EXPERIMENTAL AND NUMERICAL INVESTIGATION OF LOCAL STRESS AND STRAIN HETEROGENEITIES IN A BAINITIC STEEL

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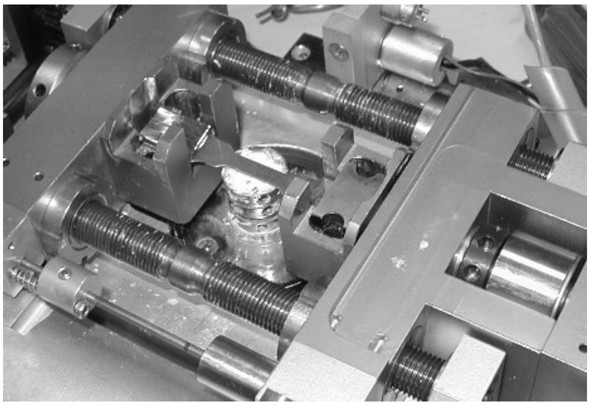
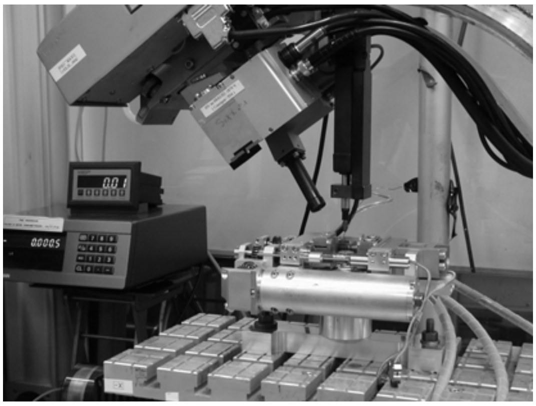
ABSTRACT- Microstructural features of bainitic steels are complex and a special attention has to be paid on carbides distribution and poly-crystalline nature of bainitic steels. An in-situ tensile test device has been set up in an X-ray diffractometer. Stress is determined in the ferritic phase during loading and unloading, at low temperature. $\sin^2\psi$ curves are also finely analyzed to provide a quantitative estimation of intergranular stress heterogeneities. Experimental results are compared with a two scales crystal plasticity model, describing the elasto-plastic behavior of the bainitic steel and also the local response of ferritic grains. Experimental results are in good agreement with modeling.

INTRODUCTION: Several analyses of the bainitic steels used for European nuclear power plants vessels have illustrated the complexity of this type of microstructure. In order to propose an accurate mechanical modeling of bainitic steels, and especially to predict the brittle fracture regime at low temperature, macroscopic formulation are not sufficient. The real microstructural and crystallographic features of baintic steels must be introduced as finely as possible. A two-scale modeling has been proposed. The first level takes the carbides distribution into account to estimate the effective behavior of a single crystal of bainite (composed of carbides in a ferritic matrix). The second homogenization level describes the poly-crystalline nature of the bainitic steels. Unlike for most of homogenization works on heterogeneous media, the formulation can be validated with a direct measurement in one of the two phases. The association of fine in-situ measurements and a two-scale modeling scheme offers wide investigation possibilities to study complex microstructures and to evaluate classical homogenization methods.

PROCEDURES, RESULTS AND DISCUSSION: The experimental device is composed of a micro tensile machine, which can be set up in the chamber of a SEM or in an X-Ray diffractometer. A specific cooler is in contact with the sample for the temperature monitoring during the stress measurement (see Fig. 1). Liquid nitrogen is used in a loop to achieve low temperatures, from –160°C to 0°C. Deviation of the {211} diffraction pick is measured during loading and converted into elastic strain and stress in the ferritic phase. The stress in the bainitic steel is measured in the same time with a classical load cell.





(a) (b)

Fig1. In-situ tensile test device. (a) Micro tensile machine and cooler device. (b) X-Ray diffractometer.

A two-scale homogenization method is proposed to take into account the carbides distribution in a metallic polycrystalline medium (Pesci et al. [2003]). The elasto-plastic behavior of each single crystal of the ferritic phase is described in the frame of small strain and the activated slip systems are determined according to the Franciosi-Zaoui energetic criterion (Franciosi, Zaoui [1991]). A Mori-Tanaka model is used to compute the effective tangent modulus of a single crystal including carbides. A classical self-consistent method is then applied to the tangent moduli to determine step by step the effective behavior of the bainitic aggregate.

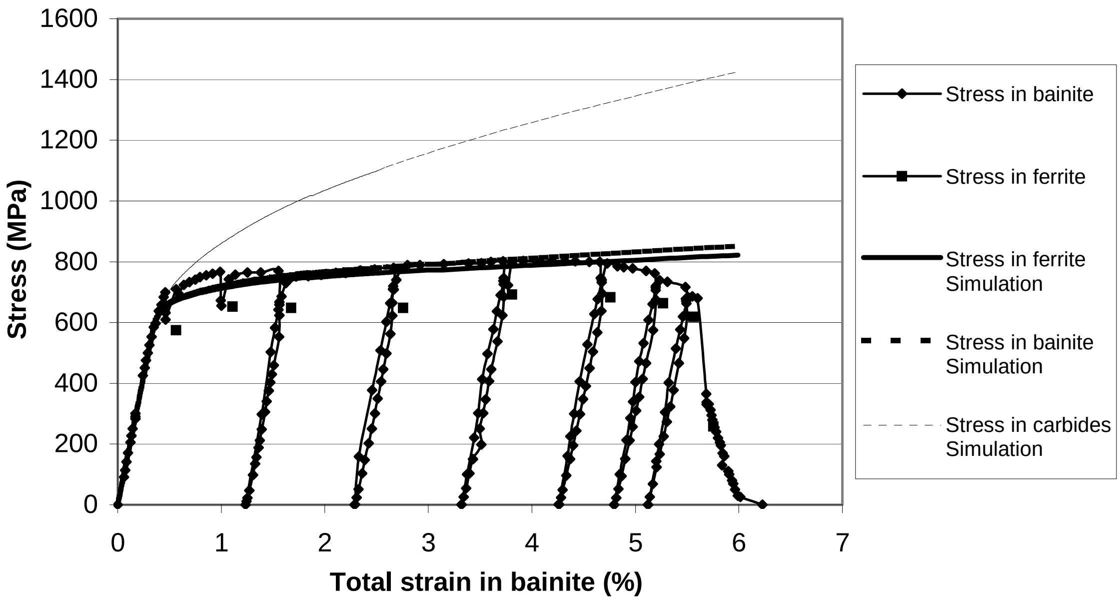


Fig2. X-Ray measurement of stress in the ferritic phase and classical measurement of stress in the bainitic steel. Comparison of experimental results with simulations.

X-ray measurements and results of simulations are reported in Fig. 2. The stress mismatch between the ferritic phase and the baintic steel is well measured *during loading* and the two-scale modeling is also able to predict this behavior.

$Sin^2(\psi)$ curves are also reported in Fig. 3. Measurement by XRD of $sin^2(\psi)$ curves provides a quantitative estimation of strain and stress heterogeneities in the ferritic phase. According to those results, several homogenization methods can be evaluated, not only on average responses in each phase but also on the prediction of intra-phase heterogeneities. In this work, simulations are in general agreement with experimental results.

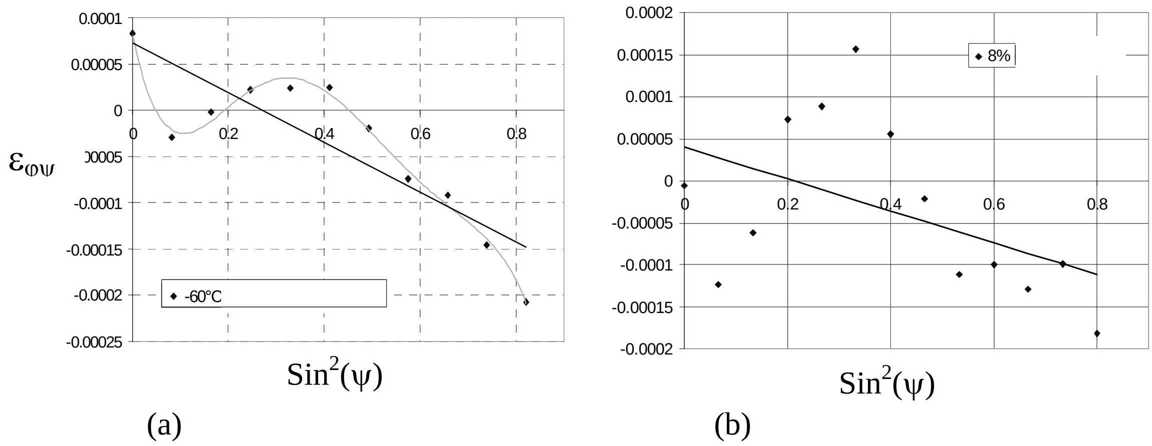


Fig3. Strain heterogeneities in the ferritic phase. (a) X-Ray measurement of a $sin^2(\psi)$ curve in the ferritic phase (plane {211}) after unloading. (b) Results of the simulation.

CONCLUSIONS: A specific in-situ tensile device has been set up in an X-Ray diffractometer. Stress can be measured at low temperature during loading in the baintic steel and in the ferritic phase. A two-scale modeling has been proposed and evaluated on three levels, means stress in the baintic steel, stress in the ferritic phase and stress heterogeneities in the ferritic phase. Simulations are in general agreement with experiments.

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