# MICROMECHANICAL MODELLING OF THE SOFTENING OF METALLIC MATERIALS DURING CYCLIC AND CREEP LOADING

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*Summary* Metallic polycrystals presenting high dislocation densities and low (sub)grain size in the as-received condition are generally prone to softening during cyclic and creep loading. A physically-based mean-field homogeneization model is proposed accounting for free dislocation annihilation and production as well as low-angle boundary dislocation annihilation. All parameters have physical meaning and are generally known from either measurements or literature. The predicted macroscopic softening behaviour and microstructure evolutions are generally in fair agreement with experimental data obtained for various materials and loading conditions.

## INTRODUCTION

Metals and alloys with initial high dislocation density and small (sub)grain size are generally prone to large softening during cyclic or creep loading. This softening behaviour is characterized by stress amplitude decrease during strain-controlled tests (Fig. 1 a) and short stationary stage followed by long tertiary stage showing increasing strain rate during creep, even before necking and intergranular damage become influent macroscopically. This behaviour is observed for various metals and alloys: martensitic steels [1,2], bainitic steels [3] and ultrafine-grained polycrystals [4], whatever the crystallographic structure. Two main microstructure observations partially explain this softening behaviour: the dislocation density decreases strongly and (sub)grain size increases largely (Fig. 1 b), mainly due to low-angle boundary (LAB) vanishing. A multiscale model based on the most probable annihilation mechanisms has been developed and predictions compared to experimental data and observations for various materials and loading conditions.

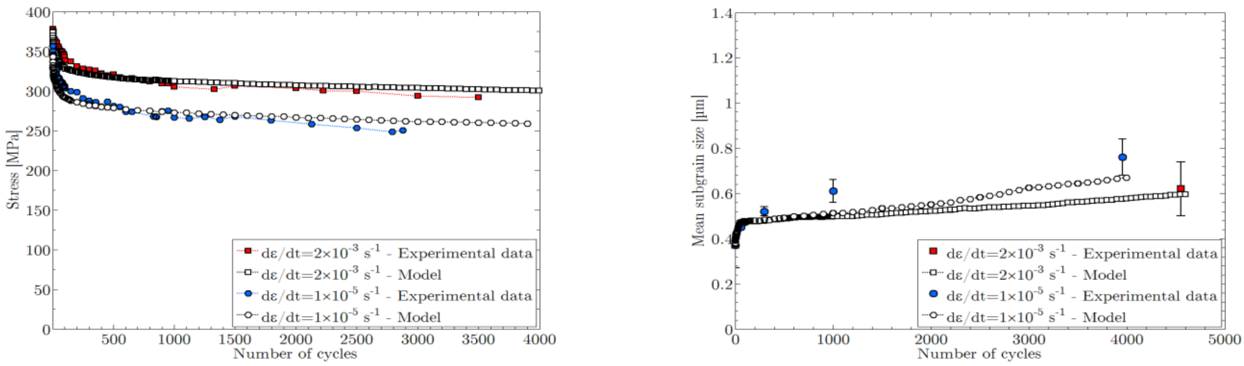


Fig. 1: a) predicted and experimental evolutions of the maximum peak stress during cyclic loading. Strain-controlled test, amplitude: ±0.35%; b) predicted and measured evolutions of subgrain size in similar conditions. Measurement by transmission electron microscopy. Tempered martensitic steel grade 92, 550 °C.

## CONSTITUTIVE LAWS AND HOMOGENEIZATION PROCEDURE

In the as-received condition, each crystal is assumed to be full of dislocations and LABs. Depending on the considered material, crystals represent martensite blocks, ferrite blocks or grains which boundaries are large-angle ones. These crystals are embedded in a matrix which mimics the behaviour of the whole polycrystal following the self-consistent hypothesis. For low-strain amplitude cyclic loading, the thermo-elastic localization rule proposed by Kröner [5] is used whereas the Molinari viscoplastic tangent localization rule [6] is adopted more generally, such as in the case of creep.
At the crystal scale, isotropic elasticity is used as well as thermal activation of viscoplastic glide. The hardening laws are based on the forest obstacles (isotropic shear stress) and tension line effects induced by the bowing-out of dislocations, which introduced a first (sub)grain size effect (Fig. 2 a). The hardening law linking the kinematic shear stress rate with the viscoplastic slip one has been deduced from geometry considerations and the Orowan law (Fig. 2 a). Finally, the evolution laws of free screw and edge dislocation densities take into account a production term based on the bowing-out mechanism which introduces a second (sub)grain size effect [7,8], and annihilation terms based on the spontaneous annihilation between two close parallel dislocations of opposite signs. An additional annihilation term arises from the interactions between incident free dislocations and LAB dislocations (Fig. 2 b) [9]. Such annihilations lead to LAB dislocation lineic density decrease during viscoplastic deformation and finally LAB vanishing and (sub)grain size increase [9]. All parameters have physical meaning and their possible ranges of variation such as the ones of the initial values of dislocation density and (sub)grain size are known following either literature or our measurements. An

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extensive parametric study has shown that the predictions are stable with respect to the parameter values. Only two parameters should be adjusted, using two experimental macroscopic tensile curves at different strain rates, but no cyclic data. These two parameters are the activation free energy and volume which may be linked to thermally-activated interactions of gliding dislocations with various obstacles such as solid solution, nanometric precipitates… and then could not be evaluated following a more straightforward way.

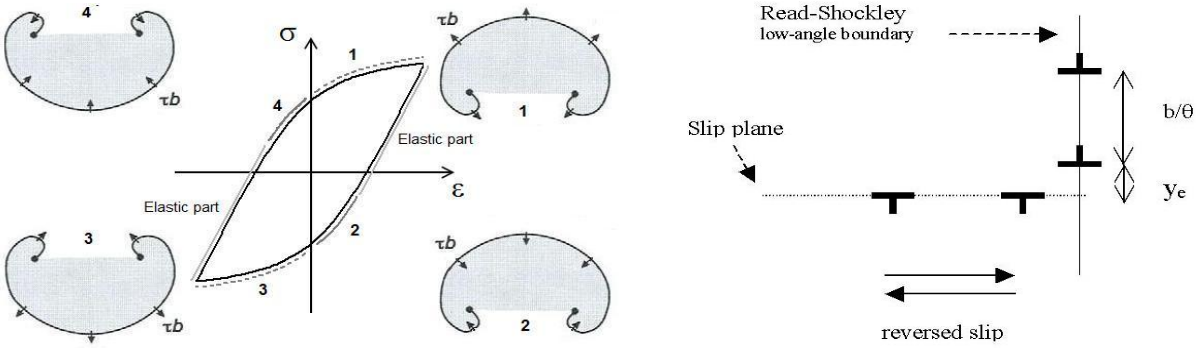


Fig. 2: a) bowing-out of a dislocation loop during tensile loading and reverse glide during compression loading; b) sketch of the annihilation process occurring between a LAB dislocation and a free dislocation of opposite sign gliding toward the symmetric tilt LAB (b: Bürgers vector length, θ: LAB misorientation, ye: edge dislocation annihilation distance).

## RESULTS

The cyclic behaviour of tempered martensitic steels at high temperature is first discussed. Twenty-four easy slip systems are considered taking into account their crystallographic structure which is very close to the body-cubic centred one. The predicted macroscopic softening behaviour is in agreement with experimental data (Fig. 1 a). At the microscopic scale, the simulated evolutions of both dislocation density and subgrain size are close to the measured evolutions (Fig. 1 b). The effect of strain rate is rather well reproduced. The effect of both viscoplastic strain amplitude and loading multiaxiality is correctly predicted too. Their increases both trigger softening partly because the induced numbers of activated slip systems are higher and consequently the probabilities of dislocation annihilation. Simulations of the cyclic behaviour at room temperature are encouraging as well.

The microstructure evolutions observed during creep of similar steels are fairly predicted as well, such as the ones of (sub)grain size and mean LAB misorientation [9,10].

## CONCLUSIONS

Such multiscale modelling based on both physical recovering mechanisms and mean-field homogeneization leads to predictions in rather fair agreement with experimental data concerning cyclic and creep softening of steels. Work is in progress concerning:

- the effect of time-dependent recovering mechanisms such as climb which has been implemented in the used numerical code and precipitation.
- the comparison between predictions and experimental data in the case of ultra-fine grained materials

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