

# An in situ study of hardening and softening of iron by carbon interstitials

D. Caillard\*

CNRS, CEMES, 29 rue Jeanne Marvig, BP 94347, Toulouse, 31055 Cédex, France

Received 4 January 2011; received in revised form 18 April 2011; accepted 19 April 2011

Available online 26 May 2011

## Abstract

Transmission electron microscopy in situ straining experiments were carried out in Fe–110 at.ppm C, between 95 and 375 K, in order to determine the origin of the softening/hardening effects of carbon in an iron matrix. The local stresses in microsamples are in fair agreement with the corresponding macroscopic yield stresses as a function of temperature, and the softening/hardening effects of carbon are well reproduced at the microscopic scale. Dislocations multiply at sources and glide in {1 1 0} planes, as in pure Fe. The motion of straight screw dislocations is much steadier than in pure Fe, however, showing that the transition between the two mechanisms observed in pure Fe was shifted to a lower temperature. This allows one to interpret straightforwardly the softening effect of carbon at intermediate temperatures. The hardening effects at lower and higher temperatures are also discussed.

© 2011 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

**Keywords:** Transmission electron microscopy; In situ experiment; Iron; Dislocation mobility

## 1. Introduction

Solute elements strongly influence the low-temperature mechanical properties of body-centred cubic metals, even at very low concentrations for interstitial atoms. Solute effects, however, are relatively complex, as they can result in either hardening or softening, depending on the temperature and the type of solute [1]. In iron, softening is observed upon alloying with interstitial atoms such as carbon and nitrogen [2–7] or after irradiation creating self-interstitials [8,9].

In the case of carbon interstitials, to which this article is devoted, softening is observed in the temperature range 170–280 K, as shown in Fig. 1. Below 170 K, the results can be differently interpreted, depending on the choice of the internal stress which can be subtracted from the yield stress, in order to isolate the thermally activated “effective stress”. If the internal stress is neglected, i.e. if one refers to

the original yield-stress vs. temperature curve, softening changes to hardening <170 K [2,4–6] (see Fig. 1). However, if the stress measured slightly above 300 K is considered to be the internal stress (higher after carbon addition), and if this stress is subtracted from the yield stress, the corresponding effective stress exhibits a more pronounced softening at intermediate temperatures, but no hardening <170 K. This latter procedure was used by Cottu et al. [5], and also for nitrogen and Fe interstitials by Brunner and Diehl [7,10]. Since the origin and the amplitude of the internal stress are difficult to estimate a priori, this procedure has not been used in the present study. Therefore, only the total stress (effective plus internal) is considered, and the effect of carbon is described as hardening <170 K, softening between 170 and 280 K, and again hardening >280 K, in agreement with the non-corrected curves (Fig. 1).

The softening effect at intermediate temperatures is very surprising, because solute atoms are a priori obstacles to dislocation motion, which should result in the opposite effect. In iron, where plastic deformation is controlled by the motion of screw dislocations, softening indicates a

\* Tel.: +33 5 62 25 7872; fax: +33 5 62 25 7999.

E-mail address: [caillard@cemes.fr](mailto:caillard@cemes.fr)

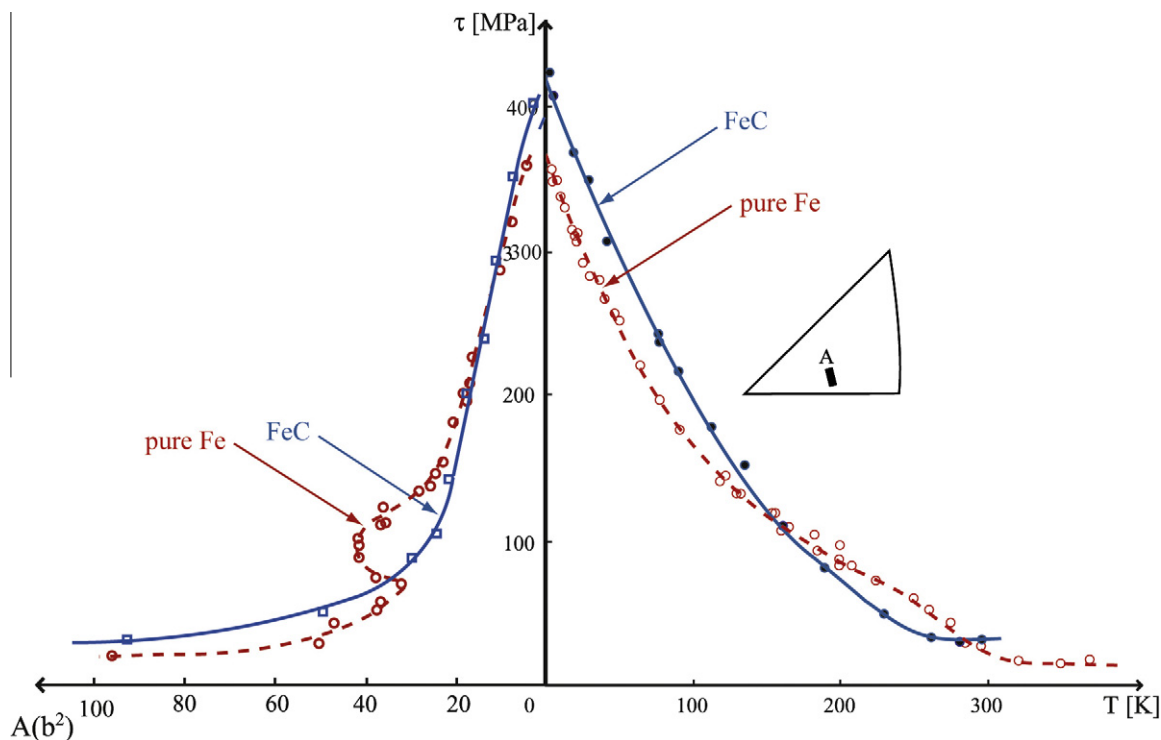


Fig. 1. Experimental activation area  $A$  and yield stress  $\tau$  as functions of temperature  $T$  in Fe and FeC. The yield stress is taken as the resolved shear stress on the most stressed plane, and in a  $\langle 111 \rangle$  direction (strain rate  $1.7 \times 10^{-4} \text{ s}^{-1}$ ). From Kuramoto et al. [6].

possible decrease in the Peierls friction force. Following this idea, Sato and Meshii [11] and Kubin et al. [12] proposed an increase in the rate of kink-pair formation in the vicinity of solute atoms. However, as pointed out by Aono et al. [13] and Brunner and Diehl [7], this explanation cannot account for the absence of softening at very low temperatures, where the same mechanism should operate. According to Ref. [7], the critical kink-pair distance at low temperature is smaller than the average distance between solute atoms along the dislocation line, which indicates that (i) solute atoms do not facilitate kink-pair formation, and (ii) propagating kinks are not significantly slowed down by solute atoms. On the basis of the observation of three different regimes in pure iron, Brunner and Diehl [7] proposed an easier constriction-pair nucleation in their regime II, where kink-pair formations are assumed to be followed by a reversion of the threefold core structure. This latter interpretation is invalid, however, for the non-degenerate core structure expected in Fe, according to the most recent calculations (see Refs. [14,15] for a more complete discussion).

At low temperature, the hardening effect of interstitials was proposed by Kubin and Louchet [16] to result from a decrease in the mean free-path of kinks along screw dislocations. This interpretation has been criticized by Aono et al. [13], however, who pointed out that this could not explain the hardening near absolute zero temperature. Indeed, the yield stress extrapolated to 0 K should always correspond to the Peierls stress, which does not depend

on the kink mobility. As an alternative explanation, Aono et al. proposed the enhancement of sessile jog formation.

The above softening/hardening mechanisms have been described in a recent book by Argon [17]. Similar solute–dislocation interaction effects have also been studied recently by Trinkle and Woodward [18] in Mo. By electronic structure calculations, they confirmed that softening may result from an easier kink-pair nucleation at low solute concentrations and low temperatures, and hardening may result from the interaction between mobile kinks and clusters at higher solute concentrations and higher temperatures. The main questions raised by these interpretations (see above) are, however, still not resolved.

In another article, Kuramoto et al. [6] pointed out that the softening effect of carbon interstitials is associated with the vanishing of the peak in the activation area vs. stress curve in pure Fe (Fig. 1). Then, the interpretation of the softening effect may be restricted to the interpretation of the peak removal by carbon addition. According to Kuramoto et al. [6], the peak may result from a Peierls potential with a “camel-hump” shape (see e.g. Ref. [19]), which implies that the softening effect of carbon should be due to a transition to a more classical Peierls potential. However, recent in situ experiments in pure Fe [14,15] have shown that the peak of activation area originates from another kind of discontinuity. According to these recent observations, the peak is the limit between two regimes of screw dislocation motion: (i) a steady regime, controlled by the classical kink-pair mechanism  $>250 \text{ K}$ ; and (ii) a

Download English Version:

<https://daneshyari.com/en/article/1447076>

Download Persian Version:

<https://daneshyari.com/article/1447076>

[Daneshyari.com](https://daneshyari.com)