Theoretical and Applied Fracture Mechanics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

journal homepage: www.elsevier.com/locate/tafmec

Damage modeling in Small Punch Test specimens

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ARTICLE INFO

Article history:
Received 23 June 2016
Revised 1 September 2016
Accepted 4 September 2016
Available online xxxx

Keywords:
Small Punch Test
Fracture toughness
Ductile damage
Finite element method

ABSTRACT

Ductile damage modeling within the Small Punch Test (SPT) is extensively investigated. The capabilities of the SPT to reliably estimate fracture and damage properties are thoroughly discussed and emphasis is placed on the use of notched specimens. First, different notch profiles are analyzed and constraint conditions quantified. The role of the notch shape is comprehensively examined from both triaxiality and notch fabrication perspectives. Afterwards, a methodology is presented to extract the micromechanical-based ductile damage parameters from the load-displacement curve of notched SPT samples. Furthermore, Gurson-Tvergaard-Needleman model predictions from a top-down approach are employed to gain insight into the mechanisms governing crack initiation and subsequent propagation in small punch experiments. An accurate assessment of micromechanical toughness parameters from the SPT is of tremendous relevance when little material is available.

1. Introduction

Many engineering applications require a mechanical characterization of industrial components from a limited amount of material. Under such circumstances, it is often not possible to obtain specimens of the dimensions demanded by standard testing methodologies. With the aim of overcoming this hurdle, a miniature non-standard experimental device was developed in the early 80s [1]. The aforementioned testing methodology, commonly known as Small Punch Test (SPT), employs very small specimens (generally, 8 mm diameter and 0.5 mm thickness) and may be considered as a non-destructive experiment. The SPT has consistently proven to be a reliable tool for estimating the mechanical [2,3] and creep [4,5] properties of metallic materials and its promising capabilities in fracture and damage characterization have attracted great interest in recent years (see, e.g., [6–18]).

Although brittle fracture has been observed in certain materials at low temperatures [10,16,17], the stress state inherent to the SPT favors ductile damage. It therefore comes as no surprise that efforts to characterize the initiation and subsequent propagation of cracks in SPT specimens have mostly employed models that account for the nucleation, growth and coalescence of microvoids (see, e.g., [8–12,18] and references therein). The model by Gurson [19], later extended by Tvergaard and Needleman [20], is by far the most frequent choice, but other models - such as the one by Rousselier [21] - have also been employed [9]. These models are able to quantitatively capture the experimental results by fitting several parameters that account for the ductile damage mechanisms taking place. A variety of inverse techniques - including the use of evolutionary genetic algorithms [11–13] and neural networks [8] - have been proposed to compute the Gurson-Tvergaard-Needleman (GTN) [19,20] parameters from the load-displacement curve of unnotched SPT specimens. Void-based models have been particularly helpful in the development of new methodologies to estimate fracture toughness from SPT specimens [18]. However, some relevant aspects remain to be addressed. The substantially different constraint conditions attained in the SPT, relative to conventional testing procedures, constitute the most important problem to overcome. As depicted in Fig. 1, the high triaxiality levels (defined as the ratio of the hydrostatic stress to the von Mises equivalent stress) of standardized fracture toughness experiments - such as compact tension or three point bending tests - translate into conservative estimations of the fracture resistance. This is not the case of the SPT, hindering a direct comparison and leading to predictions that may significantly differ from the plane strain fracture toughness. Hence, current research efforts are mainly devoted to the development of notched or cracked SPT samples with the aim of increasing the attained triaxiality level [7,18].

In this work, the influence of the shape of the notch on the SPT response is extensively investigated, considering both the constraint conditions and the fabrication process. Crack initiation

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http://dx.doi.org/10.1016/j.tafmec.2016.09.002
0167-8442/

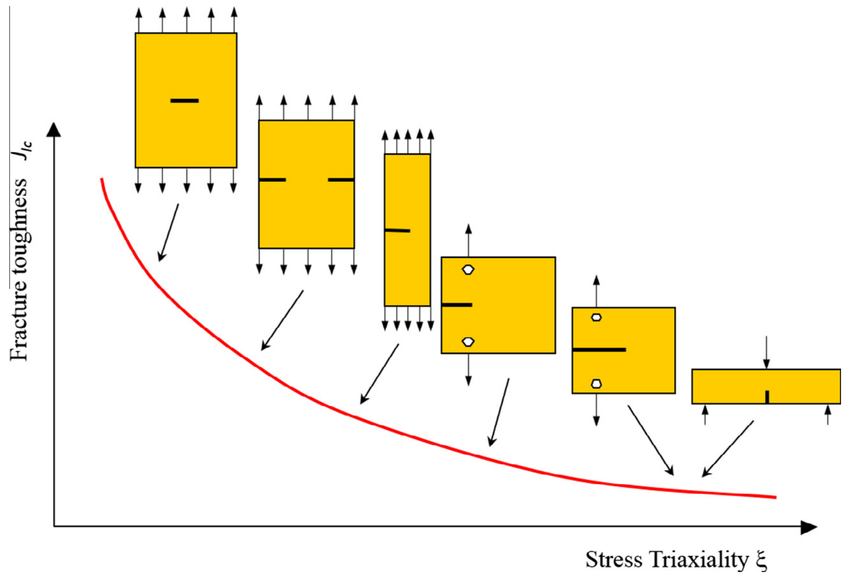

Fig. 1. Influence of the specimen configuration on fracture toughness.

and subsequent propagation is computed by means of the GTN model for various geometries of notched SPT specimens and results are compared to experimental data. Different methodologies to extract the micromechanical-based ductile damage parameters are proposed and the past, present and future capabilities of the SPT to characterize fracture and damage are thoroughly discussed.

2. Experimental methodology

The SPT employs a miniature specimen whose entire contour is firmly pressed between two dies with the load being applied at the center by means of a 2.5 mm hemispherical diameter punch. The special device outlined in Fig. 2 is coupled to a universal testing machine. A free-standing extensometer is attached to the experimental device to accurately measure the punch displacement. The experiments are performed at room temperature with a punch speed of $v = 0.2$ mm/min. Lubrication is employed to minimize the effects of friction.

The mechanical response of the SPT specimen is therefore characterized by means of the measured applied load versus punch displacement curve. Fig. 3 shows the different stages that can be identified in the characteristic SPT curve of a material behaving in a ductile manner. Different criteria have been proposed to estimate mechanical and damage material parameters from the curve [2,15].

3. Gurson-Tvergaard-Needleman model

The influence of nucleation, growth and coalescence of microvoids is modeled by means of the well-known Gurson-Tvergaard-Needleman (GTN) [19,20] ductile damage model. Within the aforementioned framework, the yield function is defined by,

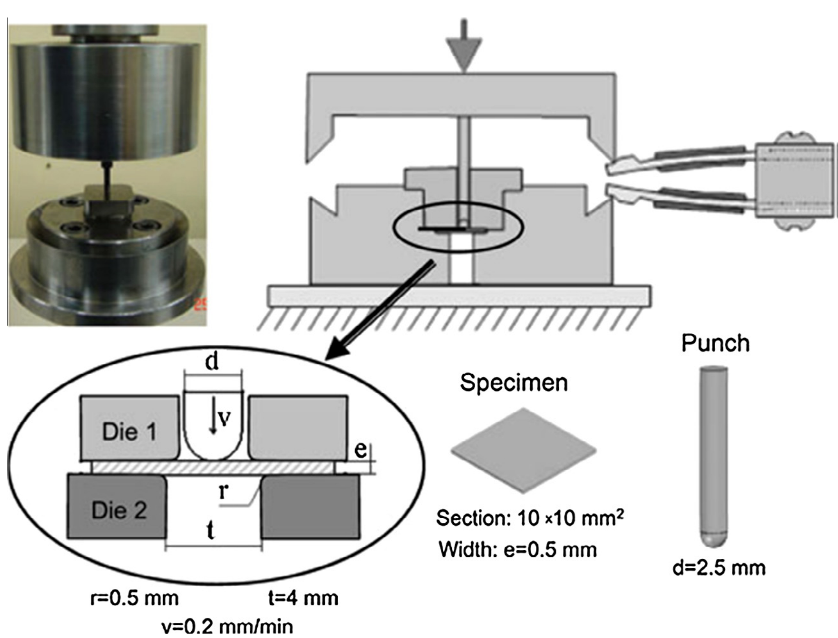

Fig. 2. Device and schematic description of the Small Punch Test.

Please cite this article in press as: E. Martínez-Pañeda et al., Damage modeling in Small Punch Test specimens, Theor. Appl. Fract. Mech. (2016), http://dx.doi.org/10.1016/j.tafmec.2016.09.002