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Cosserat crystal plasticity and recrystallization

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Cosserat crystal plasticity *Recrystallization* *Phase field*

Abstract Cosserat crystal plasticity aims at introducing the effect of lattice curvature and torsion induced by dislocations in the continuum modelling of work-hardening in metals and alloys. The Cosserat lattice curvature generally is a good approximation of Kröner's and Nye's dislocation density tensor whose impact on plasticity is accounted for by single crystal gradient plasticity [2]. On the other hand, the phase field approach to grain boundary migration involves strong lattice orientation gradients at grain boundaries associated with the diffuse interface description [3,4]. Combining crystal plasticity in the bulk and grain boundary motion is possible via the Cosserat continuum framework, as proposed in [5]. In that model, the skew-symmetric part of the stress tensor plays a central rôle in the distinct bulk and grain boundary behaviour. In the bulk, the skew-symmetric part of the stress tensor is the reaction stress to the constraint that the Cosserat micro-rotation degrees of freedom coincide with the crystal lattice rotation. In contrast, it obeys to a viscoplastic constitutive equation allowing for lattice reorientation to relax lattice compatibility stresses inside grain boundaries. It explicitly appears in the Kobayashi-Warren-Carter phase field model for grain boundary motion and in the Cosserat crystal plasticity framework. The combination of both field equations makes it possible to tackle problems of microstructure evolution induced by, or even during, plastic deformation in polycrystals. The advantage of the model compared to existing multi-phase field approaches is that 7 degrees of freedom (3 displacements, 3 micro-rotations, one order parameter) are sufficient to account of intragranular heterogeneous deformation and lattice rotation, and grain boundary migration. Recent advances in [6] show that, under circumstances, lattice orientation gradients may become unstable according to the model. A linear orientation distribution will split into a finite number of grains depending on the various energy levels at stake. We think that this phenomenon is part of the mechanisms leading to grain nucleation in complex heterogeneous plastic deformation fields. The simulation of torsion tests on single crystal wires in [6] predicts the formation of a bamboo grain microstructure after annealing, as confirmed by some rare experiments on single crystal aluminium wires. The figure 1 below shows the migration of a longitudinal grain boundary in a bi-crystal wire induced by elastic-plastic torsional loading. The grain boundary becomes horizontal before new parallel grains nucleate. It remains that this promising model still requires systematic experimental validation and improved computational efficiency to address more realistic polycrystalline aggregates.

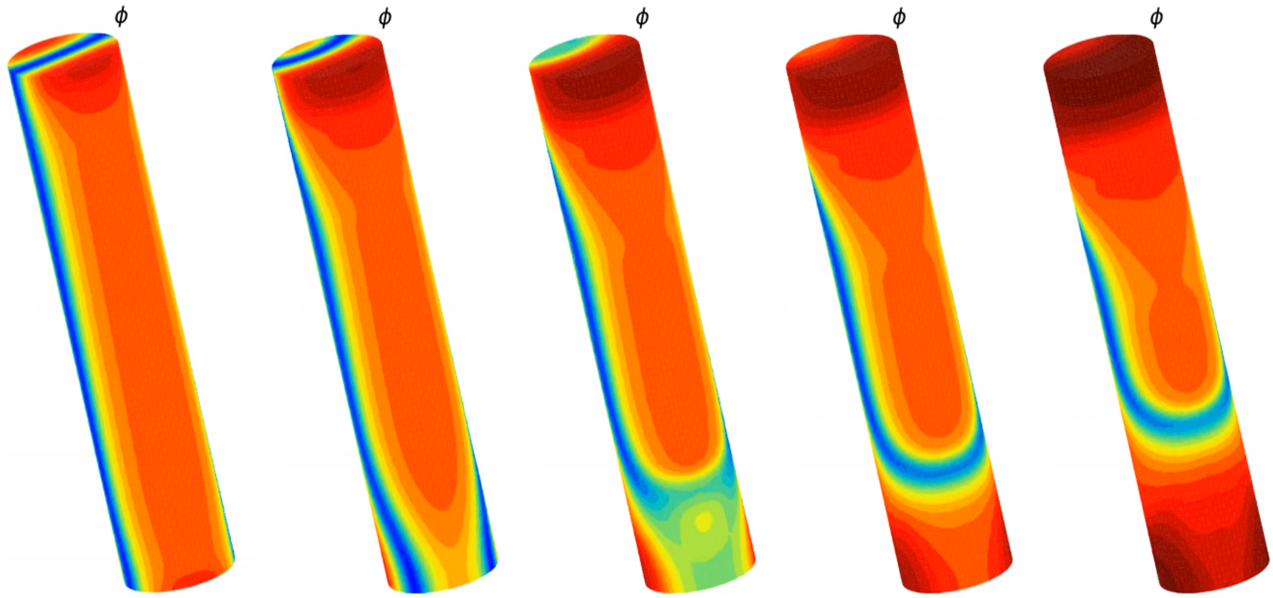

Figure 1 - *A vertical grain boundary in a metallic wire migrates and rotates under the effect of elastic-plastic torsion [6]*

References

[1] N.M. Cordero, A. Gaubert, S. Forest, E.P. Busso, F. Gallerneau and S. Kruch, *Size effects in generalised continuum crystal plasticity for two-phase laminates,* Journal of the Mechanics and Physics of Solids, vol. 58, pp. 1963-1994, 2010. doi:10.1016/j.jmps.2010.06.012

[2] S. Wulfinghoff, S. Forest and T. Böhlke, *Strain gradient plasticity modelling of the cyclic behaviour of laminate microstructures,* Journal of the Mechanics and Physics of Solids, vol. 79, pp. 1-20, 2015. doi:10.1016/j.jmps.2015.02.008

[3] G. Abrivard, E.P. Busso, S. Forest and B. Appolaire, *Phase field modelling of grain boundary motion driven by curvature and stored energy gradients. Part I: theory and numerical implementation*, Philosophical Magazine, vol. 92, pp. 3618-3642, 2012. doi:10.1080/14786435.2012.713135

[4] G. Abrivard, E.P. Busso, S. Forest and B. Appolaire, *Phase field modelling of grain boundary motion driven by curvature and stored energy gradients. Part II: Application to recrystallisation*, Philosophical Magazine, vol. 92, pp. 3643-3664, 2012. doi:10.1080/14786435.2012.717726

[5] A. Ask, S. Forest, B. Appolaire, K. Ammar, O.U. Salman, *A Cosserat crystal plasticity and phase field theory for grain boundary migration*, Journal of the Mechanics and Physics of Solids, vol. 115, pp. 167-194, 2018. doi.org/10.1016/j.jmps.2018.03.006

[6] F. Ghiglione, A. Ask, K. Ammar, B. Appolaire and S. Forest, *Cosserat-phase-field modeling of grain nucleation in plastically deformed single crystals*, Journal of the Mechanics and Physics of Solids, vol. 187, pp. 105628, 2024. doi:10.1016/j.jmps.2024.105628