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Assessment of the constitutive law by inverse methodology: Small punch test and hardness

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Abstract

The relevance of small-punch tests and indentation (hardness) tests are compared with regard to the determination of a constitutive law in the case of non active ferrite–bainite steel taken from a French power plant. Firstly, small-punch tests were performed on material samples and the load deflection curves were compared with finite element calculations using the FORGE2 Standard code. As a result the strength coefficient and the strain hardening exponent of Hollomon's constitutive law were determined by an inverse method (Simplex method). Besides, it was shown that a three-parameter constitutive law such as Ludwik Hollomon's leads to an indetermination since its parameters are correlated with each other. Secondly indentation tests were performed with a ball indenter and the parameters of the constitutive law were determined from the analysis of the load–indentation depth curves. Both methods give results in good agreement with the true stress–true strain curve obtained by classical tensile testing, thus proving their applicability to nuclear materials.

1. Introduction

Because of the desire to increase the exploitation lifetime of nuclear plants, the degradation of the components' mechanical properties requires careful attention and monitoring over time. Unfortunately, there is a natural decrease in the available samples which were placed in situ earlier. Under these conditions, small-scale specimen techniques and non-destructive tests become thus more and more attractive in order to characterize the mechanical properties and the in-service degradation of the components.

Among these techniques, the small-punch test and the indentation test allow information to be obtained while using only a very small quantity of material. Initially the small-punch test was developed to study irradiation effects [1]. This test was used to evaluate the ductile to brittle transition temperature (DBTT) [2,3], but also yield stress, ultimate tensile stress [4,5], fracture toughness [6,7] and creep behavior [8,9]. Among the indentation tests, the instrumented tests, which enable to dissociate elastic

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behavior from plastic behavior, are the most useful to obtain intrinsic characteristics other than the resistance to penetration. For instance, the ABI (automated ball indentation) method [10] can also be used for the estimation of DBTT and fracture toughness.

The aim of the present investigation is to compare the relevance of indentation and small-punch tests with regard to the determination of a tensile constitutive law for a nuclear material.

2. Experimental procedure

2.1. Materials

This study focuses on a low alloyed steel 15 Mn Mo V (US denomination: A508) taken from a piece of a steam vessel of the power plant located in Montereau (France) after exposure for 145 000 h at a temperature of 613 K and a pressure of 130 bar. The microstructure of this alloy, which is presented in Fig. 1, consists of banded ferrite and bainite known as ghost lines resulting from the segregation of the alloying elements and impurities. The grain size is very heterogeneous particularly in the case of the bainite phase.

For the different mechanical tests performed in this investigation, the behavior of the material was assessed in the three usual orientations L (long), T (transverse), S (short-transverse) shown in Fig. 1.

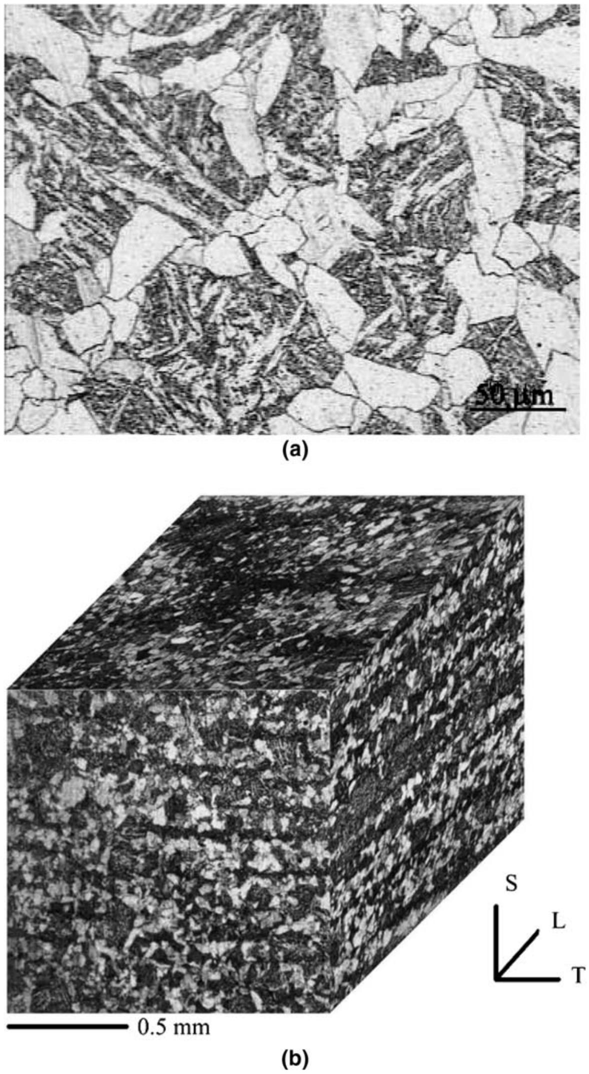

Fig. 1. (a) Microstructure of the low alloyed steel A508 revealed by a Stead le Chatelier solution and (b) the banded structure.

2.2. Tensile tests

Tensile tests have been carried out on 4 mm diameter and 10 mm gauge length specimens with a hydraulic testing machine at a nominal strain rate of $8.32 \times 10^{-3}\ s^{-1}$. The strain hardening exponent n and the strength coefficient k have been calculated from the stress (σ)–strain (ε) curve according to the guidelines of the ISO 10275 standard considering Hollomon's constitutive law

$$\sigma = k\varepsilon^n. \quad (1)$$

2.3. Small-punch tests

2.3.1. Sample preparation

Firstly, specimens have been machined from the piece of vessel by Electro discharge machining to obtain rough discs of 9 mm in diameter and 0.7 mm in thickness. Secondly, the two sides of these discs have been polished with a 1200 paper grade up to a final thickness of 0.5 mm ± 10 µm. Finally, the samples have been electro-polished in a perchloric and acetic acid solution. It is well known that using small specimens for mechanical testing can induce a scattering in the data due to a large size of micro structural constituents relative to the size of the sample. However, in the present investigation, it must be mentioned that the thickness of the overall samples tested was larger than the diameter of 10 grains.

2.3.2. Mechanical testing

The small-punch tests have been carried out with a low speed tensile test machine. The experimental device includes the disc specimen, a 2.5 mm diameter ball and a specimen holder. The specimen holder