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Small punch test evaluation methods for material characterisation

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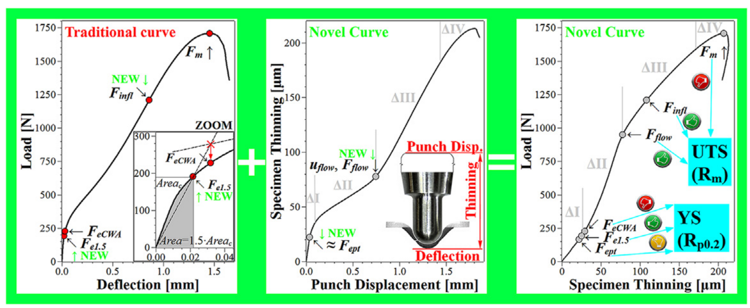
HIGHLIGHTS

- The newly proposed methodology significantly improved results of SPT.
- Plastic deformation starts inside the specimen from the very beginning of loading.
- Specimen thinning = punch displacement−specimen deflection.
- Material response to loading is well illustrated by the novel load-thinning curve.

GRAPHICAL ABSTRACT



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ABSTRACT

The Small Punch Test (SPT) is one of the most widespread mechanical testing methods using miniaturized specimens. The paper presented deals with the time independent SPT, in which a flat specimen is bent by means of a (hemi)spherical punch moving at a constant velocity. The main goal is to relate the measured data to deformation processes taking place during specimen loading. Understanding of such relations is crucial for characterizing a material using any non-standardized experimental procedure. Using enhanced instrumentation, not only traditional load-displacement or load-deflection curves could be obtained, but also specimen thinning could be continuously measured and evaluated. Five alloys having a broad range of mechanical properties were tested. The results obtained were evaluated using both traditional and newly proposed methods and they were correlated with results of the conventional tensile test. The methods proposed seem to lead to a universal correlation between SPT results and tensile characteristics.

1. Introduction

Nowadays there is a great demand for a reliable and, if possible, standardisable mechanical testing technique using miniaturized specimens. Research and development of testing techniques with miniaturized specimen started primarily due to running service prolongation programs in nuclear industry [1]. In order to obtain or estimate the required mechanical properties (such as the yield strength $R_{p0.2}$, the ultimate tensile strength R_m, the ductile to brittle transition temperature, creep properties, etc.) the testing must be a-priori destructive. However, using special equipment only a minimal volume of material can be sampled from in-service components without any significant harm [2]. Changes in mechanical properties across welds and heat affected zones [3], anisotropy of material produced in very limited volumes [4], surface modifications [5], or hydrogen degradation [6] can all be advantageously studied employing such miniaturised specimens.

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Nomenclature

SPT		Small Punch Test
LDC		Load-Deflection/Load-Displacement Curve
$R_{p0.2}$	[MPa]	yield strength (tensile)
R_m	[MPa]	ultimate tensile strength
h_0	[mm]	specimen thickness
u_{def}	[mm]	specimen deflection (measured at the centre-point)
u_{pun}	[mm]	punch displacement
u_{cro}	[mm]	crosshead displacement
F	[N]	load (reaction force of the specimen)
$\Delta h'$	[μm]	specimen thinning summed with the deformation of the punch
Δh	[μm]	specimen absolute thinning (deformation of the punch was subtracted from $\Delta h'$)
c_{pun}	[μm/kN]	compliance of the punch
u_{tip}	[mm]	punch tip displacement (punch contraction was subtracted from u_{pun})
F_e	[N]	load characteristic from the elastic→plastic transition region of a LDC
F_{eCWA}	[N]	actual measured load under the crossing point of two least-square-method fitted lines
$F_{\|m\|}$	[N]	maximal measured reaction force
F_m	[N]	maximal reaction force before the first load decrease
u_m	[mm]	deflection/displacement at F_m (in the paper presented $u_m = u_{def\_m}$)
E_j	[mJ]	energy (the area under the load-deflection curve integrated until deflection u_j)
t	[−]	time (number of data acquisition counts)
u_{ept}	[mm]	deflection at the first maximal curvature point of a u_{def} - u_{pun} curve
F_{ept}	[N]	load at the u_{ept} deflection
$F_{e1.5}$	[N]	load derived from area under the load-deflection curve (energy), i.e. the point at which area under the curve is equal to 1.5 of its complement above the curve
F_{infl}	[N]	load at the second inflection point of a load-deflection curve
u_{infl}	[mm]	deflection at F_{infl}
u_{flow}	[mm]	deflection at the maximal curvature point of a $\Delta h'$-u_{pun} curve
F_{flow}	[N]	load at the u_{flow} deflection

This paper deals with a testing method which is commonly called the Small Punch Test (SPT) or the Miniaturised Disc Bend Test. Even though SPT has become widespread during the last 30 years and numerous practical applications can be found, standardization of this method is still in progress [1]. In European countries there exists the CEN Workshop Agreement (CWA), giving basic suggestions on experimental design and procedures [7]. In Japan, SPT creep testing has already been standardised [8] and SPT standard GB/T 29459−2012 was published in China [9]. SPT standardisation is also currently discussed in the ASTM. In spite of considerable efforts to reach, if possible, worldwide standardization, significant differences between the employed experimental procedures and evaluation techniques still persist - according to the current literature and to international Small Sample Test Technique conferences (SSTT2010-SSTT2014).

The Small Punch Test is extremely sensitive, not only to precise sensors and loading machines [10], but also to precise machining of samples and to real geometry of testing jigs [11]. It can be assumed that the majority of discrepancies influenced by the "hardware" could be overcome by a detailed definition of testing apparatus given by a standard. Unfortunately, it follows from extensive searching that numerous incomparable methods for characterizing a material by SPT are used in different laboratories ([12], [13]). Related procedures for estimating conventional material parameters ($R_{p0.2}$, R_m, DBTT, J_{Ic}, …) can therefore hardly be transferred from one laboratory to another.

To illustrate the differences between SPT evaluation methods found in the literature, seven methods for determining the characteristic load F_e from a typical load-deflection curve are compared in Fig. 1. Load F_e shall be related to transition from elastic to plastic material response [14]. In the literature, the F_e characteristic is frequently related to conventional yield strength $R_{p0.2}$ (e.g. Refs. [15], [14], [16], [17]).

Note that F_e may also be obtained from load-displacement curves using similar procedures. Nevertheless, the values obtained from load-displacement/load-deflection curves should definitely not be interchanged as the displacement/deflection are measured in different positions (at least at the opposite sides of a specimen).

The first method for determining F_e was proposed by Mao and Takahashi in 1987 [15]. In their paper, the method for determining F_{e_Mao} was neither defined nor specified, but only indicated in a load-deflection plot. It may only be assumed that the authors used two tangents or two fitted lines on an interval, which was not specified. The crossing point of both lines determines the F_{e_Mao} value. This method was later modified to reading the characteristic value from actual measured data under the crossing point (F_{e_CWA} or F_{e_tan}). Unfortunately, this "two-line" method has later split into a "bilinear method", in which two separate lines are fitted using the least mean squares method [7], and to a "two-tangents" method, in which two tangents from the beginning and from the end of the chosen data interval are led [16]. Regardless of the particular method, all these suffer from the necessity of determining finite data interval(s) used for fitting. Due to the smoothly curved nature of a typical load-deflection/displacement curve, these intervals are being specified without any physical basis. In the case of total fitting interval selection (bilinear method), the most frequently used interval is (0; h_0), which is also recommended by CWA [7] (h_0 stands for specimen thickness). When considering the "two-tangent" method, which also needs two specified data intervals for fitting, no detailed specification was found in the literature.

Obviously, using some of the methods described must be specified, and special attention has to be paid to choosing the data interval(s), because this choice can significantly influence the results obtained (compare $F_{e\_tanX0.3}$ to $F_{e\_tanX0.5}$ in Fig. 1).

Several other methods for F_e determination, inspired by conventional tensile stress-strain evaluation procedures, were established later. These methods are based either on fitting the initial interval with a line, or by leading a tangent from point [0; 0]. Subsequently, a parallel line is led through a point on the x-axis, and finally the crossing point of this line with the experimental curve gives the characteristic F_e value. A choice of the x-axis point differs