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MICRO-SCALE FULL-FIELD STRAIN MEASUREMENT ON A STAINLESS STEEL SAMPLE ELASTO-PLASTICALLY TESTED

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ABSTRACT: This study deals with the characterisation of the mechanical behaviour of an austenitic stainless steel at the micrometric scale in its elasto-plastic domain. For that, the full-field "*grid method*", adapted to this scale, is implementeded. The images of the grating are recorded thanks to a white-light interferometric microscope. The results show that the strain localization is in accordance with the microstructure. Some considerations about the average strain within different grains of the steel sample are made to show how the plastic deformation begins locally before the global yield point.

1. INTRODUCTION

To be able to precisely predict the global mechanical behaviour of a material, it is necessary to understand the physical phenomena taking place at the scale of its heterogeneities. Indeed, once the local mechanical behaviour is known, it is possible to deduce the overall properties via homogenisation schemes [1]. However, the experimental determination of the local behaviour still remains challenging as the classical experimental procedures are not robust anymore at a reduced scale.
In this context, this work is aimed at characterising an austenitic stainless steel sample (FCC crystal system) under tensile loading at the scale of its grains in its elasto-plastic domain. This is done by applying the experimental procedure developed in [2-3]. This methodology is shortly recalled before introducing the results on the stainless steel sample.

2. METHODOLOGY

The micro-extensometric method used here has been previously developed [2-3]. It is based on the so-called "*grid method*" [4] fitted to a micrometric scale. The overall procedure is schematically summarized in Fig. 1 and recalled hereafter.

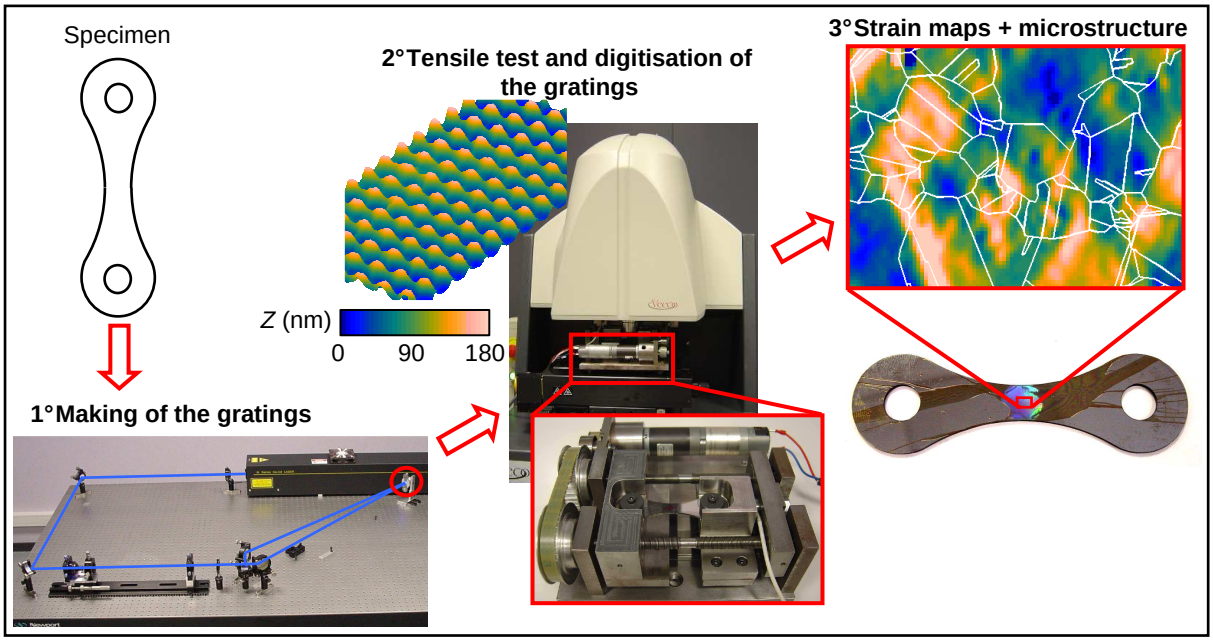

Figure 1- Schematic summary of the experimental micro-scale full-field strain measurement procedure

First of all, the samples are prepared: they are cut from a laminated plate of the studied stainless steel, then submitted to a recrystallization tempering heat treatment (to get bigger and equiaxed grains) and finally polished.

Cross-gratings (pitch: 5 μm) are then produced at the surface of the specimen by direct interferential photolithography: the principle is to "record" the optical interferences of two coherent light beams on a photoresist deposited onto the studied surface (first step on Fig. 1). The deformation of the photoresist is assumed to follow exactly the one of the underlying substrate.

Then, the samples can be submitted to a tensile test thanks to a small home-made mini tensile machine. The mechanical test is performed *in-situ*, while "pictures" of the grating on the region of interest are recorded thanks to a white light interferometric microscope. This microscope gives access to the topography of the surface, which is relevant as the produced grating on the photoresist is "3D-etched" (second step on Fig. 1).

Finally, the recordings of the grating are computed by the "*grid method*", based on a windowed spatial phase shifting algorithm, leading to the displacement maps. These maps undergo a 2x2 "stitching" operation in order to enlarge the field of view (finally equal to 450x340 μm^2). They are then numerically differentiated thanks to a diffuse approximation scheme [5] leading to the strain maps. Finally, the observed microstructure of the region of interest is plotted on the strain maps to allow a comparison between it and the localizations of strain components. With this approach, it has been shown that the local strain resolution is inferior to 2.10^{-3} for a spatial resolution of 20 μm [3]. It has to be compared to the average size of a grain (≈ 100x100 μm^2).

3. RESULTS AND DISCUSSION

The mechanical test performed on the stainless steel sample has consisted in a 52 load steps tensile test. Fig. 2 shows the stress-strain curves obtained from both a gauge glued onto the back side of the sample and an averaging of the ε_{xx} maps on the whole surface of the region of interest. It also shows the three in-plane strain maps for the last stage of loading, once the material has reached its overall elasto-plastic domain.

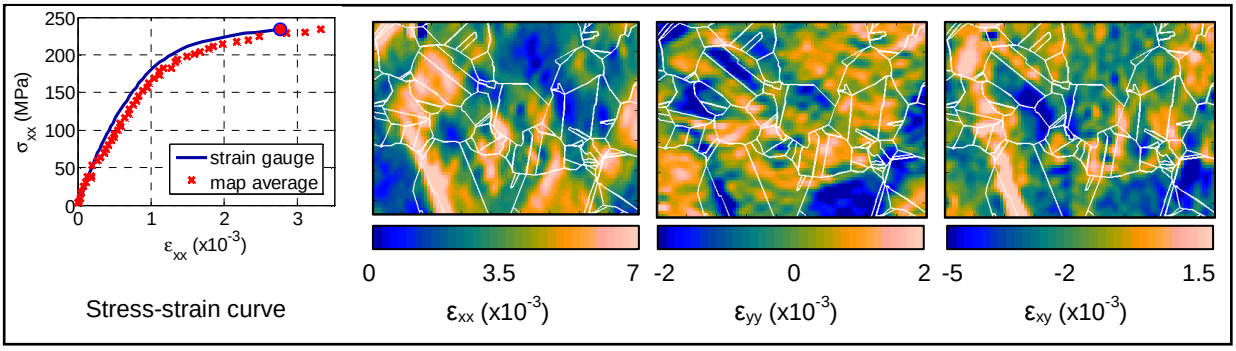

Figure 2- Micro-extensometric results for the last step of loading

From this figure, two main remarks can be made:

- The two stress-strain curves are quite different. This can be due to two main causes. The first possible cause is that there was some bending moment superimposed to the tensile load during the test leading to different longitudinal strain components on the two sides of the sample. The second possible cause is that the size of the observed region is inferior to the one of the representative volume (which is possible considering the total number of grains).

- The different strain maps for the last step of loading show localizations that are in accordance with the positions of the grain and twin boundaries. It has to be noted that on the micrograph made after the test on the sample, some slip lines can be seen on some of the regions where ε_{xx} is maximal. This reinforces the confidence and relevancy of the obtained strain maps.

One way to exploit these full-field data in order to characterize the onset of micro-plasticity is to perform an averaging of the strain values over the surface of a single grain or a single twin (considered here as the same kind of "unitary cell" of the microstructure). The averaging has two main advantages:

– it gives access to a single representative value for the whole grain;

– on a metorological point of view, the averaging increases the signal to noise ratio.

This allows plotting a stress-strain curve per grain. Fig. 3 shows such curves (grains 1 and 2 are grains that are submitted to large plastic deformation, showing slip lines on the micrograph whereas grains 3 and 4 are grains that are less deformed; see Fig. 2) to be compared to the one obtained for an averaging on the whole surface of the region of interest.

These curves show that, for this stainless steel sample, the local strain can vary of a 2.5 factor from a little solicited grain to a hugely solicited one. From this observation, it can be asserted that the proposed technique should be able to give information about the local onset of micro-plasticity.

To this purpose, two semi-automatic procedures of determination of a local yield point have been implemented.

- The first one is simply based on the transposition of the normalized value calculation of the yield point to this scale: a value of the "0.02% yield stress" is thus proposed for the considered local regions. For that, a linear regression is made on the first value of strain/stress (up to a stress value equal to 100 MPa, to be sure to stay in

the elastic domain while having enough experimental value to get a relevant regression law). Then, the deduced straight line, shifted by a value of 0.02 % in strain, is plotted. The intersection point between this line the experimental curve gives the $\sigma_{Y\ 0.02\%}$ value (Fig. 4(a)).

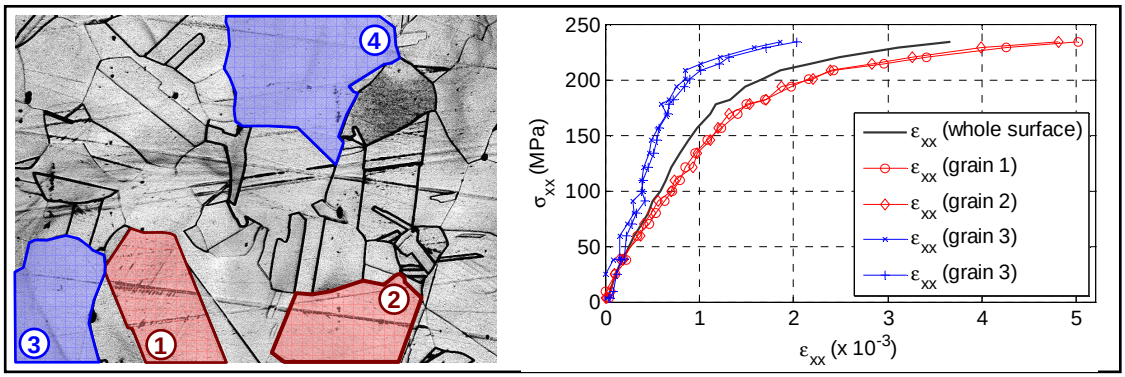

Figure 3- Average stress-strain curves for several grains or twins of the sample

- The second one consists in finding the intersection between the regression line previously obtained from the first sets of values, and a 4th order polynomial curve computed by regression on the last stages of loading. This allows getting rid off the possible influence of the noise affecting the experimental data on the determination of $\sigma_{Y\ 0.02\%}$ by the previous method and to get a closer value to the local loss of linearity (Fig. 4(b)).

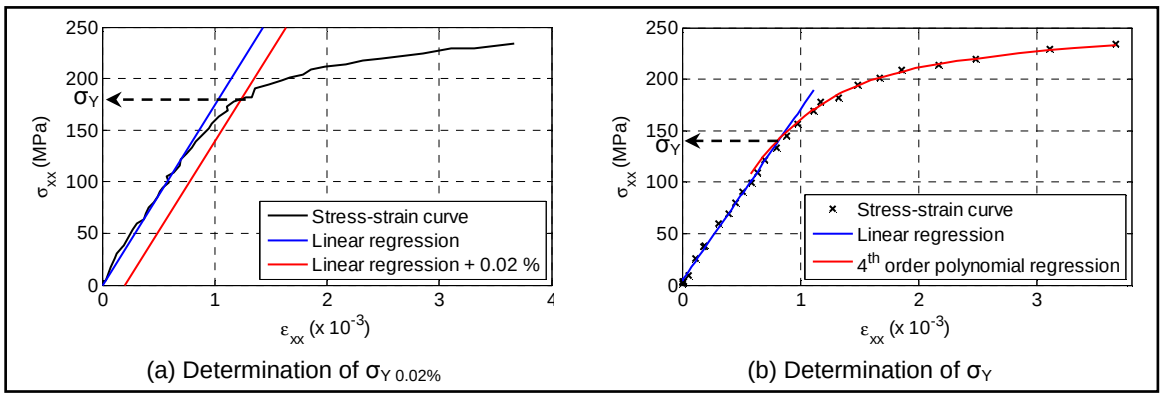

Figure 4- The two ways to determine the local yield point

Thus, two values characterizing the onset of micro-plasticity are available. They, and the difference between them and the reference value obtained for the whole surface of the region of interest, are given in table 1.

	Whole surface	Grain 1	Grain 2	Grain 3	Grain 4	Average / 4 grains
$\sigma_{Y\ 0.02\%}$	**180 MPa**	164 MPa	164 MPa	211 MPa	204 MPa	185 MPa
Difference from the whole surface	-	– 16 MPa	– 16 MPa	31 MPa	24 MPa	5 MPa
σ_Y	**145 MPa**	122 MPa	105 MPa	195 MPa	171 MPa	148 MPa
Difference from the whole surface	-	– 23 MPa	– 40 MPa	50 MPa	26 MPa	3 MPa

Table 1- Values of local yield points for different grains of the sample

One can conclude from this table that grains 1 and 2, which are more solicited, are entering in their plastic domain earlier that the whole observed region (for a nominal tensile stress ≈ 20 MPa lower). On the contrary, grains 3 and 4, less solicited, are entering in their plastic domain later (for a nominal tensile stress ≈ 30 MPa higher). The difference of values for grain 2 and grain 3 between the two values of $\sigma_{Y\ 0.02\%}$ and σ_Y can be explained by the noisier experimental data for these grains.

4. CONCLUSION

The exposed study, based on a full-filed micro-extensometric methodology, has been applied to a austenitic stainless steel sample submitted to a tensile test.

The proposed experimental procedure has confirmed its robustness and relevancy to measure local small strains (strain resolution ≈ 2.10^{-3} for a spatial resolution about 20 μm). Moreover, it has allowed showing that the plastic domain starts earlier than the macroscopic yield point (which can be considered only as an average value of all the local yield points). This was known for a long time (especially, once studying fatigue behaviour, the permanent deformations appearing before to reach the macroscopic yield stress are decisive) but has hardly been experimentally measured.

Equipped with this method, a possible continuation to this work could be to combine it with thermographic observation to link the local measured plastic strains to the heat dissipation of a studied material and, thus, develop a tool to better characterize the endurance limit.

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