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Crack growth characterization in single-edge notched tension testing by means of direct current potential drop measurement

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Single-edge notched tension (SENT) testing has gained attention for the characterization of crack growth resistance in scenarios of low crack tip constraint conditions. One challenge of SENT testing is the experimental characterization of crack extension during the test. Two common methods exist: unloading compliance and direct current potential drop (DCPD). Whereas the former method is fairly extensively described in existing procedures, applying the latter mostly depends on user experience and in-house developed analysis algorithms. This paper describes Ghent University's approach for DCPD measurements of ductile crack extension in SENT testing. A reference voltage drop measurement is advised, aiming to account for current leak and changes in electrical conductivity. Then, attention goes to the sensitivity of the procedure with respect to changes in crack size and its robustness with respect to probe positioning errors. Finally, DCPD is shown to have similar capabilities to unloading compliance with respect to defect sizing accuracy. The results of this paper are aimed to contribute to a more prescriptive description of DCPD measurements in revised SENT test procedures or standards.

1. Introduction

During the last decade, the fracture mechanics research community has witnessed a strongly increased interest into fracture toughness testing in low crack tip constraint conditions. These conditions are highly relevant to thin walled structures (such as pressure vessels, oil and gas pipelines and offshore structures), for which the ligament of a shallow (weld) defect or crack is primarily loaded in tension rather than bending. These loading conditions are poorly represented by conventional toughness test configurations such as single-edge notched bending (SENB) or compact tension (CT), which underestimate the fracture toughness of the material in the structure. The resulting (over)conservatism leads to unnecessary repairs of safe defects, which can be alleviated by executing low constraint fracture toughness tests.

The single-edge notched tension test has become a mainstream solution for fracture toughness testing under low crack tip constraint conditions [1]. The SENT specimen has a constraint level similar to (and slightly higher than) that of thin walled structures under tension, having similar wall thickness and defect depth (e.g. [2,3]). Albeit initially developed in the 1960s [4] for quantification of fracture toughness, the current application of SENT testing is aimed towards the characterization of tearing resistance curve. This curve can be obtained by multiple specimen methods or from a single specimen approach. The latter requires experimental procedures to derive crack driving force (*J*-integral or crack tip opening displacement CTOD) and crack extension on a regular basis as the test progresses. Measurement of crack driving force requires specific clip gauge mounting strategies (e.g. direct mounting on the crack mouth for *J* [5]; double clip gauge assembly for CTOD [6,7]) and a good definition of the quantity of interest. For instance, there is debate on eta factors to obtain *J* from crack mouth opening displacement (CMOD) [8] and, more fundamentally, on the definition of CTOD [9].

This paper focuses on crack extension measurement in single-specimen SENT testing. Different methods exist, of which the unloading compliance (UC; e.g. [10–12]) and potential drop (PD) techniques [13–15] have received most attention, and other techniques (e.g. normalization [16], optical deformation analysis [13,17]) are mentioned. This paper focuses on potential drop measurements of crack growth. PD techniques can be based on either a direct current (DCPD) or an alternating current (ACPD). DCPD is typically preferred because of its simplicity: a constant current source injects a high electrical current into the specimen, and an

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accurate volt meter captures the voltage drop across the notch. In contrast, the electronics for ACPD are far more complex as secondary pick-up voltages have to be filtered out (which requires input current typically in the kHz range). Also, the skin effect on which ACPD is based, restricts its use to the measurement of surface-breaking defects [18]. Finally, the capacitance effect over the crack flanges (which is influenced by the distance between both crack faces) [15] and a strong effect of strain on magnetic permeability and electric conductivity [19] influence the relation between potential drop and crack extension, thus complicating the ability to size growing cracks (especially when adopting higher alternating current frequencies).

The single-specimen SENT test was first standardized in 2014 by the British Standards Institute (BSI Group) and published as BS 8571 [20]. The development of the standard is comprehensively described in Ref. [21]. BS 8571 mentions UC and DCPD as suitable methods for crack growth characterization. However, prescriptive guidance on the application of these methods is missing. Instead, references are provided to a list of papers that can be used as a basis. This is appropriate for UC testing, for which fully documented procedures are available (including test procedure requirements and conversion of compliance to crack size). Given as examples are the CANMET single-specimen J-R test procedure reported in 2009 [10], and procedures developed in the framework of round robins for SENT testing organized by CANMET and BMT [22,23].

In sheer contrast, the use of potential drop methods is far less documented which limits its application. This is clearly reflected in Zhu's recent review of fracture toughness test methods for ductile materials in low-constraint conditions [1], which summarized the vast majority of relevant literature related to SENT resistance curve testing. Whereas this review paper has multiple paragraphs devoted to unloading compliance testing, the potential drop method was only briefly mentioned once to be an equivalent alternative to UC testing, and referred to research performed at Ghent University [24]. CANMET's round robin test procedure (discussed in Ref. [22]) explicitly recommends UC over DCPD testing. BMT's round robin test procedure is not biased towards any of both methods. However, its guidance for DCPD test parameters (to a large extent based on ExxonMobil's SENT procedure [7]) is less explicit than that for UC testing. Hereby, reference [23] reported that 12 out of 15 participants adopted UC for crack growth measurement, whereas only 3 participants performed DCPD. Despite its limited popularity, recent research at Emc^2 preferred the DCPD technique over UC, as the latter approach was found to provide more scattered crack growth predictions and anomalies such as a negative crack growth estimation [14]. This outcome is likely assisted by ample experience with DCPD monitoring as shown in Ref. [15]. Moreover, DCPD assisted SENT testing involves a potential economic advantage, since the DCPD assisted test series are performed faster than UC assisted testing (which requires a time consuming and tedious sequence of unloading/reloading cycles). Further, DCPD typically provides more resistance curve data points than UC assisted testing and may be better suited to tests performed in environmental chambers or furnaces. Finally, DCPD may be used for tests at various rates of loading, whereas UC is more restrictive in this respect [15].

This paper reports on Soete Laboratory's experience with (and guidance towards) crack extension measurements in single-specimen SENT tests by means of DCPD. First, the test procedure is discussed (section 2). Section 3 discusses an experimental database and numerical (finite element) model which have been used to evaluate the test procedure. Section 4 validates the soundness of the transfer function between potential drop and crack extension, discusses the sensitivity of crack extension to potential drop measurement and provides a robustness analysis with respect to unavoidable variations in testing conditions. Finally, section 5 provides a comparison between crack growth predictions obtained by UC and DCPD.

2. UGent SENT test procedure

2.1. General aspects

The test specimens considered in this paper have a square (B x B) cross section and daylight grip length (H) to width ($W = B$) ratio of ten (Fig. 1 [24]). Specimens were notched with a fine saw blade, producing a notch width at the tip of 150 μm. No fatigue precracking was performed. The initial notch depth is denoted as a_0 (not to be confused with the crack depth a at any moment during the test). To overcome the anticipated crack tunnelling, the majority of reported specimens had V-shaped side grooves machined at both sides of the test specimens, with a root radius of 0.5 ± 0.2 mm and an opening angle of 45° (in agreement with existing procedures for SENB [25] and SENT testing (e.g. Refs. [7,10])). Through these side grooves, the cross-sectional area was reduced by 15% for all specimens (B_N = net thickness = 0.85 B). This value was chosen in accordance with CANMET's round robin test procedure [10]. The variety of tested specimen configurations is discussed in more detail in section 3.1.

In combination with the crack growth measurements, the crack mouth opening displacement (CMOD) and crack tip opening displacement (CTOD) were calculated using a double clip gauge method [6]. Hereto, two miniature knife blocks are bolted onto the test specimen using two screws each (self tapping, type #2-56 x 3/16" Phillips Pan Head Thread Cutting Screw), whose center is located 4.5 mm from the notched section. The centreline distance between both screws is 6.0 mm. The clip gauges used for evaluating the opening displacement are located 2.0 and 8.0 mm above the specimen surface. The adopted double clip gauge assembly is common for SENT testing and a graphical representation is provided in test procedures and standards such as BS 8571 [20].

The SENT specimens were tested using hydraulic test setups with a capacity of either 150 kN (typical) or 1 MN (when required) and were rigidly clamped at both ends using hydraulic clamps. A constant displacement rate of either 0.01 mm/s or 0.005 mm/s was applied. Both values are sufficiently low to ensure quasi-static conditions according to existing procedures. Some specimens were monotonically loaded; others were periodically unloaded and reloaded to allow for an UC analysis. To obtain sufficient crack growth, the tests were continued beyond the maximum load until the load dropped below 80% of its maximum observed value. The following signals were captured: tensile load, actuator displacement, readings from both clip gauges, potential drop crossing the notch, reference potential drop.

After testing, specimens were heat tinted (for instance, at 220 °C for two hours) and fractured in a brittle manner after cooling in a bath of liquid nitrogen. Initial notch depth and final crack depth were measured using the nine-points average method.

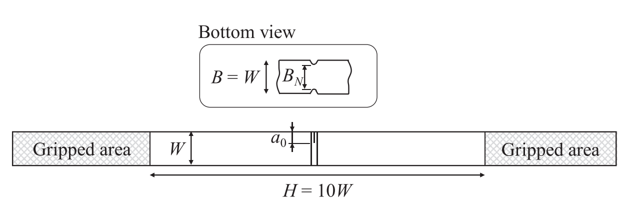

Fig. 1. Schematic representation of SENT specimen [24].

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