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ANALYSIS OF THE THERMOMECHANICAL BEHAVIOR OF COARSE-GRAINED POLYCRYSTALLINE ALUMINUM UNDER TENSILE CONDITIONS

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ABSTRACT: The aim of this paper is to present the advantages of using Digital Image Correlation (DIC) and Infrared Thermography (IRT) to investigate the thermomechanical behavior of aluminum at the scale of its microstructure. The study combines these complementary imaging techniques: Electron Backscatter Diffraction (EBSD) to characterise the microstructure of the sample, DIC to obtain strain fields and IRT to reach heat source induced by the mechanical loading. The aim of this study is to provide energy balance during mechanical test at the scale of the microstructure, in order to propose thermomechanical constitutive modelling of crystalline plasticity.

Digital image correlation / Infrared thermography / EBSD / Crystal plasticity / Temperature and strain mapping

1. INTRODUCTION

In polycrystalline metallic materials, a mechanical loading generates plastic strains in the sample beyond some threshold [1, 2]. Thanks to the pioneering work of Farren and Taylor [3, 4], it is well known that the plastic deformation of metals also triggers heat generation inducing temperature variations during the loading of the specimen.

However, even under homogeneous loadings, a heterogeneous spatial distribution of mechanical fields can be recorded due to the anisotropic nature of the crystal slips [5]. These heterogeneities have been widely studied using imaging techniques such as Infrared Thermography (IRT) since the end of the 1970s [6], and Digital Image Correlation (DIC) since the last two decades [7]. With the expanding application of infrared techniques and the progress achieved in the fields of optical techniques associated with quantitative image processing, the quality and precision of displacement and temperature full-field measurements have tremendously increased in the last decade.

The microstructure of metals has been widely studied due to its relationship with the mechanical properties. The development of automated EBSD imaging techniques [8] in Scanning Electron Microscope (SEM) has contributed to better understanding of the microstructure evolution during plastic strain [9, 10].

Recently, samples containing only a small set of grains in the millimeter range have been studied to evaluate the deformation-induced plastic heterogeneity of polycrystals [11-13]. In such materials the size of the area concerned with the micro level deformation mechanisms is large enough to be observed with our experimental set up.

The objective of this work is to obtain fully-coupled thermomechanical measurements to analyze the relationship between thermomechanical heterogeneities and material structure during the loading. In that way, the relation between the microstructure evolution and the thermomechanical response of the sample during the test are investigated.

2. EXPERIMENTAL PROCEDURES

2.1 Sample preparation

The as-received material used in this study consists in a 3mm thick aluminum sheet, grade A1050. A classical thermomechanical treatment of the samples allows us to adjust the microstructure between 100 μ m to 50 μ m grains [14].

The elaboration of Al specimen exhibiting "millimetric" grains requires the following three consecutive steps:

- *Homogenization:* the tensile samples were continuously annealed at 560°C for 1h in order to remove residual stresses resulting from initial sheet forming operation, and to restore the metal to an energy level close to its original state.
- *Critical hardening:* the annealed samples were then hardened by a "critical strain", around 1.8% [14], in order to store enough energy to allow the dynamic recrystallization.
- *Recrystallization and grain growth:* the stretched samples were then annealed at 620°C for 1h to initiate dynamic recrystallization and grain growth to the millimetre scale.

The microstructure of a sample corresponding to a critical strain of 1.8%, revealed by a metallographic etching using Keller's reagent is presented in Figure 1. The graphic in Figure 2 indicate that the choice of the critical strain

impact directly the global size of the grains and that high levels of critical strains leads to smaller grains and *vice versa*. However, a minimal strain is needed to activate dynamic recrystallization and therefore grain growth.



Figure 1: Revealed microstructure after recrystallization

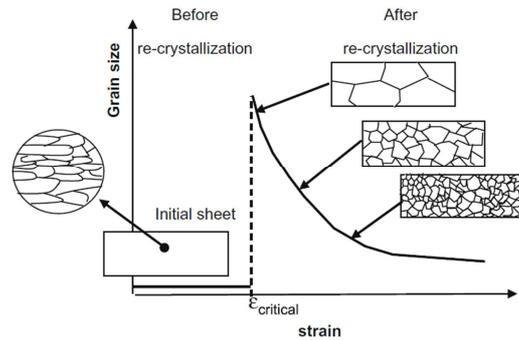


Figure 2: Variation of grain size obtained after sample recrystallization as a function of applied tensile strain [15].

2.2 EBSD analysis

EBSD analysis is a powerful technique to provide microstructure morphology, local grain orientation and texture measurements. The dimensions of the specimen were fixed to $3 \times 20 \times 80 \text{mm}^3$ in order to take into account the limited size of the SEM chamber.

In order to obtain the initial EBSD grain orientation mapping without flaws relative to non-indexed Kikuchi patterns, special attention has been paid in the surface preparation before analyses. So, a mechanical polishing has been performed up to colloidal silica to obtain a mirror finish.

The EBSD analyses were made using a JEOL JSM 5600 field emission gun SEM with a step size of $100 \mu\text{m}$ which provides sufficient spatial resolution to capture the fine description of the initial microstructure. The initial grain orientation map of the sample before testing is presented in Figure 3. Grain boundaries and grain disorientations appear clearly in this map, and the average grain size can be directly measured. These four black dots were placed in order to allow the mapping of EBSD orientations with thermal and kinematic data.

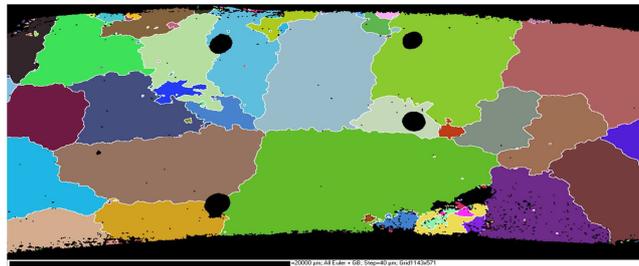


Figure 3: Tested sample orientation maps based on the Euler angles

2.3 Experimental setup and data processing

Tensile tests were performed at room temperature with a hydraulic testing machine: MTS-810 (frame: 100 KN, load cell: 25 KN), and the monitoring was done by controlling the displacement of the crosshead at a speed of 0.25 mm/s.

The experimental set-up used to perform coupled kinematic and infrared measurements is shown in Figure 4. A high speed CCD camera is set perpendicularly to the sample on one side of the specimen and an IR camera is placed on the other side. The optical axis of the CCD and IR cameras was set perpendicularly to the frame of the testing machine, and thereby perpendicular to the surface of the sample. A simultaneous fully-coupled observation of both sides of the sample by both the CCD and IR cameras is performed. Two stereoscopic devices were also used to measurement the third components of the displacement field on each side of the sample (but they were not exploited in this study).



Figure 4: Experimental set-up

In order to use IRT and DIC techniques, the surface emissivity of the sample placed in front of the IR camera was increased and homogenised using a mat black paint, while the surface in front of the CCD camera was speckled in order to get an optimised contrast. The main camera characteristics are given in Table 1.

The cameras are synchronized using a specific electronic device developed in the laboratory, it allows to record all the images at different frame rate but using a unique time base, and to digitize the analogical signals (load, displacement) given by the testing machine.

	Image size (pixels)	Scale factor ($\mu\text{m}/\text{pixel}$)	Frame rate (Hz)
IR: Cedip Titanium	512x640	92	20
High Speed CCD: Phantom V12	1280x800	58	40

Table 1: Main camera characteristics

3. RESULTS AND DISCUSSION

The principles of the data processing are detailed in references [16-18]. The data processing provides the different components of the strain fields on the monitored surfaces for each image acquisition. Using the pixel calibration protocol presented in [19], the maps of the temperature variations of the specimen induced by the mechanical loading were deduced from the infrared images.

The mechanical response of aluminum sample for a load-unload tensile test is presented in Figure 5.

As show in Figure 4 and Figure 5, at one of the instants (No.5) marked in the loading curve of Figure 5, we have superimposed the strain field and the temperature field on the map of microstructure to illustrate its evolution on sample surface.

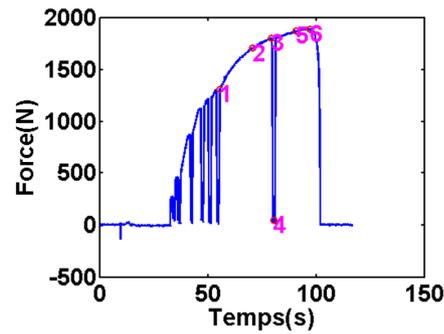


Figure 5: Mechanical response of the sample

On the strain map, we can notice easily the localization of strain, with a maximum value of deformation up almost to 80% locally in the upper right of the carte, where there is an aggregate of small grain and the rupture was occurred in the same locus. On the same time, strong heterogeneity but pretty good correspondence is obviously observed between the map of temperature and the grains with different orientations. The variation of temperature does not exceeded 1°C because of the high thermal diffusivity of the aluminum.

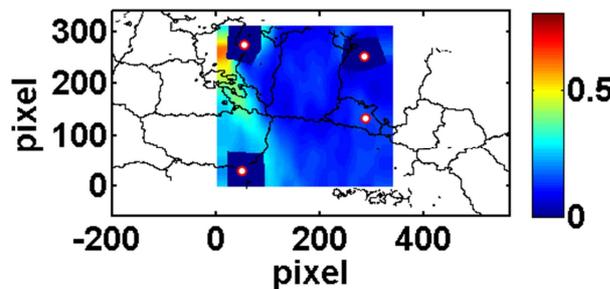


Figure 4: Axial strain field ϵ_{xx}

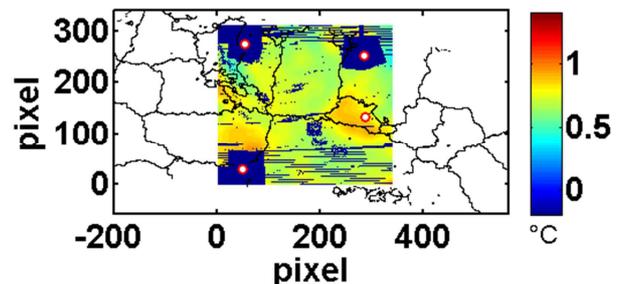


Figure 5: Temperature field

3.1 Results of one-dimensional

We have brought a monitoring zone to the sample axis, in order to illustrate the evolution of strain and temperature throughout the loading. In Figure 6, the place where the fracture appears is clearly observed (around pixel 50). At the same time, we can identify several localization zones of stain in this map. Figure 7 shows the evolution of temperature in Kelvin versus time, a particular attention should be focused in the load-unload part of loading, the temperature variation in this part underscores the thermo-elastic effect of the materiel.

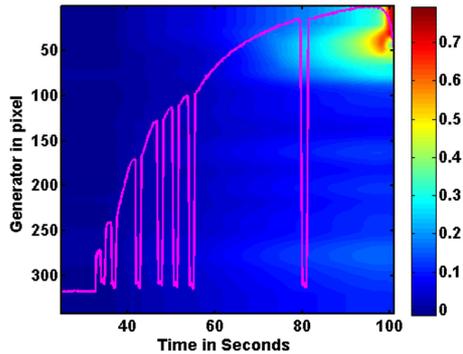


Figure 6: Evolution of the deformation over time

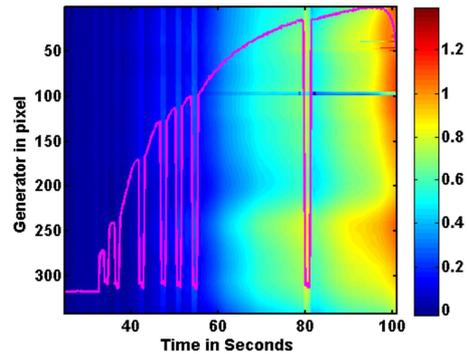


Figure 7: Evolution of the temperature over time

4. CONCLUSION

The experimental setup described in this paper allows estimating the local distribution of strain and temperature in aluminum polycrystal using classical DIC and IRT methods. A specific data processing allowing the determination of these data respecting the microstructure of the material (*i.e.* in each grain) is now being developed in order to obtain averaged values of the different thermomechanical variables and to build an energy balance at the scale of the microstructure in order to characterize the thermomechanical consistency of classical polycrystal plasticity modeling.

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