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Fracture toughness characterization through notched small punch test specimens

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ABSTRACT

In this work a novel methodology for fracture toughness characterization by means of the small punch test (SPT) is presented. Notched specimens are employed and fracture resistance is assessed through a critical value of the notch mouth displacement δ^{SPT}. Finite element simulations and interrupted experiments are used to track the evolution of δ^{SPT} as a function of the punch displacement. The onset of crack propagation is identified by means of a ductile damage model and the outcome is compared to the crack tip opening displacement estimated from conventional tests at crack initiation. The proposed numerical–experimental scheme is examined with two different grades of CrMoV steel and the differences in material toughness captured. Limitations and uncertainties arising from the different damage phenomena observed in the lowest toughness material examined are thoroughly discussed.

1. Introduction

The mechanical characterization of industrial components by means of conventional methodologies is, in many engineering applications, an extremely complicated – or even infeasible – task. These are, e.g., the cases of a structural element with complex geometry, small size (with respect to standard testing specimens) or that requires to be characterized without compromising its remaining in-service life. Furthermore, some particular applications require a continuous structural integrity assessment from a limited amount of material. This is the case of reactor pressure vessels, where the characterization of irradiated materials is hindered by the restricted number of specimens available. Hence, small scale techniques and micromechanical damage models have been developed with the aim of estimating mechanical and fracture properties while optimizing resources. From the modeling perspective, accurate toughness predictions have been obtained by extracting model parameters from Charpy V-notch and uniaxial tensile tests [1,2]. While on the experimental side, a significant progress has been achieved with the small punch test (SPT), a miniature non-standard experimental device developed in the early 1980s [3]. Its main attribute resides in the very small specimens employed (generally 8 mm diameter and 0.5 mm thickness), such that it may be considered a non-destructive experiment. The SPT has consistently proven to be a reliable tool for estimating the mechanical [4,5] and creep [6,7] properties of metallic materials, as well as its environmentally assisted degradation [8]. However, its capabilities in fracture toughness characterization are still a controversial subject.

A large experimental literature has appeared seeking to estimate the fracture toughness in metals by means of the SPT. Several authors [9–11] have tried to accomplish this task by establishing a correlation with the so-called maximum biaxial strain, measured in the failure region of the SPT sample. Although good empirical correspondences have been found, results reveal a strong dependence on the material employed. Other schemes involve the use of neural networks to identify ductile damage parameters [12] or energy-based approaches [4]. Recent research efforts have been mainly focused on the development of notched samples with the aim of increasing the attained constraint level [13,14]. The notch acts as a stress concentrator aiming to provide a triaxiality state closer to the standard fracture tests.

In this work a hybrid numerical–experimental methodology for estimating the fracture toughness by means of the SPT is presented. The key objectives are: (i) to establish a procedure to classify industrial components as a function of their fracture resistance and (ii) to set an appropriate correlation with standard tests, enabling a quantitative toughness assessment. A micromechanical damage model is employed to overcome the existing experimental shortcomings and enable the former objective, while the latter goal is facilitated by the use of the notch mouth opening displacement δ^{SPT} as a fracture parameter, inspired by the standard crack tip opening displacement (CTOD) δ [14]. As depicted in Fig. 1,

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Nomenclature

δ	crack tip opening displacement
δ^{SPT}	notch mouth opening displacement of the small punch notched specimen
δ_c^{SPT}	notch mouth opening displacement of the small punch notched specimen at crack initiation
δ_c	crack tip opening displacement at crack initiation
δ_{IC}	crack tip opening displacement fracture toughness
SPT	small punch test

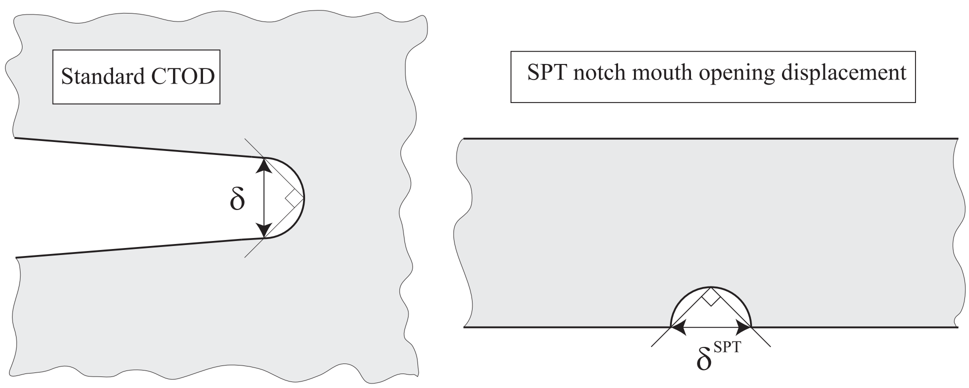

Fig. 1. Correlation between the standard CTOD in standard fracture tests and the notch mouth opening in the SPT.

a parallelism can be established between the standard definition of the CTOD and the displacement of the notch faces in the SPT. The proposed methodology is comprehensively examined, with interrupted tests being performed to gain insight into the mechanisms behind cracking nucleation under SPT load conditions. Results obtained for two different grades of CrMoV steel are compared with standard fracture measurements and the outcome is thoroughly discussed.

2. Materials and conventional characterization

As service conditions of hydrogen conversion reactors in the petrochemical industry are shifting to higher work temperatures and pressures, high thickness steel plates are being used in pressure vessels manufacturing and conventional 2.25Cr1Mo and 3Cr1Mo steels are progressively replaced by vanadium-modified low alloy steels such as 2.25Cr1MoV, 3Cr1MoV and 9Cr1MoV. In the present work, the structural integrity of a CrMoV steel welding joint is assessed through small scale test techniques by examining both base and weld metals. Thus, a 108 mm thick plate of 2.25Cr1Mo0.25V steel (SA 542 Grade D-Class 4) is employed for the base metal, which is subsequently normalized at 950 °C, quenched in water from 925 °C and tempered during 3 h at 720 °C. The weld metal is obtained from a weld coupon of 1300 mm length and 600 mm width that is produced using a maximum gap of 30 mm by means of a submerged arc welding procedure using alternating current, a 4 mm diameter Thyssen Union S1 CrMo2V consumable and a heat input of 2.2 kJ/mm (29–32 V, 425–550 A and 45–55 cm/min); with an essential de-hydrogenation being performed immediately after welding. The chemical composition of the base (CrMoV1) and weld (CrMoV2) metals examined are shown in Table 1.

2.1. Smooth tensile tests

Three tensile tests per steel grade are performed following the ISO 6892-1:2009 standard. Smooth cylindrical bars are employed to mechanically characterize the behavior of both base and weld metals. The plastic behavior in the resulting stress–strain curves is fitted by means of Hollomon type power law:

Table 1
Chemical composition of the CrMoV base (CrMoV1) and weld (CrMoV2) metals.

Steel	% C	% Si	% Mn	% Cr	% Mo	% V	% Ni
CrMoV1	0.15	0.09	0.52	2.17	1.06	0.31	0.19
CrMoV2	0.08	–	–	2.28	0.93	0.24	0.03

$$\sigma = k\varepsilon_p^n \tag{1}$$

where σ is the uniaxial stress, k is the strength coefficient, ε_p is the equivalent plastic strain and n is the strain hardening exponent. The experimental data for both CrMoV1 and CrMoV2, along with the power law fitting, are shown in Fig. 2.

The mechanical properties of both materials, particularly relevant for the finite strains finite element (FE) model, are summarized in Table 2; where E is Young's modulus, ν is the Poisson's ratio, σ_Y is the yield stress and σ_{UTS} is the ultimate tensile strength.

2.2. Notched tensile tests

Uniaxial tensile tests are performed on circumferentially notched cylindrical bars to extract the micromechanical parameters

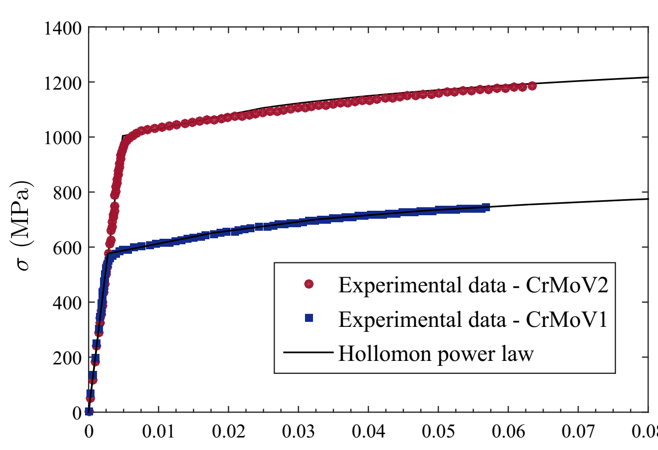

Fig. 2. Uniaxial stress strain curve for both base (CrMoV1) and weld (CrMoV2) metals.