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Different methodologies to obtain the fracture properties of metallic materials using pre-notched small punch test specimens

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ABSTRACT

One important topic in the application of the Small Punch Test (SPT) is to analyze its viability for the determination of the fracture properties of a material. This article describes three different approaches using pre-notched SPT specimens (p-SPT): the first one is based on the concept of crack tip opening displacement (CTOD), the second is based on measuring the area under the load-displacement curve for different initial pre-notch lengths, and the third approach is based on the numerical simulation of the specimen p-SPT for the J-integral determination. To explore the feasibility of this miniature test for obtaining the fracture properties of steels the test values obtained by the different approaches are compared with results obtained from conventional compact specimens C(T). The results indicate that p-SPT specimens can be used, when there is not enough material for conducting conventional fracture test, as an alternative method to estimate a value of the fracture properties under low constraint conditions.

1. Introduction

The Small Punch Test (SPT) is a mechanical testing method in which a small square or disk shaped sample (thickness of 0.5 mm) is clamped in a die and punched until fracture with a spherical indenter. This reduced specimen size means that the SPT can be regarded as an almost non-destructive test that can be used to assess the in-service degradation of materials produced under thermal or irradiation conditions. The result of the test is a load-displacement curve, in which the most important parameters to be extracted are the yield load, the maximum load, the displacement at failure and the area under the curve.

During the last decades, a great number of works can be found in the literature with the main objective to obtain the elastic plastic material properties, elastic modulus or tensile strength using un-cracked SPT specimens [1–5]. Most studies to date are focused on metallic materials, although SPT applications are recently spreading to other materials [6,7].

The application of the SP test has gained significant interest in Europe over the last decades, primarily as a result of a coordinated research by the European Pressure Equipment Research Council (EPERC) to develop a CEN Code of Practice for the application and use of the small punch test for creep rupture, tensile and toughness properties [8,9].

Over recent years, there have been several studies dedicated to obtaining the fracture properties of a material using conventional SPT's, which provide empirical equations for the estimation of a fracture initiation parameter based on the measure of the maximum thickness deformation undergone by the specimen at the moment of fracture [10–12]. In a first approach, the absence of a crack or crack-like notch reduces the precision of those methods.

Recently, a number of works [13–17] can be found that use SPT specimens, notched or pre-cracked (denoted here as p-SPT), to validate such miniaturized specimens for obtaining the fracture properties of metallic materials. Different techniques can be applied to generate the crack-like notch, such as micro-machining, laser micro-cutting or Electric Discharge Machining (EDM) [18].

The main objective of this paper is to analyze the feasibility of the pre-cracked SPT's to obtain a representative value of the fracture parameter of metallic materials. In order to obtain the fracture parameter from these specimens three different approaches have been considered here.

The first method is based on the *crack tip opening displacement* (CTOD) concept [19]. The opening of the notch can be considered as a representative parameter of the crack initiation. This technique can be considered as purely experimental and it needs to obtain the crack initiation point by means of interrupted tests. After that, a SEM analysis of the miniature specimen tested is required. The second approach is based on the measurement of the *fracture energy*, using the area under the load displacement curve for different crack sizes [20–22]. And finally, the third

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approach is based on the direct numerical simulation of the p-SPT specimen and the *numerical calculation of the J-integral* as a representative parameter of the material fracture [23–26].

In order to validate the methodology proposed in this paper, the fracture properties of the material obtained from p-SPT have been compared with those obtained from conventional fracture tests. The compact tension (CT) specimen has been used for the experimental determination of the fracture toughness of material, following the standard ASTM E1830 [27]. The materials selected for this research exhibit a ductile behavior, in order to allow a comparison of the results from notched specimens (p-SPT) with cracked specimens (CTs).

2. Geometry of the p-SPT specimens

The experimental device used in this research is the proposed in the CEN code of practice. The diameter of the punch was $d_p = 2.5$ mm, the diameter of the lower die was $D_d = 4.0$ mm and the accord radius of the lower die was $r = 0.5$ mm. The initial geometry of the specimens used in this research was square of 10×10 mm with a thickness of $t = 0.5$ mm. The process zone of this squared geometry is the same that in the disc shape specimen, 8 mm in diameter, proposed in [8], being the only difference between both geometries the area clamped by the upper and lower dies. The tests were conducted at room temperature using a displacement rate for the punch of 0.01 mm/s.

An initial notch was created in the SPT specimens by means of different techniques. In this study, the type of pre-notching used on the specimens was of the through-thickness crack type, from the middle point of one side to a point just passing the center of the specimen. This pre-notching was done using wire electrical discharge machining (WEDM), transverse laser-induced microcracking (TLIM).

The first technique, WEDM, once properly adjusted, yields a pre-notch in the desired position in one step. In the TLIM technique a laser beam is applied in several passes, using a 30 µm diameter Nd:YAG pulse beam (50 W and 1064 nm), working at a frequency of 7500 Hz and a linear displacement rate of 15 mm/s. The laser is applied perpendicularly to the notch direction. The notch shape resulting from this technique can be seen in Fig. 1. A tip notch radius of about 200–250 µm is obtained for WEDM and 75–100 µm for TLIM.

Different notch lengths were machined to a length of a equal to 4.0, 4.5, 5.0 (center of the specimen), 5.5 and 6.0 mm respectively. Taking into account the distance of the notch relative to the punch center, the specimens are referred as: (−1.0), (−0.5), (+0.0), (+0.5) and (+1.0) mm respectively.

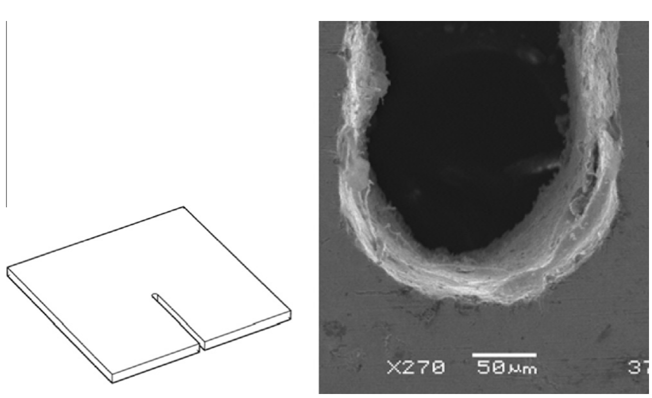

Fig. 1. p-SPT specimen and the notch obtained by laser micro-cutting.

3. Optimum initial pre-nocht length for p-SPT

The objective of practicing a pre-notch in the SPT specimen is to ensure the crack propagation during the test, which allows the application of the different fracture mechanics approaches to be applied.

In order to determine the optimum pre-notch length range, machined in the SPT specimens, for witch a crack propagation on the specimen takes place, Alegre et al. [13,14] have conducted several tests on specimens p-SPT with different notch lengths from 4 mm to 6 mm, being 5 mm the corresponding position of the load line of the punch. The material used in this research was a 15.5pH stainless steel.

Fig. 2 shows the representative curves associated with each notch length tested. A clear difference is observed in the load-displacement curve for different notch sizes, and this difference is associated with the failure mode of the specimen.

In this sense, Fig. 3 shows the mode of fracture of the specimens for different depths of the initial notch. The first one corresponds to the typical circumferential fracture for ductile materials usually observed in conventional unnotched SPT specimens. In the case of a SPT specimen with a pre-notch length of $a = 4.0$ mm, a circumferential fracture without crack propagation in the direction of the notch was obtained. For those cases, with a notch length immediately preceding the line punch ($a = 4.5$ mm) to another immediately passing the line punch ($a = 5.5$ mm), a crack advance in the longitudinal direction of the initial notch was clearly observed. The crack advance was greater for lower a values, as a consequence of a greater ligament of the specimen to propagate. Finally, for initial notches greater than $a = 6.0$ mm a large deformation of the notch tip was observed allowing the punch to pass without detecting significant crack propagation in the direction of the notch.

As a consequence, it is possible to assume an interval for the length of the initial pre-notch, in which the crack extension during the test takes place in the same direction as the initial pre-notch. Such an interval has been found to be for initial pre-notch lengths between 4.5 mm and 5.5 mm, being 5 mm the load line of the punch.

4. First approach: CTOD measurement

The first method proposed for the estimation of fracture mechanics parameters is based on the measurement of notch tip opening displacement (similar to CTOD parameter in standard

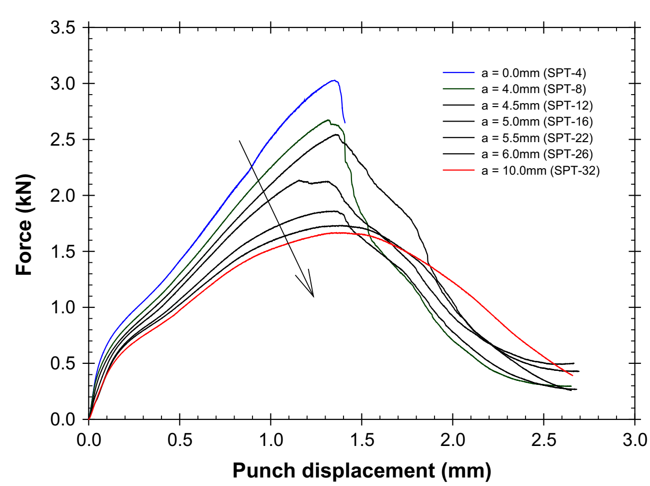

Fig. 2. Load-displacement curves representatives of different pre-notch length for p-SPT specimens.

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