In situ straining experiments in iron and iron alloys

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In situ straining in the TEM remains up to now the most efficient experimental method to analyse the mechanisms controlling the mechanical properties of crystals at the nano-scale. This technique has been continuously improved, and it can now yield detailed quantitative information on the kinetics of individual dislocations, as a function of local stress and temperature between 100K and 1500K. Different methods to study the motion of dislocations in three dimensions and to determine local stresses and velocity-stress dependences of individual dislocations will be described in a first part (figs. 1 and 2). Results of in situ experiments in iron and iron alloys are described in a second part. Iron is a usefull model material to study Peierls friction forces and the influence of solute atoms on mechanical properties, at low and high temperatures.

Mechanical tests at very low temperatures show that the yield stress is about three times lower than that deduced from atomistic calculations. The origin of this important discrepancy is still unexplained, although probably involving quantum effects.

Alloying induces a strong hardening close to room temperature which cannot be interpreted in terms of a classical Cottrell interaction between dislocations and immobile solute atoms.

At high temperatures, dislocations interact dynamically with various interstitial or substitutional solute atoms, leading to dynamic strain ageing (DSA). Here again, the detailed mechanisms are not well understood.

To interpret these properties, in situ straining experiments have been carried out in a JEOL 2010 transmission electron microscope, between 100K and 800K, in pure Fe and in various binary alloys.

Solid solution hardening between 200K and 300K results from the pinning of screw dislocations at super-jogs formed by cross-slip in the vicinity of substitutional solute atoms [2]. The corresponding hardening has been correlated to the density of pinning points and to the concentration of solute atoms.

Dynamic strain ageing has also been studied above room temperature. The effect of interstitial carbon is characterized by a surprisingly low mobility of screw dislocations controlled by a high-temperature resurgence of the Peierls mechanism [3, 4]. Substitutional atoms can either move the domain of dynamic strain ageing to higher temperatures or not, depending on their chemical affinity for carbon. The results are interpreted by a shielding effect of carbon atoms connected to dislocations[4].

[1] D. Caillard, Acta Mater: **62**, 267 (2014)
[2] D. Caillard, Acta Mater: **61,** 2793 and 2808 (2013).
[3] D. Caillard and J. Bonneville, Scripta Mater: **95**, 15 (2015).
[4] D. Caillard, Acta Mater: **112**, 273 (2016).

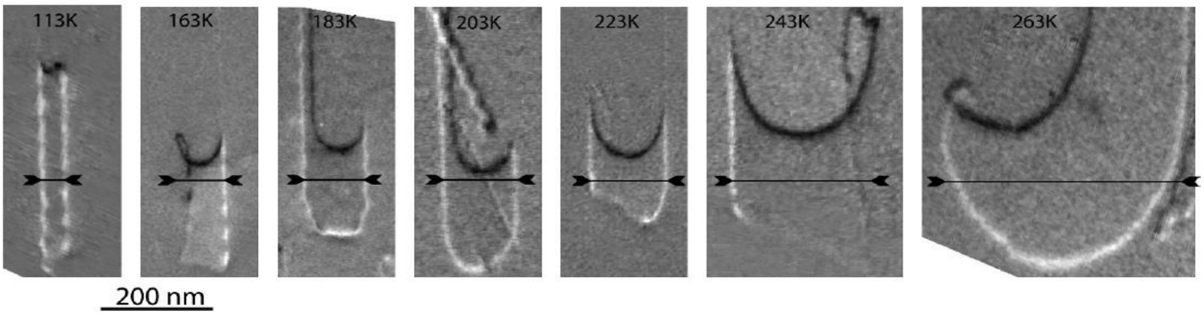

Fig. 1: Series of dipole expansions at increasing temperatures in pure iron. Note the increase of the critical distance arrowed, which corresponds to the decrease of the local stress with increasing temperature.

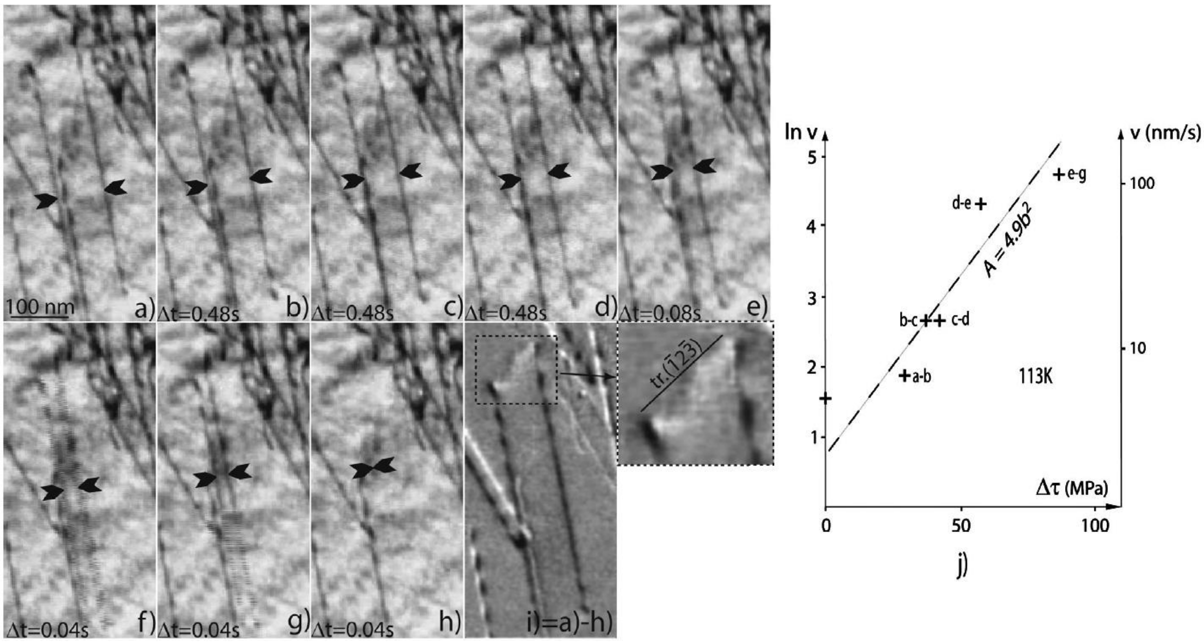

Fig. 2: Dipole annihilation at 113 K in pure iron. The velocity of two opposite screw dislocations increases as their distance decreases (note the decreasing time intervals Dt between two successive images). The increase in velocity as a function of the interaction stress Dt in (j) yields the microscopic activation area A.