Enhancing the information-richness obtain from Berkovich nanoindentation to quantify slip systems interactions in FCC crystal

Alexandre Bourceret [1], Yves Gaillard [1], Arnaud Lejeune [1] and Fabrice Richard [1]

[1] Université de Franche-Comté, Institut FEMTO-ST, CNRS/UFC/ENSMM/UTBM, Département Mécanique Appliquée, 25000, Besançon, France

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ABSTRACT

Single crystal plasticity laws [1] parameters identification remains of a great interest for the aeronautic and nuclear domains. Such material parameters drive the anisotropic hardening at microscopic scale and allow finest description of the plastic behaviour. Determination of the slip systems interaction coefficients ($h_i, i \in \{1,..,7\}$), plasticity laws core, is critical for reliable simulations applied to industrials fields. In the meanwhile, those parameters are difficult to identify experimentally. Nanoindentation test seems to be a great choice for enhancing slip systems interaction identification [2], [3]. Nevertheless, the inverse method (Finite Element Model Updating) used to identify those parameters requires a CPFEM (Crystal Plasticity Finite Element Model) of the test which is sustainable with the fewer computation time possible. The 10 hardening parameters (Q, b, τ_0 and h_i) must identified simultaneously using FEMU to correctly describe the hardening behaviour of a material. To optimize and enhance the identification process, a prior identifiability study is performed to build an optimal experiment design. Identifiability study measure the information richness that could be given to the identification process, leading to a better control of the future identification process. This optimal experiment design will be in another used in the FEMU process, leading to the quantification of the interaction.

Firstly, indentations simulations and experiments are performed within a single grain. We investigate the experimental crystal orientations and the relative orientation between crystals references frames and the Berkovich tip to simulate the nanoindentation test in the same configuration than the experimental one. To highlight the impact of the slip systems interactions coefficients on residual topographies, we first used three sets of interaction from literature [4], [5]. The crystal reference frame (in red) and the numerical reference frame (Ansys reference frame) are represented figure 1 c) on the top of the experimental residual topography. The three parameters of the hardening law (Q, b, τ_0) are identified from tensile test using polycrystals modelling, to have the same macroscopic behaviour as presented figure 1 a). Using those three sets of parameters, figure 1 d) to f) illustrates the sensitivity of the residual topography to the interaction coefficients. We can observe on Figure 1 the difference between the three topographies in terms of height, shape and distribution of pile-ups. These simulations highlight the sensitivity of the topography and $P - h$ curve to the interaction coefficients.

Thereafter, to quantify this information richness, an identifiability analysis from some observables ($P - h$ curves, topographies) and tip/crystal experimental orientations is performed. This analysis allows us to define the best orientation and observables. The quantification of the information richness is based on an I-index [3], computed from the eigen values of a quasi-hessian matrix of a cost function which could be used in the FEMU method. This I-index measures the parameters identifiability (i.e., the sensitivity of a set of parameters to the observables). It allows us to compare the information richness brought by each experiment.

Finally, some combinations of experiments will be investigated using the I-index, in order to find some complementarity between observables. This may lead to an optimal experiment design, providing enough information to well-posed the inverse problem.

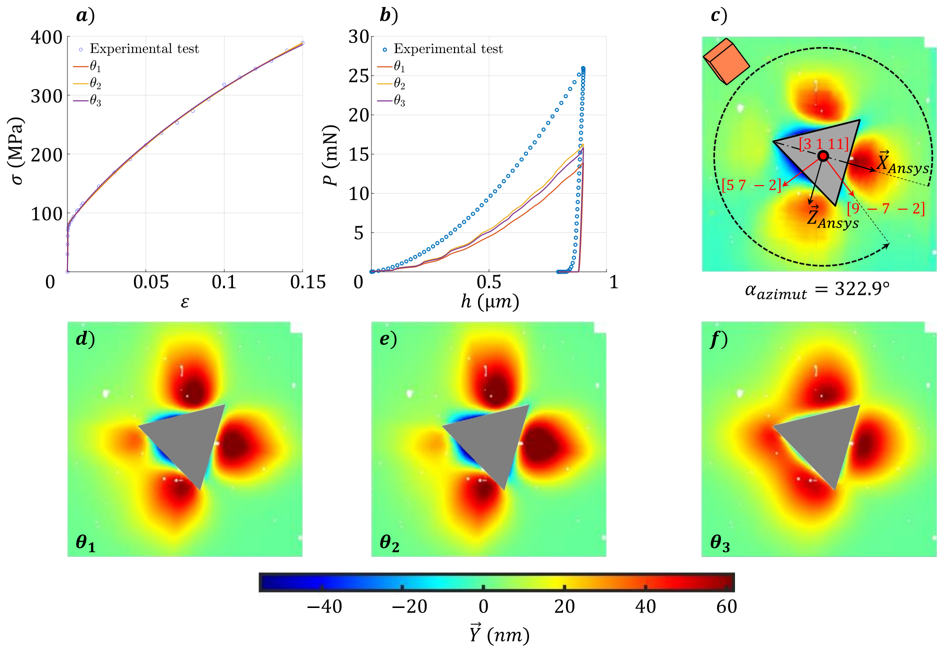

Figure 1 : a) Simulations and experimental tensile curves on polycrystal sample. b) Simulations and experimental $P - h$ curves. c) Crystal (red axis)/indenter tip configuration represented on the experimental topography. The $\vec{X}$ and $\vec{Z}$ component define the indentation plane and $\vec{Y}$ the elevation. Crystal orientation is illustrated by a cube shape in the upper left corner. Figures d) to f) are the simulated topographies for the three θ_i sets of parameters.

REFERENCES

[1] L. Méric et G. Cailletaud, « Single Crystal Modeling for Structural Calculations: Part 2—Finite Element Implementation », *J. Eng. Mater. Technol.*, vol. 113, nº 1, p. 171-182, janv. 1991, doi: 10.1115/1.2903375.

[2] E. Renner, Y. Gaillard, F. Richard, F. Amiot, et P. Delobelle, « Sensitivity of the residual topography to single crystal plasticity parameters in Berkovich nanoindentation on FCC nickel », *Int. J. Plast.*, vol. 77, p. 118-140, févr. 2016, doi: 10.1016/j.ijplas.2015.10.002.

[3] E. Renner, A. Bourceret, Y. Gaillard, F. Amiot, P. Delobelle, et F. Richard, « Identifiability of single crystal plasticity parameters from residual topographies in Berkovich nanoindentation on FCC nickel », *J. Mech. Phys. Solids*, vol. 138, 2020, doi: 10.1016/j.jmps.2020.103916.

[4] L. Méric, G. Cailletaud, et M. Gaspérini, « F.E. calculations of copper bicrystal specimens submitted to tension-compression tests », *Acta Metall. Mater.*, vol. 42, nº 3, Art. nº 3, mars 1994, doi: 10.1016/0956-7151(94)90287-9.

[5] R. Madec et L. P. Kubin, « Dislocation strengthening in FCC metals and in BCC metals at high temperatures », *Acta Mater.*, vol. 126, p. 166-173, mars 2017, doi: 10.1016/j.actamat.2016.12.040.