Quantitative Infrared Lagrangian Thermography for the thermomechanical determination of the granular yield stress in a polycrystal

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abstract

Polycrystalline metallic materials are made of an aggregate of grains more or less well oriented with respect to the loading axis. During mechanical loading, the diversity of grain orientations leads to heterogeneous deformation. It is well known that most of the plastic work generated during the deformation process reappears in the form of heat whereas a certain proportion remains latent in the material and is associated with microstructure changes. To access the local stored energy during deformation processes, experimental energy balances are needed at a suitable scale. In this way simultaneous measurements of thermal and kinematic necessary fields have already been done in-house at the microstructural scale of a 316L stainless steel submitted to macroscopic monotonic tensile test. The aim of the present study is to propose a complete calibration strategy allowing the estimation of thermal variations of each material point along its local and complex deformation path. This point constitutes one of the key element within the experimental and granular energy balance achievement including two major experimental problems: the own dynamic of each IRFPA sensors leading to undesired spatial and temporal noise and the complexity of the local loading path which must be captured by simultaneous complementary measurement. The improvement of such multifield strategy will lead to the experimental and local achievement of energy balances required for the building of new energetically based criteria.

1 Introduction

Since the beginning of the last century, many authors studied the plastic deformation process in metallic materials in order to improve the global understanding of deformation mechanisms, elasto-plastic transition, deformation localization and obviously the damaging processes which lead to the ultimate failure. One can cite, for example, the pioneering works of [17, 19].

In this context, the thermal effects associated to the deformation process have been underlined and the partition of the extended mechanical energy has been studied. It is now well known that during cold working, the most important part of the plastic work reappears in the form of heat and a certain proportion remains latent in the material. This part of energy, classically called stored energy, is associated with microstructure changes and could therefore constitute a great indicator of damage evolution. In this way, experimental energy balances are necessary. An extensive review of the early work within this field was published by Bever [4] including the pioneering works of [18]. However, most of energy balances presented in the literature has been performed at macroscale thus dealing with macroscopic appearance of inelastic processes. One can cite works on necking, Lüders bands, Portevin-Le Chatelier (PLC) phenomenon, dynamic deformation and shear bands [20, 14, 1, 9]. The consequence is a lack of energetics information associated to local deformation processes in heterogeneous material, as polycrystals. These information are necessary in order to study microstructure leaded phenomena as microplasticity or fatigue process. The literature reports some works trying to obtain this type of microstructural information: a study on a Al1050 Al bi-crystal [16], an other one on an oligocrystal (7 grains) of a commercial pure aluminium [2], and finally on a AlSi 316L stainless steel polycrystal (2000 grains) [7].

To our knowledge, no paper deals with the entire necessary procedure to obtain a temperature field within each specific grain of a polycrystal along its deformation path from Digital Level provided by I.R. camera. Especially, the three main problems in fully coupled measurements at such scales are the following: (1) no uniformity of emissivity, (2) the calibration method, and (3) the temperature data treatment smoothing. The objective of this communication is to propose such a complete procedure. This paper is then decomposed in three main parts. In the first one, one presents the data used in the present work. In the second part, the proposed calibration procedure allowing a fine estimation of each specimen surface material points temperature along a their deformation path is described. Finally, one presents an application of such calibrated thermal field for the analysis of a A316L polycrystals subjected to a monotonic tensile test.
2 A "single-face" experimental setup

The experimental set-up and data used in this study are based on the one introduced in [7]. It allows to obtain a fully coupled measurement of kinematic and thermal fields at the grain scale of a polycrystal. This is particularly possible thanks to two elements : a dicroic mirror and a specific coating. The dichroic mirror is located in front of the sample in order to transmit the infrared radiation (wavelength between 2 and 6 \( \mu m \)) toward the infrared camera, located in front of the sample and to reflect the rest of the radiation, including the visible radiation, to the CCD camera which is perpendicular to the sample surface (see figure 1). The second keystone of the fully-coupled measurements lies in the coating applied on the sample and the difference in resolution of each camera. On the one hand, the coating exhibits a speckle aspect at a very fine scale, covering a wide range over the grey scale, which is required for the DIC computation. On the other hand, to perform IRT, this coating tends towards a high and uniform emissivity at the working scale, as close as possible to the one of the blackbody used for the calibration.

Displacement fields are obtained thanks to DIC performed with Correli\textsuperscript{LMT} developped at the "Laboratoire de Mécanique et Technologie" (LMT) of Cachan in France [10]. Images of the deforming sample are grabbed thanks to a Jai CV-M4+ CCD camera. It is used with a Tamron 23FM50SP 50 mm lens and extension tubes, leading to a spatial resolution of 6.5x6.5 \( \mu m \) per pixel and a field of view of 8.9x6.7 mm\(^2\). Since the DIC computation is performed with 16x16 pixels subsets, the spatial resolution of the displacement and strain fields data is finally 104x104 \( \mu m \)\(^2\).

Temperature fields are obtained by IRT. The sample is filmed by a FPA (Focal Plane Array) Cedip Jade III MWIR camera. It is used with a high magnification lens called \( G_1 \). The spatial resolution for the temperature fields data is 30x30 \( \mu m \)\(^2\).

![Figure 1: Principle of the two-faces QIRT and DIC measurement technic, from [7]](image)

3 Eulerian thermal metrology

Following the thermal evolution of a material point during a mechanical loading is not a trivial task as:

1. the infrared camera does not measure temperature but radiative flux and does not express it in physical units but in Digital Level (\( DL \)).

2. the measurement could be affected by optical distortions.

3. each sensor of the IRFPA (Infrared Focal Plan Array) camera has its own dynamic and noise.

4. the relation between radiative flux and temperature depends on surface material properties of specimen as emissivity, diffusivity . . .

5. external heat sources could dramatically affect the observed thermal scene.

It is therefore essential to establish a calibration strategy which minimizes the error at each step. This part focus on calibration steps which must be done in Eulerian configuration.

3.1 Calibration

3.1.1 Pixel to pixel

The infrared camera converts the received flux (emitted by an object) in DL. To convert it in physical units, it is therefore necessary to calibrate each pixel/sensor of the IRFPA camera. A "flux based calibration" method is proposed. Its principle is to determine, thanks to a least square method, the optimal function to pass from DL to flux emitted by the observed object \( \phi \) for a fixed integration time \( IT \) of the camera. Contrary to temperature calibration the function does not depend on the emissivity of the observed object. Finally, as each IRFPA sensor of the camera has its own dynamic, this calibration must be done for each detector (pixel to pixel calibration as described in [3]).
With the help of an extended BlackBody (BB) at different given uniform temperature \( T_k \) and the corresponding Digital Level (\( DL^i_k \)) of each pixel \( i \) of matrix sensor provided by the infrared camera, one could build each calibration curves. The procedure is performed according to the following equation:

\[
\Phi (IT, T_k, i) = \sum_{u=1}^{p} \alpha_u (DL^i_k)^u
\]

where coefficients \( \alpha_u \) are determined by the least square method, \( p \) corresponds to the degree of a classical polynomial calibration law. Equation 1 is actually a system of \( k \) equations for every calibration temperature \( T_k \) of the BlackBody which have to be minimized. In practice, in order to limit the temporal noise of each sensor, the calibration is done thanks to Matlab by using the mean field over 100 IR pictures.

Picture 2 (a) presents the whole flux calibration function of the IRFPA camera sensors based on 6 order polynomial functions. One could note that most of the pixels constitute a set of curve with a maximum deviation of 3000 DL at a given homogeneous emitted flux and that some pixels have a flat response as a function of the flux. These pixels are considered defective and replaced by the mean value of their direct neighbors. Once each calibration function is determined, the corresponding thermal fields of the BlackBody are calculated following the Boltzman law. It allows determining the accuracy of the calibration (in \( mK \)).

\[
\Phi = \varepsilon \sigma T^4
\]

where \( \phi, \varepsilon, \sigma \) are in the present case, the flux radiated by the BlackBody at fixed temperature \( T \), the uniform emissivity of the BlackBody (\( \varepsilon_{BB} = 0.97 \)) and the Boltzmann constant \( \sigma = 5.67032\times10^{-8} \) respectively.

![Image](image_url)

**Figure 2:** (a) 76800 flux calibration functions associated to each IRFPA sensors and (b) error between radiative and measured temperature (mK)

Picture 2 (b) presents the mean and extreme deviation between the effective temperature of the BlackBody and the "measured" or calibrated one. It shows that the mean error within each pixel when the flux radiated by the object remains in the \([405 \text{ - } 465] W.\text{mm}^{-3}\) domain fluctuates from -10 to 10 \( mK \) and that the absolute error is locally inferior to 30 \( mK \). Note that such result remains valid under the presented flux domain regardless of any temporal noise.

It is relatively important to note that the camera is here calibrated for a specific range of flux and not for a range of temperature. Picture 2 (b) presents two domains: the blue one is the flux domain corresponding to the interval \([25^\circ C - 27^\circ C]\) assuming the mean specimen emissivity (\( \varepsilon_s = 0.927 \)), the red one correspond to the interval \([25^\circ C - 27^\circ C]\) assuming BlackBody emissivity (\( \varepsilon_{BB} = 0.97 \)). Obviously, the interval \([25^\circ C - 27^\circ C]\) does not lead to the same range of flux, in the case of BlackBody or specimen, because of the difference of emissivity. It is therefore important to approach as close as possible specimen emissivity by an other measure to determine the appropriate range of flux calibration especially in the case where the specimen emissivity is far from 1. According to [5] the present coating emissivity standard deviation is about \( 9\times10^{-3} \) with a mean value of 0.927. According to figure 2 (b) and considering the interval \([25^\circ C - 27^\circ C]\) for specimen temperature variation during monotonic tension test, one
could conclude that the present calibration remains valid for a coating emissivity which would range from 0.92 to 0.98. Thus it seems enough to take into account the effective emissivity distribution [5].

### 3.1.2 Temporal noise

As previously introduced, the calibration function results from a mean field over 100 IR pictures of BlackBody regulated at different temperatures. Nevertheless, these functions are applied to each IR pictures of the specimen in order to follow its thermal behavior at the imposed measurement frequency (140Hz). Consequently, the effective measurement uncertainty will necessarily increase. To maintain this one under $30 \text{ mK}$ at a high measurement frequency and a high resolution, the pixel to pixel calibration is applied to each 100 IR scenes at a fixed temperature and then the maximal local deviation from the effective temperature is observed. Figure 3 presents the local maximal deviation from the effective temperature for different BlackBody temperatures and for different treatments: (1) black lined curve is the thermal deviation considering full frequency (140Hz) and full resolution, (2) black dotted curve is the one considering lower frequency (25Hz) and full resolution, (3) is finally the one considering low frequency (25Hz) and low resolution, i.e. average over 3x3 pixels. Note that a low frequency signal is obtained by using a low-pass filter in Fourier space. One note that the curve note (3) is the only one who allows maintaining the measurement uncertainty under $30 \text{ mK}$. The average over 3 by 3 pixels has been decided considering previous works based on SRF (Split Response Function) which show that a zone of interest of 3x3 pixel at worst is sufficient to capture 100% of emitted radiations [15]. Then, the minimal resolution provided by IR imaging system is 90x90 $\mu\text{m}$ (3x3 pixels).

Thus the figure 3 shows that when both constraints are verified (low pass filter at 25Hz and average over 3 by 3 pixel) the highest local deviation from effective temperature of BlackBody is at worst $30 \text{ mK}$. Note that the low-pass filter will be applied on Lagrangian signal and not directly on the Eulerian one. This point will be treated in 3.3.3. Finally, the thermal signal must be considered as having a frequency of 25Hz, a resolution of 90x90 $\mu\text{m}^2$ (3x3 pixels) and an uncertainty of $30 \text{ mK}$.

### 3.1.3 Flux decomposition

In order to perform real quantitative infrared thermography at local scale, two phenomena have to be taken into account. The first one is the necessary reflections which could appear even if the test is performed in a totally controlled environment. In the present case, the fully coupled measurement is performed thanks to a dichroic mirror. It is unfortunately a preferential source of reflections. Considering the fixed I.R. camera, this first phenomena is Eulerian (reflection spots does not move when the specimen deforms). The second one is the spatial variation of emissivity and diffusivity due to the coating properties. Considering the fixed I.R. camera, this phenomenon is Lagrangian (the “apparent emissivity” field moves and deforms with the specimen). Both have to be removed before determining and then analyzing thermal fields.

A reasonable physical assumption is to consider that reflections affect the field in Low Spatial Frequency (LSF) and are Eulerian whereas “apparent emissivity” field affects the observed field in High Spatial Frequency (HSF) and
is Lagrangian (see figure 4 (b)). To treat both aspects, one focuses on a period \( A \) on figure 4 (a). During this period the specimen is around the thermal equilibrium as the specimen is unloaded. During this period the whole local and/or global spatial flux variation are linked to reflection (environment) and “apparent emissivity” (coating). Figure 4 (a) part \( B \) presents the mean thermal response of the specimen during the tensile test.

Let us decompose the flux captured by IRFPA sensors. The flux measured by the infrared camera \( \phi \) is the difference between the observed flux \( \phi_{\text{obs}} \) and the flux radiated by camera IRFPA sensor \( \phi_{\text{cam}} \) cooled at \( T_{\text{cam}} = 77K \).

\[
\begin{align*}
\phi &= \phi_{\text{obs}} - \phi_{\text{cam}} \\
\phi_{\text{obs}} &= \phi_{\text{obj}} + \phi_{\text{refl}} \\
\phi_{\text{cam}} &= \sigma T_{\text{cam}}^4
\end{align*}
\]

(3)

The observed flux \( \phi_{\text{obs}} \) is the composition of two terms: the flux really emitted by the observed object \( \phi_{\text{obj}} \) and some possible reflection fluxes \( \phi_{\text{refl}} \) caused by external heat sources and the fact that the emissivity is not equal to one. In the case of gray body, the flux emitted by the object follow the Boltzman law as introduced in equation 2:

\[
\phi_{\text{obj}} = \epsilon \sigma T_{\text{obj}}^4
\]

(4)

with \( \epsilon_{\text{obj}} \) and \( T_{\text{obj}} \) respectively the emissivity field and the temperature of the surface specimen. Combining equations 3 and 4 one could write:

\[
\phi = \frac{\epsilon_{\text{obj}} \sigma T_{\text{obj}}^4 + \phi_{\text{refl}} - \sigma T_{\text{cam}}^4}{(\text{HSF,LSF}) \cdot \text{LSF}}
\]

(5)

The main interest of this decomposition is to put in light the variables separation previously announced. Analyzing Low Spatial Frequency of \( \phi \) by spectral decomposition, one could write:

\[
\phi_{\text{LSF}} = \frac{\epsilon_{\text{obj}} \sigma T_{\text{obj}}^4 + \phi_{\text{refl}} - \sigma T_{\text{cam}}^4}{(\text{HSF,LSF})}
\]

(6)

with \( \phi_{\text{LSF}} \) the measured flux without high spatial frequencies. High spatial frequency phenomena are assumed here if the spatial period is lower than 500 \( \mu \text{m} \), i.e. lower than 10% of the picture. Within this assumption, LSF signal does not take into account any local variations. \( \epsilon_{\text{obj}} \) is the measured mean emissivity of surface specimen (indirect emissivity measurement [5]), \( T_{\text{obj}} \), the measured mean temperature (thermocouple) of surface specimen during part A (see figure 4). Picture 4 (b) presents the radiative flux decomposition introduced in equations 5. HSF signal fluctuates from -0.2 to 0.5 \( \text{W.mm}^{-2} \); it results from the high frequency part of \( \epsilon_{\text{obj}} \sigma T_{\text{obj}}^4 \) in eq. 5. LSF signal fluctuates from 15 to 25 \( \text{W.mm}^{-2} \); it corresponds to \( \phi_{\text{refl}} \) in eq. 5 and the constant signal corresponds to the term
\( \bar{\epsilon}_{obj} \sigma T^4_{obj} - \sigma T^4_{cam} \) in eq. 6. Its value is 416.6 \( W.mm^{-2} \).

Equation 6 leads to:

\[
\phi_{refl} = \phi|_{LSF} - \bar{\epsilon}_{obj} \sigma T^4_{obj} + \sigma T^4_{cam} \tag{7}
\]

Combining equations 7 and 5, it is possible to determine the “apparent emissivity” field of the specimen around a thermal equilibrium.

\[
\bar{\epsilon}_{obj} = \frac{\phi - (\phi|_{LSF} - \bar{\epsilon}_{obj} \sigma T^4_{obj})}{\sigma T^4_{obj}} \tag{8}
\]

Classically, in coupled field measurement where an heterogeneous coating (for DIC) is necessary, emissivity is considered constant and homogeneous [6, 8]. Firstly, it is not a so rude assumption in most cases and secondly, no direct and in situ method for emissivity field measurement exists even if some authors tried to obtain it by observing the specimen in two distinct spectral bands [13].

\[\text{Figure 5: (a) Temperature error field with homogeneous emissivity (0.927) considering non homogeneous emissivity field as reference and corresponding apparent emissivity field. (b) Coating in visible wavelength and zoom on a specific micrometric grain.}\]

Figures 5 (a) presents the temperature error field and the corresponding emissivity built from equation 8. Temperature error field is built from the difference between the field obtained with a uniform emissivity and the one obtained with the apparent emissivity map (see equation 8). Thanks to the relation 8, it is then possible to correct the temperature error field induced by the hypothesis of homogeneous emissivity. The classical assumption of homogeneous emissivity leads here, to more than 200 mK of thermal spatial noise which is clearly connected to the heterogeneity of coating. Its mean value is null but its standard deviation is 23 mK. The obtained emissivity map allows avoiding this temperature error. The obtained emissivity field ranges from 0.92 to 0.93 with a mean value of 0.927 (experimental measure) and the standard deviation of 1x10^{-3}. As regard to the experimental data provided by [5], one could conclude that the standard deviation of coating emissivity is underestimated even if the mean value is conserved. Nevertheless, the error on final thermal field is here locally reduced and it remains widely lower than the measurement uncertainty.

3.2 Digital Image Correlation

Kinematic fields are here obtained from visible pictures taken by CCD camera, and thanks to Digital Image Correlation software Correli\textsuperscript{2}4 [11]. The main principle of Digital Image Correlation is the comparison of two pictures of a same specimen area at two different states of the loading: a reference one and a deformed one. It is expressed as follows:

\[ x_i - x_0 = u_0(A) \tag{9} \]
\[ y_i - y_0 = v_0(A) \tag{10} \]

where \( A(x_i, y_i) \) are coordinates of point A in deformed configuration, \( A(x_0, y_0) \) are coordinates of point A in reference configuration and \( \{u_0(A), v_0(A)\} \) the axial and transversal displacements of a material point A expressed in the reference configuration. Obviously, specimen must exhibits a sufficient speckled texture in term of gray level which
is the case in the present study with the proposed specific coating. Then, in line with [5], 16x16 subset windows has been chosen as ZOI and the kinematic resolution is then 104x104 µm² since the imaging system provides a resolution of 6.5x6.5 µm² per pixel. The systematic error, i.e. the mean error over each ZOI, is 6.24x10⁻⁴ pixels or 4.1x10⁻³ µm and the uncertainty of the kinematic measurement is consequently 5.72x10⁻³ pixels or 4x10⁻² µm.

3.3 Lagrangian metrology and thermography

To express the infrared scene in its undeformed configuration it is necessary to follow then to move back radiative flux associated with each material points of the observed zone. It is realized thanks to DIC performed on CCD camera pictures. It constitutes the concept of "Lagrangian thermography". In this way, a time and space matching between kinematic and thermal fields has to be done.

3.3.1 Time and space matching

Kinematic and IR measurement are first synchronized in space by using some marks on the specimen observable in visible as well as in invisible wavelength. It allows to rotate, translate and stretch fields in order to perfectly match each other at the initial instant. The time synchronization is realized thanks to the trig offset of each camera running at its own fixed frequency. In order to use a unique spatio-temporal mesh for any data, the interpolation of kinematic and IR fields are realized on:

- EBSD mesh for space (Electron Back-Scattered Diffraction map which gives microstructural information as grain boundaries and orientations)
- IR grid for time

It constitutes a trilinear interpolation (2D space, 1D time) of data which is realized under Matlab using the function interp3. Note that this procedure does not change the resolution of each quantity as they are only linearly interpolated on a unique reference mesh.

3.3.2 Lagrangian thermography

The principle of the Lagrangian thermography is the following. \( P_{IR,i} \) denotes a point in the infrared camera coordinate system expressed in current configuration, i.e. at time \( t_i \), \( P_{CCD,i} \) a point in the coordinate system of CCD camera in the same configuration. Note that \( P_{CCD,0} \) and \( P_{IR,0} \) are in the same coordinate system thanks to space and time synchronization and then spatio-temporal linear interpolation (see previous section). Then, the displacement between instant \( 0 \) and \( t_i \), expressed in the initial configuration and denoted \( U_{ii} \), could be directly applied to \( P_{IR,i} \). Following equations 9 and 10, one obtains:

\[
P_{IR,0} = P_{IR,i} - U_{0i}
\]

Equation 11 must be applied to each material point \( P_{IR,i} \) at each time \( t_i \). Finally, displacement, radiative flux and emissivity fields are henceforth expressed in the same reference system.

3.3.3 Time treatment

The time noise which appears in infrared fields (see figure 4) is mainly due to the variation of flux in the room during the test, and the intrinsic noise of each pixel. Thus it has to be removed before applying the emissivity correction and determining the temperature fields. Within Lagrangian thermography framework each material point is affected by the sensibility of each pixel along its deformation path. As already introduced in section 3.1, a low-pass filter cutting frequencies strictly higher than 25 Hz has been chosen. Such low pass filter guarantee the thermal uncertainty. Picture 6 presents the raw and smoothed radiative flux evolution of one of the material points within the center zone of the specimen. One observes that main variations of radiative flux are conserved.

3.3.4 Apparent emissivity correction

In section 3.1.3 a local spatial variation of flux response was identified on unloaded specimen. The nature of this flux distribution has been quantified and attributed to emissivity distribution due to the coating. Then, in section 3.3.2, Lagrangian thermography has been performed on IR scene in order to express both fields in same initial configuration. Now, the apparent emissivity correction can be applied on the whole IR scene to finally express from \( \phi_{obj} \) the effective surface temperature of specimen.

\[
T_{obj} = \left( \frac{\phi_{obj}}{\epsilon_{obj}} \right)^{\frac{1}{4}}
\]

with \( \epsilon_{obj} \) introduced in section 3.1.3. The calibrated thermal scene expressed in undeformed configuration will be analyzed in the next section thanks to microstructural data.
4 Microstructural thermal fields in a 316L austenitic stainless steel

The obtained calibrated fields can now be used in order to analyse thermal fields in a polycrystal. However, in order to analyse grain by grain data, microstructural based analysis have to be conduct.

4.1 Field projection on microstructure

An original method is proposed here and the details can be founded in [?]. This method projects primal fields (temperature and displacements) on the specimen grains whose geometry has been obtained by an EBSD analysis. Grains of microstructure at each step of loading constitute a natural set of continuous and smooth spatio-temporal domain separated by grain boundaries where kinematic and thermal continuities are not necessarily ensure. For displacements, this is comforted by complementary profilometric analysis done on the specimen after test and for temperature, this is justified by some studies on the Kapitza effect [12].

This technic is based on the assumption that surface measured fields are representative of the surface microstructure, i.e. surface temperature and displacement fields are principally related on surface grains. This assumption is justified by the deformation mechanisms which are much more limited in depth than on a free surface. A minimization, in the sense of the Least Square Method, between calibrated thermal field and a polynomial function is done within each grain regardless of its neighbours at each time increment. A second-order polynomial projection basis for both displacements and temperature within each grain is chosen. Main consequences on resulting fields are the following:

1. Biparabolic displacement field: as strain is calculated from the displacement gradient, we implicitly assume here a bilinear strain field within each grain. This is in agreement with the main plastic deformation mechanism at grain scale and at low strain level, i.e. single shear along a particular direction.

2. Biparabolic thermal field: as conductive fluxes are calculated from the temperature Laplacian, uniform conductive exchanges within each grain at each instant are implicitly assumed through this hypothesis. As every local heat sources initiated within the grain are quickly uniform due to conductive phenomenon, it is therefore assumed that conductive exchanges are instantaneously uniform within the grain and on its boundaries.

One has to point out that the whole decomposition is additive. Residual fields between initial fields and projected one are complementary and can be separately analyzed. It has been verified that in the present case, the standard deviation on temperature residual values is almost constant and is 24mK which is lower than the uncertainty of measurement. Note that for displacement fields, more regular than Infrared measurement due to DIC method, the residual part is in the order of 1%.

4.2 Some results

The studied material is an AISI 316L austenitic stainless steel. Dog-bone shaped flat samples of 2 mm thick were heat treated under air for 2 hours at 1,200°C and immediately water-quenched. A displacement controlled monotonic tensile test was applied to the sample with a constant strain rate of \(5 \times 10^{-3} \text{s}^{-1}\) [6].

Figure 6: Raw and time smoothed (>25 Hz) radiative flux of one material point within the center zone of specimen gauge section
Figure 7: Comparison between (a) original temperature field and (b) projected one (mK) both at 250 MPa of nominal stress

Figure 7 (a) and (b) present the original temperature field and the projected one at a 250 MPa nominal stress. One can clearly observe a smoothed field on figure 7 (b) where the contribution of each grain to the global field can now be identified and measured. It exhibits a 100 mK thermal gradient from a specific area to the gauge section borders which clearly reflects a conductive phenomenon from the center circle to the specimen border. Note that the hot region is not centered within the gauge section which is certainly the sign of a thermal localization due to the microstructure and not to the specimen geometry. One can also underline some thermal grain discontinuities, which are very clear on some grain boundaries, notably around the big center one.

5 Conclusion

In this paper, the entire metrological procedure to obtain in-situ fully-coupled kinematic and thermal fields expressed in the undeformed configuration has been introduced. A special attention to the decomposition of measurement errors in:

- an Eulerian part related to the sensor dynamic
- an Eulerian part related to reflections due to the environment and the experimental setup
- a Lagrangian part related to the intrinsic emission properties of the surface specimen

has been done. The metrological procedure has been applied to Digital Levels and Gray levels frames registered by IR and CCD camera respectively within [7]. The spatial resolution of ultimate thermal field is 104x104 µm² that match the mean grain size of the specimen (≈ 120 µm), the uncertainty of measurement is lower than 30mK and the frequency of phenomena captured reach 25Hz. Finally, such calibrated field has been used to observe the thermal evolution of specimen gauge section as well as the intragranular thermal evolution of a specific grain. This analysis has been done assuming projection of thermal fields on the specimen microstructure. Observations reveal a very high heterogeneity of thermal fields at this scale as well as an early thermal localization clearly connected to high deformations observed on surface of the specimen. This technique open the way to the potential achievement of energy balance at the grain scale of polycrystal required to build future energy based criteria.

References


