. First, a review on different techniques of coupled kinematic-thermal measurements is given, and the two-face set-up, after several technical improvements, was employed in our work. Thanks to this integrated optical system, the full-field strain and temperature of the aluminium oligocrystal specimen were measured simultaneously during a tensile test. And the coupled data was further proceeded by following some particular methodologies, namely the Lagrangian thermography and the crystallography-based field projection. The surface profile of the deformed specimen was measured by interferometric profilometer, which showed clearly that the specimen had been suffered a strong out-of-plane deformation during the test. This out-of-plane effect was highlighted in the temperature field as well as in the strain field, which brought considerable affections on the measurement precisions of temperature and in-plane strain. Further data analysis shows that the heterogeneity of the out-of-plane deformation is closely associated with the crystallographic structure of the material, and reveals that the grain boundaries and grain interactions during the deformation play an important role in the process of deformation, temperature and surface profile evolutions.

Keywords Strain heterogeneity, Out-of-plane deformation, Infrared thermography, Digital image correlation, Coupled measurement

1. Introduction

The polycrystalline metal is an aggregate of grains having a distribution of crystallographic orientations. During an applied mechanical loading, according to the different orientations and the influences from neighboring grains, some grains are submitted to a more important deformation than others, leading to local heterogeneous plasticity [1]. As known that when the metal is plastically deformed, a certain part of strain energy will be dissipated as heat, and the left will remain in the material. The latter, conventionally called stored energy, is associated with microstructure changes of material and was regarded as a sensitive indicator of damage evolution [2]. As a consequence, the study on "heat source" (or stored energy) needed to be linked with the material plasticity and microstructure evolution, and an experimental energy balance was expected to be built based on a full-field measurement of strain and temperature.

Nowadays the full-field optical measurement techniques, due to its advantages in non-contact, full-field and scalability, become more and more popular. Among these techniques, DIC (Digital Image Correlation) and IRT (InfraRed Thermography) have attracted increasingly attentions, which can provide the full-field measurements of strain and temperature, respectively. The heterogeneity feature of the plastic strain occurring on polycrystal was well characterized by DIC [3, 4], as well as the heterogeneous temperature field observed by IRT [5–7]. For promoting a better understanding of heat source, a coupled kinematic-thermal measurement becomes a necessary.

Recently, this anticipated coupled measurement has been realized, and it exists actually several different techniques, which can be classified according to their experimental set-ups: namely two-face measurement [8, 9], single-face measurement [10, 11] and one-shot measurement [12, 13]. In this paper we will also present our novel two-face measurement system, with its improvements in aspects of synchronization and spatial alignment.

Beyond these advances in aspects of technique, the research interest in this field appeared a noteworthy tendency: a transformation from macroscale to microscale [14, 15]. At the same time the role and importance of the microstructure were highlighted, which gave birth to a new methodology: microstructure-based full-field analysis [16, 17]. This method was applied on a polycrystalline material made of grown but still relatively small grains in the work [16]. Recently, some more simple and well-defined crystallographic structures, such as oligocrystal and bi-crystal, were tested [9, 11]. That certainly simplified the thermomechanical behavior of the material and thus facilitated a microstructure-based analysis.

In this work the studied material is a pure oligocrystal aluminium specimen with a single layer of coarse grains. It will undergo a plastic deformation in a tensile test, being measured in real time by the fully-coupled optical system, which thus provides the strain and temperature fields. The surface profile of the deformed specimen will be also measured after the test by interferometric profilometer. The various data will be treated in Lagrangian coordination system and be projected on a crystallographic base followed by the results analysis and discussions.

2. Coupled kinematic-thermal measurement

2.1. Review of techniques

To our knowledge, it exists actually four different experimental techniques that have been developed in the last few years for achieving the combined kinematic-thermal field measurements. Among them, each technique has its advantages and disadvantages, regarding on the studied material, measurement scale and expected precision. Nevertheless, it is important to note that IRT and DIC usually have contrast technique restraints, in particular on choosing the surface coatings for the specimen. IRT generally prefers a uniform coating with a very high emissivity, such as carbon black, thus an accurate infrared measurement can be conducted. On the contrast, DIC requires a very heterogeneous coating, such as speckled painting, for the purpose of tracking material points that should differ widely in gray levels. Several ways of achieving such a coupling are presented here.

1) Two-face measurement

Each imaging device (IR and visible camera) observes one face of the specimen [8, 9]. The main advantage of this set-up is that each technique has the flexibility to choose the surface coating for its own good without special constraints. This is very important concerning the measurement precision for each technique. The disadvantage of this set-up lies in the fact: for a thin, flat specimen being studied on a macroscale, it is assumed that the two faces of the specimen show virtually the same thermomechanical behaviors. But if thermal and kinematic fields are sought for comparison at the microstructural scale, this technique requires the microstructure to be the same on both faces.

2) Single-face measurement

Both IR and visible cameras observe the same face of the specimen. Two kinds of the experimental set-up can be found:

a) Introducing an angle between the IR and visible cameras [11]. Generally this kind of set-up needs a correction of the image distortions introduced by the inclination of the camera with respect to the normal direction to the specimen surface. This angle should be as small as possible, but still restricted by the physical volumes of the cameras.

b) Introducing a dichroic mirror [10]. The dichroic mirror, thanks to its filtering properties,

transmits the IR radiations towards the IR camera placed in the front of the specimen, and reflects the rest of the radiations towards the CCD camera located on the other side. This set-up can solve the image distortion problem, but the mirror may also introduce some experimental bias due to the transmission and reflection [16].

A common problem for the single-face measurement is the coating for the specimen surface, which is desired to be heterogeneous in the visible vision and be homogeneous in the IR vision. A special coating developed in the work [10] meets such a characteristic.

3) One-shot measurement

A single IR camera is used to measure both kinematic and thermal fields on the same surface of the specimen. In other words, the IR images will be treated not only for IRT but also for DIC. This technique, called "one-shot measurement", was recently developed in [12, 13]. The main advantage of this technique is that it needs neither synchronization nor spatial matching, thus any temporal/spatial bias between the kinematic and thermal fields can be avoided. However, the main problem with this method is that the DIC precision will be inevitably lowered as the IR camera cannot provide a comparable high-resolution sensor array as the visible camera. A decrease in performance should be also found in IRT because of a wide variation in emissivity on the surface coating, which serves for the point tracking of DIC.

After an overview on the available techniques, the two-face measurement was chosen in this study for two reasons: 1) a high requirement on the measurement precision; 2) the oligocrystal specimen used in this work exhibits a quasi-identical microstructure on the two faces.

2.2. Developments on "two-face" measurement

In order to perform a precise and reliable two-face measurement, the two cameras should be firstly synchronized, and then a spatial alignment should be achieved on the two kinds of images produced by the IR and visible cameras, respectively.

2.3.1. Synchronization

The digital camera for DIC technique adopted in this work is the Elphel network camera (Elphel 353), and the IR camera is the FLIR Titanium camera (SC7000). As there is no commercial trigger box available for synchronizing these two cameras, a micro-controller (Arduino Mega 2560) was thus employed for triggering them from external.

The working principle of the micro-controller is to trigger the two cameras, by sending two periodic pulse signals, so as to command them function at the same moment. It is important to note that each camera has a time delay (the time period from receive the signal to take the image), which should be considered in the controlling program in order to assure that they take images on exactly the same moment.

The time delay of FLIR camera was given by the manufacturer, which was as low as 2.8 μs. The time delay of Elphel camera, however, was unknown, and thus needed to be tested. To this end, a special free-fall test was designed in order to estimate this time delay. In this test, the two cameras observed the same zone on a background, a small object was dropped from the air to pass this common zone, and a position difference, due to the time delay, thus appeared in the two captured images. According to the distance and velocity, the time delay can be estimated.

The results showed that the measured time delay of Elphel camera was 2.65 ms with a slight

deviation. After considering each time delay of the two cameras in the trigger program, the coupled measurement system can be synchronized.

2.3.2. Reference target

In the experimental set-up of the two-face measurement, the two cameras are placed face-to-face, each measures one face of the specimen. To set the two cameras observing on the same zone of the specimen is difficult, not to mention adjusting them perfectly perpendicular to the specimen surfaces. As a result, a spatial matching on the obtained IR and visible images cannot be reached.

In order to solve this problem, a special target of reference was developed. This target was a perforated metal plate, with around 20 holes through the thickness and randomly distributed. Thus the target has two identical faces and the holes form a special pattern.

Before the test the two faces of the target will be observed by IR and visible cameras, respectively. Thus it offers two visions of the target: one in IR image and the other in visible image. Each of them will be correlated to the analytical model of the target, and further to be deformed by the estimated transformation functions so as to reach the spatial matching with the analytical model.

Figure 1. shows an example of the overlay of the targets from IR and visible images: (a) before spatial correction; (b) after spatial correction. It shows clearly that the unmatched holes in image (a) are superposed in image (b) after the spatial correction. The transformation functions applied in this example are an affine transformation plus a B-spline transformation.

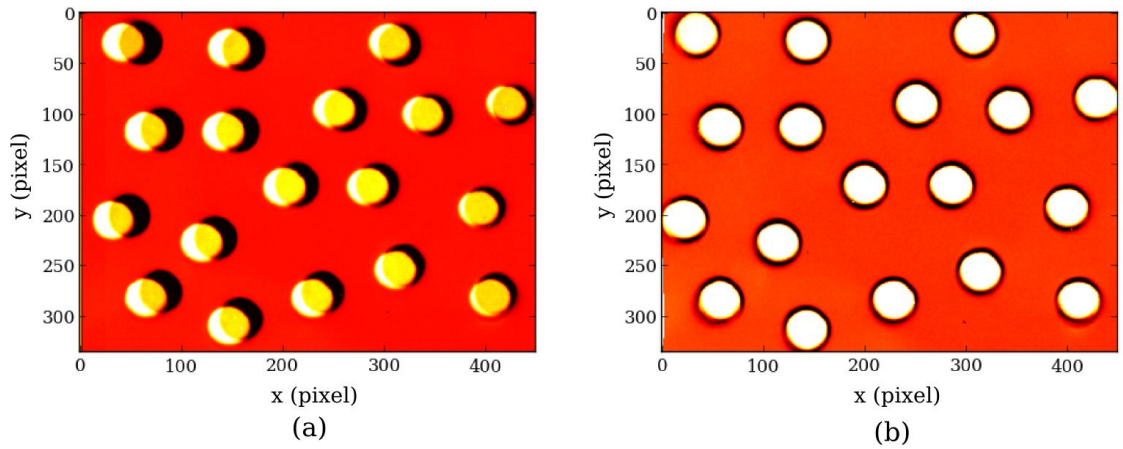


Figure 1. Overlay of the IR and visible images: (a) before spatial correction (b) after spatial correction

An affine transformation in Elastix is defined as:

$$T_\mu(x) = A(x-c)+t+c \tag{1}$$

where A is a matrix, c is the center of rotation and t the translation vector. The matrix A has no restrictions that means the image can be translated, rotated, scaled, and sheared.

B-splines are often used as a parameterization:

$$T_\mu(x) = x + \sum_{x_k \in N_x} p_k \beta^3\left(\frac{x-x_k}{\sigma}\right) \tag{2}$$

with x_k the control points, $\beta^3(x)$ the cubic multidimensional B-spline polynomial, p_k the B-spline

coefficient vectors, σ the B-spline control point spacing, and N_x the set of all control points within the compact support of the B-spline at x.

Since the two cameras are always fixed during the test and the target is placed at the same position as the specimen, so the correlation functions should be applicable for the specimen. Hence, the spatial alignment of the two faces of the specimen can be realized thanks to the reference target.

3. Experimental procedure

3.1. Specimen preparation

An oligocrystal specimen that contains only about ten grains in a single layer was prepared. The average size of the grains can attain 15 mm in diameter, and the thickness of the specimen is 1.5 mm. This type of oligocrystal specimen was prepared by the strain-annealing method [18, 19], from a very pure aluminium (purity 99.99%). The preparation of the oligocrystal specimens, following the strain-annealing method, required three steps.

1. Specimens cut from the original metal sheet were annealed at 545 ℃ 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 which corresponds to the ‘‘critical strain” value necessary to obtain, after a second annealing of re-crystallization, maximum grain size.

3. Stretched specimens were finally annealed at 545 ℃ for 1 h.

Concerning the two-face measurement, one important issue here is the identity of the crystallographic features of the two faces of the specimen. This point can be checked by overlapping the grain boundaries from the two faces. Figure 2. shows the grain textures of the two faces (face A for visible measurement and face B for IR measurement) and the overlay of the grain boundaries. The overlapping effect is, on the whole, satisfactory, in particular for the big grains in the middle.

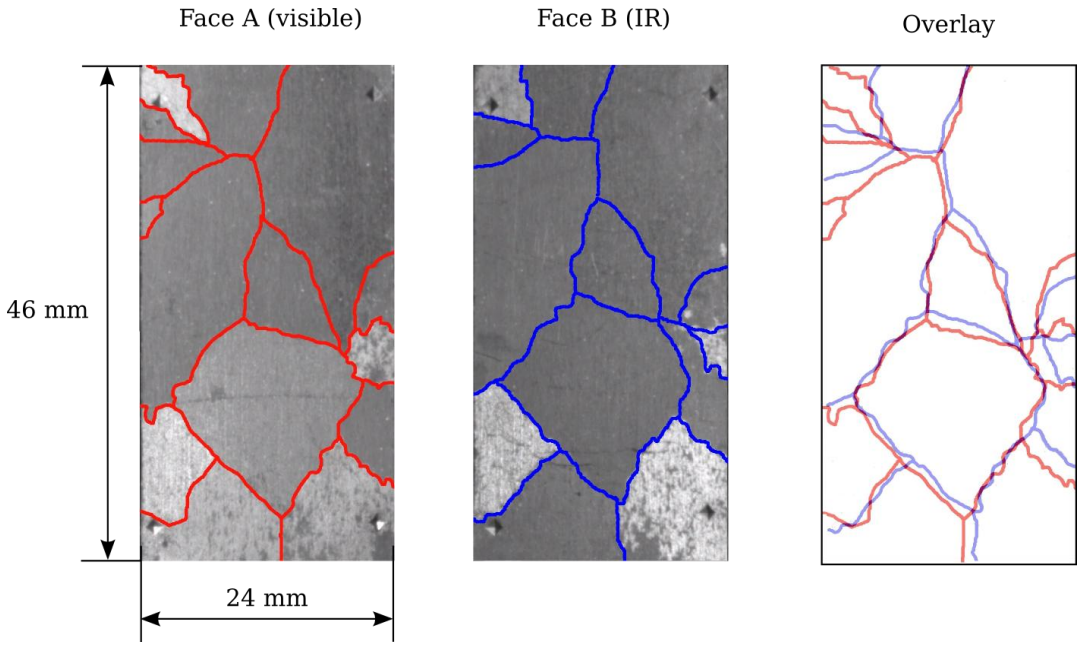


Figure 2. Grain textures of the two faces and the overlay of the grain boundaries

3.2. Test and measurements

Before the tensile test, an in-situ calibration was carried out in order to calibrate the IR camera, and the reference target was also measured in advance.

The tensile test was performed at room temperature and at a constant crosshead velocity of 1 mm/s. Strain and temperature were measured simultaneously by the two-face measurement system. The experimental set-up is shown in Figure 3. In the IR aspect, there was an enclosed box between the camera and the specimen for isolating the influences from environment; and for strain measurement a light made of LEDs was adopted to illuminate the specimen.

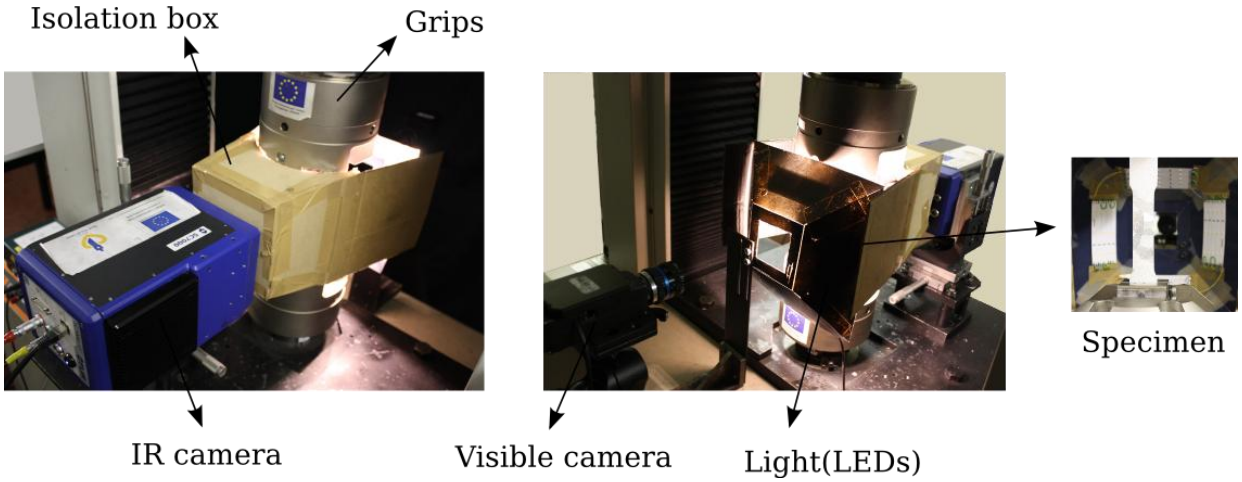


Figure 3. Experimental set-up of the two-face measurement system

The surfaces of the specimen were treated by depositing speckled painting for face A (strain measurement) and carbon black for face B (temperature measurement). Visible images were recorded by Elphel camera at 20 Hz with a resolution of 1712 × 1552 pixels. And IR images were recorded by FLIR Titanium camera at a frequency of 100 Hz with a resolution of 472 × 368 pixels.

It is important to note that there is an apparent difference in the sampling frequency for the two cameras, one is 5 times lower than the other. This is owing to our strategy on the parameter setting, as the sampling frequency was considered a priority for IR camera and the spatial resolution for visible camera. In this case, the two cameras were not synchronized in a strict sense, but the micro-controller guarantees that each visible image has a temporal corresponding IR image.

After the tensile test, the deformed specimen was measured by interferometric profilometer (Wyko NT1100) that provided the surface profiles of the two faces. Four marks on each face (see Figure 2) are the landmarks for the spatial alignment with the measured full-field strain and temperature.

3.3. Data treatment

First of all, the spatial alignment of IR and visible images was realized thanks to the reference target. Then, due to the fact that the visible camera has a lower sampling frequency, the visible images were interpolated linearly in order to produce the same number of images to the IR images. At this step, a data coupling, spatially and temporally, was done.

DIC technique was realized by Elastix [20], an open source software. B-spline transformation was applied as the correlation function with a final deformation grid 32 × 32 pixels following a

multi-resolution strategy. IR images were proceeded by converting original Digital Level (DL) to temperature through a so-called Quantitative Infrared Thermography (QIRT) procedure [16]. In this procedure, a N points Non-Uniformity Correction (NUC) was applied in order to eliminate the radiometric artifacts [21].

During the tensile test, as the two cameras were always fixed and the specimen had been displaced, thus the data recorded is in Euler coordination system. Since DIC provides the displacement information of the specimen and the kinematic-thermal data have been coupled, thus all IR images can be deformed so as to return to the initial coordination. This method is called Lagrangian thermography [10, 16]. The interest of performing Lagrangian Thermography is to follow the temperature evolution of each physical point of material, which is not evident when the material points are in the movement.

Another special data treatment was applied is so-called crystallography-based full-field projection proposed by Seghir [16]. In this method, the strain, temperature and profile data were projected on a crystallographic base: the data were fitted as polynomials in units of individual grains. Thus the hypothesis made here is the physical discontinuity of polycrystal because of grain boundaries.

5. Results and discussions

5.1. Out-of-plane deformation and its influences on measurement

The first noticeable phenomenon found in the results is that the specimen has suffered a strong out-of-plane deformation during the tensile test, as shown by Figure 4, the surface profiles of the deformed specimen. The two faces shows almost the same statistic results: the surface roughness average is about 70 µm, but the maximum height of the surface reaches around 700 µm regarding a thickness of 1.5 mm for the specimen. It is also interesting to notice that the two faces show a profile pattern similar and in opposite signs.

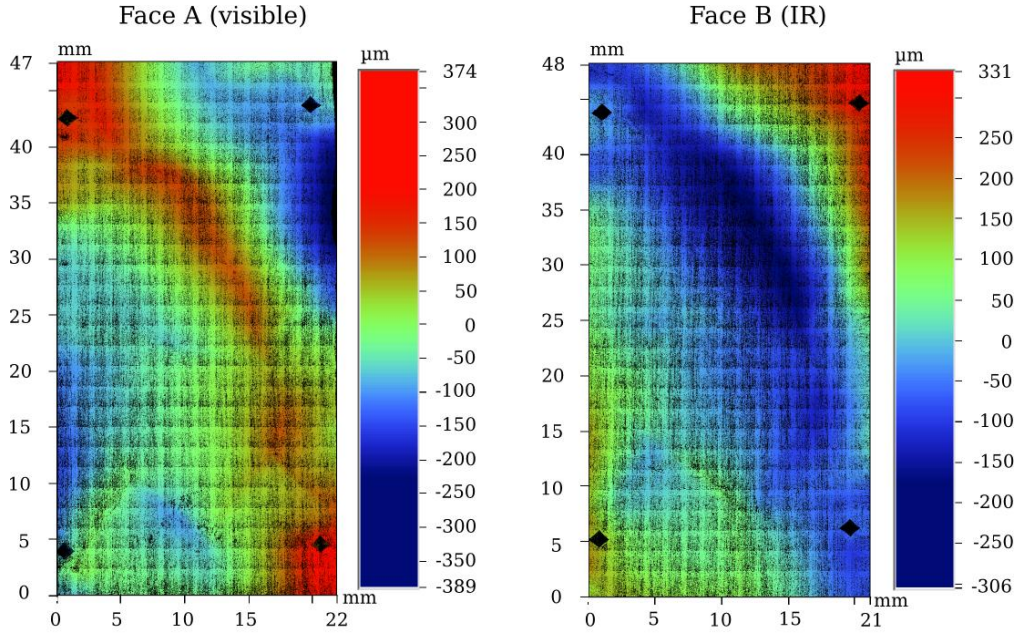


Figure 4. Surface profiles of the deformed specimen

This type of out-of-plane deformation has considerable influences on the in-situ full-filed measurements. For a 2D in-plane DIC system adopted in this work, the out-of-plane deformation brought inevitably errors on the image correlation. Figure 5(a). shows an error map (or residual

image) of DIC calculation for the last visible image (i.e., the final state of the deformed specimen). The special pattern observed in this residual image reflects the out-of-plane deformation, which changed the gray levels of the material points during the test in the light of the reflection effect.

Concerning IRT, the non-plane surface of the specimen will change the apparent emissivity of the surface coating due to the varied incidence angles with respect to the IR camera [22]. The apparent emissivity can be changed and re-distributed heterogeneously corresponding to the deformed shape of the specimen. Figure 5(b). shows the temperature field of the specimen in the final state, derived from the last IR image after proceeding Lagrangian thermography. Comparing to Figure 5(a), a similar pattern can be remarked, globally and in some zones particular. This is due to the fact that the two faces of the specimen showed a very similar profile feature and the optical reflection effect influenced the two optical measurements, DIC and IRT, almost in the same way.

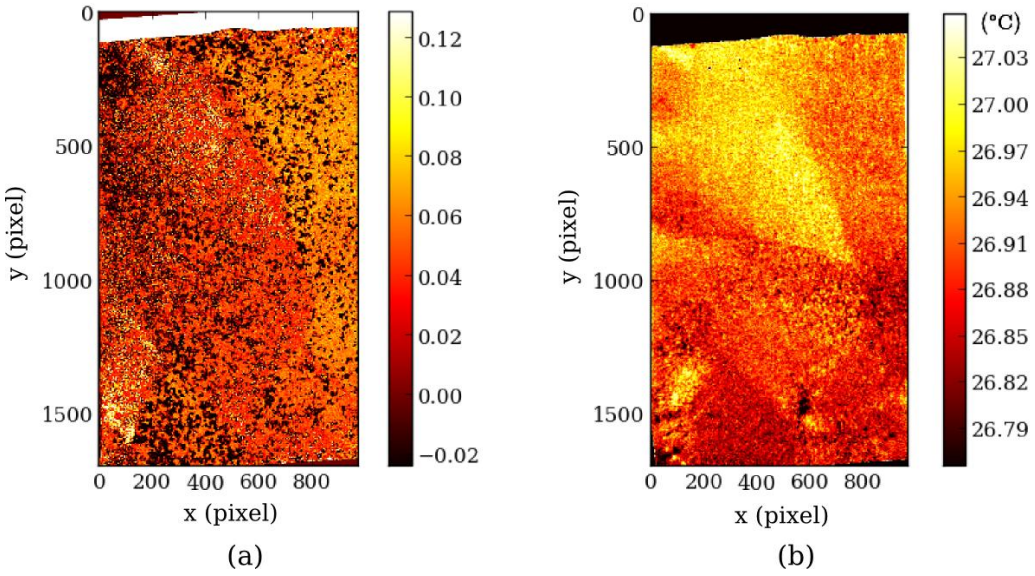


Figure 5. Reflection effects caused by out-of-plane deformation demonstrated by:
(a) Residual image of DIC (b) Temperature field

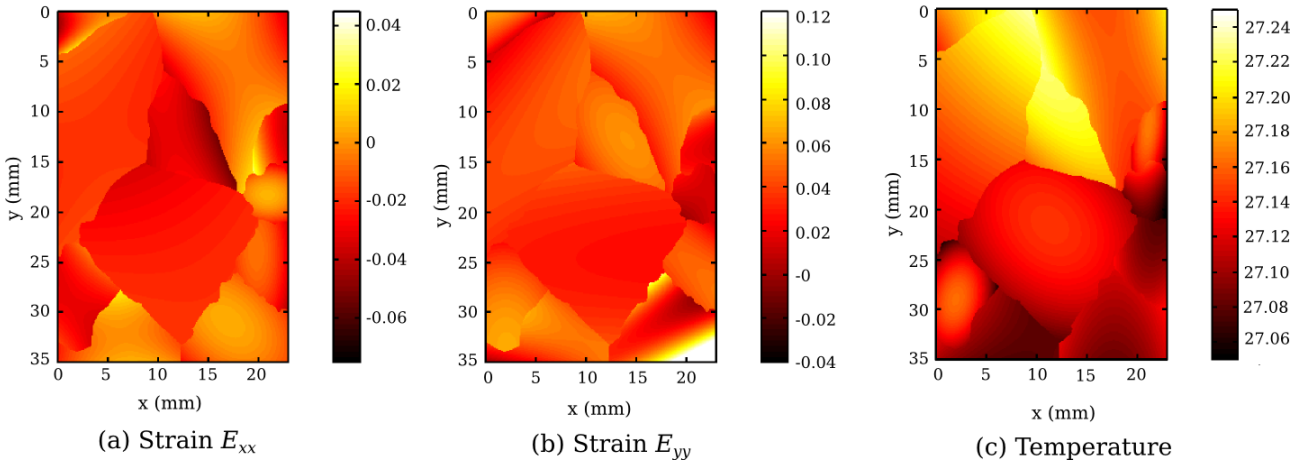
Nevertheless, it is worthy to mention that this type of artifact due to reflection is not so important regarding the absolute errors it may introduce, but its influences can be much magnified when a relatively homogeneous strain or temperature field is involved. This is what happened in this test, especially for the temperature field, as aluminium has a very high thermal conductivity.

5.2. Out-of-plane deformation and microstructure

For oligocrystal specimen, because of the difference in crystallographic orientations, the grains were subjected to the stresses of different levels during the uniaxial tensile test. This stress heterogeneity led to a heterogeneous deformation process. In this process, grain boundaries, as the interfaces of different grains, played an important role.

Comparing the surface profiles in Figure 4. with the initial grain texture in Figure 2, it is not difficult to find out that the most marked relieves, where the profile changes most abruptly, coincide with the grain boundaries. This point can be better investigated in the projection of full-filed measurements on a crystallographic base.

Figure 6. shows the projection results of the strains (E_{xx}, E_{yy}) and temperature at the final state of the specimen during the deformation. The interpolation, through second-degree polynomial fitting, was applied for each grain according to the grain texture provided by Figure 2.



(a) Strain E_{xx} (b) Strain E_{yy} (c) Temperature

Figure 6. The crystallography-based projection from the full-field measurements of: (a) Strain E_{xx} (b) Strain E_{yy} (c) Temperature

Both strain and temperature fields in Figure 6. demonstrate a heterogeneity, where the discontinuity of the grain boundaries is remarkable. This heterogeneity is mainly due to the out-of-plane deformation that is closely linked with the microstructure of the material. Nevertheless, a further analysis cannot be conducted unless the optical reflection effects can be quantified. This is one of the perspective studies in the near future.

Another work undergoing is the study on the thermomechanical behavior of nickel single crystal by using the two-face measurement system. One of the greatest interests on studying single crystal is to establish a quantitative relationship between the stored energy, stress-strain state and microstructural changes of the slip systems that are activated.

5. Conclusions

1. An overview of technique possibilities of coupled kinematic-thermal measurement was given, and several advances in technique have been achieved in this work for building an advanced two-face measurement system.

2. An aluminium oligocrystal specimen was measured during a monotonic deformation by the coupled optical system, which showed an important out-of-plane deformation. This kind of out-of-plane deformation has considerable affections on the optical measurements.

3. Further investigation shows that the heterogeneity of the out-of-plane deformation is closely associated with the microstructure of material, and reveals that the grain boundaries and grain interactions during the deformation play an important role in the process of deformation, temperature and surface profile evolutions.

References

[1] J. Lemaitre, J.L. Chaboche. Mechanics of Solid Materials, Dunod, Paris, 1988.
[2] M.P. Luong. Fatigue limit evaluation of metals using an infrared thermographic technique. IMechanics of Materials, 28(1998) 155–163.
[3] G. Besnard, F. Hild, S. Roux. “Finite-Element” Displacement Fields Analysis from Digital Images: Application to Portevin-Le Châtelier Bands. Experimental Mechanics, 46(2006), 789–803.

[4] A. El Bartali, V. Aubin, S. Degallaix, Surface observation and measurement techniques to study the fatigue damage micromechanisms in a duplex stainless steel. International Journal of Fatigue, 31 (2009) 2049–2055.
[5] A. Chrysochoos, H. Louche. An infrared image processing to analyse the calorific effects accompanying strain localisation, International Journal of Engineering Science, 38(2000) 1759–1788.
[6] H. Louche, A. Chrysochoos. Thermal and dissipative effects accompanying Lüders band propagation. Materials Science and Engineering: A, 307(2001), 15–22.
[7] T. Boulanger, A. Chrysochoos, C. Mabru, A. Galtier. Calorimetric analysis of dissipative and thermoelastic effects associated with the fatigue behavior of steels, International Journal of Fatigue, 26(2004), 221–229.
[8] A. Chrysochoos, B. Berthel, F. Latourte, S. Pagano, B. Wattrisse, B. Weber. Local Energy Approach to Steel Fatigue. Strain, 44(2008), 327–334.
[9] C. Badulescu, M. Grédiac, H. Haddadi, J.D. Mathias, X. Balandraud, H.S. Tran. Applying the grid method and infrared thermography to investigate plastic deformation in aluminium multicrystal. Mechanics of Materials, 43(2011), 36–53.
[10] L. Bodelot, L. Sabatier, E. Charkaluk, P. Dufrénoy. Experimental setup for fully coupled kinematic and thermal measurements at the microstructure scale of an AISI 316L steel. Materials Science and Engineering: A, 501(2009), 52–60.
[11] A. Saai, H. Louche, L. Tabourot, H.J. Chang. Experimental and numerical study of the thermo-mechanical behavior of Al bi-crystal in tension using full field measurements and micromechanical modeling. Mechanics of Materials, 42(2010), 275–292.
[12] A. Maynadier, M. Poncelet, K. Lavernhe-Taillard, S. Roux. One-shot Measurement of Thermal and Kinematic Fields: InfraRed Image Correlation (IRIC). Experimental Mechanics, 52(2012), 241–255.
[13] M.L.Silva, G. Ravichandran. Combined thermoelastic stress analysis and digital image correlation with a single infrared camera. Journal of Strain Analysis and Engineering Design, 46(2011), 783–793.
[14] L. Bodelot, E. Charkaluk, L. Sabatier, P. Dufrénoy. Experimental study of heterogeneities in strain and temperature fields at the microstructural level of polycrystalline metals through fully-coupled full-field measurements by Digital Image Correlation and Infrared Thermography. Mechanics of Materials, 43(2011), 654–670.
[15] D. Delpueyo, M. Grédiac, X. Balandraud, C. Badulescu. Investigation of martensitic microstructures in a monocrystalline Cu-Al-Be shape memory alloy with the grid method and infrared thermography. Mechanics of Materials, 45(2012), 34–51.
[16] R. Seghir. Experimental and numerical investigation of thermomechanical couplings and energy balance in metallic polycrystals. Ph.D. thesis, Ecole Centrale de Lille, 2012.
[17] R. Seghir, J.F. Witz, L. Bodelot, E. Charkaluk, P. Dufrénoy. A thermomechanical analysis of the localization process at the microstructure scale of a 316L stainless steel, Procedia Engineering, 10(2011), 3596–3601.
[18] H.C.C. Carpenter, C. Elma. The production of single crystals of aluminium and their tensile properties. Proceedings of the Royal Society A, 100(1921), 329–353.
[19] J. Philibert, A. Vignes, Y. Bréchet, P. Combrade. Métallurgie: du minerai au matériau, Edition Masson, Paris, 1998.
[20] http://elastix.isi.uu.nl/
[21] M. Poncelet, J.F. Witz, H. Pron, B. Wattrisse. A study of IRFPA camera measurement errors: radiometric artefacts. Quantitative InfraRed Thermography Journal, 8(2011), 3–20.
[22] G. Gaussorgues. Infrared Thermography, Chapman & Hall, London, 1994.