Materials and Design 157 (2018) 512–522

Contents lists available at ScienceDirect

Materials and Design

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

Effects of thickness specimen on the evaluation of relationship between tensile properties and small punch testing parameters in metallic materials

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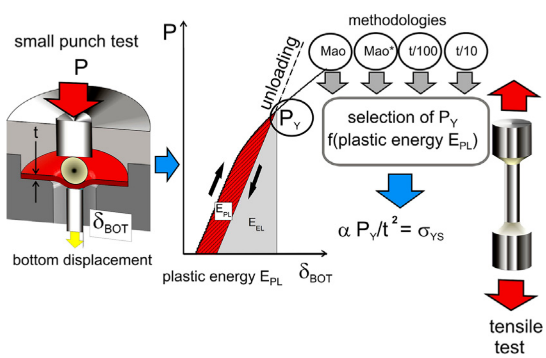
HIGHLIGHTS

- SPT correlation factors calculated are dependent of the materials.
- Bottom displacement provides more extended linearity during regime I.
- Plastic energy evaluations provide new criteria to select PY.
- t/100 method is more representative to define the plastic spreading on SPT.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 June 2018
Received in revised form 16 July 2018
Accepted 31 July 2018
Available online 06 August 2018

Keywords:
Small punch test
Young modulus
Yield strength
Characteristic load
Plastic deformation
Plastic energy

ABSTRACT

The assessment of the yield strength σ_{YS} from characteristic load P_Y obtained from small punch tests (SPT) was studied systematically in aluminum alloys and structural steels by variation in thickness of specimens. Four methodologies of calculating P_Y were considered: Mao and a modification of Mao methods and t/100 and t/10 offset methods. The attempt of correlation between σ_{YS} with P_Y/t^2 by using a unique linear parameter of correlation α was reviewed. Under this framework, it is suggested that the dependence of this correlation factor α with each material cannot be avoided for the four methodologies used to calculate P_Y. The advantage to use the bottom displacement measurement during regime I of deformation is discussed on the assessment of Young modulus and P_Y. Finally, the representativeness of P_Y as the beginning of massive yielding of SPT specimen is also analyzed in terms of plastic energy E_{PL} calculated from SPT plot. Based on the study of E_{PL} evolution during the first regime of deformation, the t/100 offset method resulted the most suitable to select P_Y as characteristic parameter of the beginning of yielding when compared with the other three methods.

1. Introduction

Small punch testing (SPT) has become an interesting technique for mechanical characterization of a wide range of structural and functional materials. Either brittle or ductile behaviors and can be clearly differentiated by SPT among ceramics, composites and metals tested by SPT.

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https://doi.org/10.1016/j.matdes.2018.07.065
0264-1275/

[1–8]. The main advantage of this technique is the minimum amount of sample required for manufacturing the specimens (e.g., disks 8 or 10 mm in diameter and 0.500 mm thickness). The size and shape of specimens allow an excellent selectivity of sampling. Thus, several cases employing SPT for mechanical characterization where traditional techniques would be impossible to be employed are found. Just two examples will be mentioned. First, the extraction of SPT disks from already tested standard size Charpy or fracture toughness specimens where the extraction is suitable from undeformed zones. Second, the removal without compromising service conditions of small flakes of material from components using some special tools [9,10]. Under those conditions SPT testing becomes a non-destructive technique. All these advantages over traditional testing techniques, which need relatively larger specimens, have positioned SPT as a potential technique for the study of nuclear materials. In this field the reducing mass of irradiated material becomes critical. Therefore the SPT has been selected as a serious candidate to be applied in hot cells [11] within the framework of surveillance programs. The aim of these programs is to characterize the degradation of irradiated structural component from nuclear plants respect to virgin material. In OPAL nuclear research reactor [12] SPT specimens 6 mm diameter were located to monitor the core reactor materials to guarantee that the surveillance of their mechanical properties are sufficient to ensure safe and reliable long-term operation. The extraction of samples was scheduled for 5, 10, 20, 30 and 40 years of full power operation.

Nowadays, the demand to know the remaining life of power plant has become of fundamental importance to industry, searching for life extension by the applying the monitoring programs [11,13], of critical components under service. In light of this philosophy, the testing by SPT has been proposed to know the level of ageing of material.

Like tensile properties, other important properties as fracture toughness [4,14] or creep strength [15,16] have been studied using SPT by the direct extraction of parameters from a load vs. displacement response (P vs. δ) derived from the test. Within all those applications of SPT is not straightforward the obtaining mechanical properties directly from SPT results. The reason is the complex state of stresses developed during the punching of the disk along the whole test; mixture of elastoplastic processes like indentation, elastic and plastic bending and stretching take place depending on puncher displacement and location into the disk specimen. To solve this obstacle some attempts of interpretation has been proposed. Semi-empirical correlations between particular values taken from P vs. δ curves of SPT and the results of standardized tensile tests were made. Although, important efforts in modeling by the finite elements, including other authors [1,17] and own [3] has been employed, this work is focused mainly in the extraction and interpretation of mechanical properties through experimental data.

In order to standardize the technique, important efforts have been made starting from the CEN Workshop Agreement [10]. This document defines the baselines for the implementation and the interpretation of the SPT results for both room temperature (RT) and high temperatures (creep). In this issue it must be considered the later advances to transform into an EN standard, they can be found summarized in the work of Matocha and Hurst [18]. Concerning RT testing a detailed guide for apparatus manufacturing, specimen preparation, test procedure and interpretation of the results are given in [10].

Typical P vs. δ curve for ductile materials up to maximum load (P_{MAX}) at RT defines regimes of deformations, which have been arbitrarily classified [1,4,17,19]. In search to define how the elastic bending stresses reach the yield strength σ_{YS}, singular points (or regions) of SPT curve have been identified. The most relevant feature is the transition between the two first regimes of deformation: the so called elastic bending (regime I) and the plastic bending (regime II). The characteristic load P_Y has been widely used as the representative parameter for this change. Under this point of view some authors [8,20–23] have established directly P_Y as the equivalent in SPT to yield strength σ_{YS} obtained in uniaxial tensile test. This type of relationship reveals the potential of SPT like a technique for further tensile properties predictions like σ_{YS}, tensile strength σ_{UTS} and other. That is the reason why SPT needs a deeper study and the present work will focus on the semiempirical relation of σ_{YS} proportional to P_Y/t^2 where t is the initial thickness of the specimen. This relation, adopted initially by Mao and Takahashi [20], has been followed by many authors [4,6,19,23,24]. The proportional factor between σ_{YS} and P_Y/t^2 is α, also known as the correlation parameter. Focusing on σ_{YS} assessment, a detailed analysis reveals that there are many proposed methodologies to define P_Y [3,4,8,17] for a single material. Of course, this leads to many α for each material depending on which definition of P_Y is adopted. Only few specific works have systematically studied the physical meaning of P_Y for each one of these methods. In the work of reference [3] the level of volume under plastic regime and the stresses distribution reached at P_Y it has been thoroughly studied. SPT specimens of 10 mm in diameter and 0.5 mm in thickness made from AISI304L stainless steel were tested and such results were modeled by finite elements (FEM).

The influence on the selection of the $P_{Y,}$ among four definitions, and its correlation between σ_{YS} and α is systematically studied as a continuation of the previous work [3]. For that purpose ductile alloys such as structural steels and Al alloys have been employed to analyze their mechanical behavior by SPT and their relationship with the properties obtained from the corresponding uniaxial tensile tests. As a consequence, an important issue to be discussed is the level of dependence of α with different materials. This parameter has been proposed as `universal´ proportionality factor between σ_{YS} and P_Y/t^2 independent of material [4,8,20,23]. Here, the proposed material independence was thoroughly revised.

Finally, the significance P_Y calculated by four methods were evaluated in terms of plastic energy obtained from experimental P vs. δ curve. The evolution of this parameter plays an important role in the interpretation of the plastic process at P_Y. Thus a new method to select P_Y as the most representative of yielding is introduced.

2. Experimental

2.1. Materials

The materials used in the present study can be arbitrary separated in two groups: Al based materials and structural steels. They were selected by the wide range of mechanical strengths and ductilities; and also they are representative of materials for nuclear, laboratory and structural applications. Denominations and details of materials are given in Table 1. AISI 304 L stainless steel and heat resistant high Cr P91 steel belong to

Table 1
Materials used for the present study.

Denomination	Al	Aluar	AlZn	6061	304	P91	ADN
Material	Al 99.99999	Al 99.5	AlZn11Mg0.5	6061-T6	AISI304L	ASTM A335 grade P91	ADN420
Provider	Chempur, Germany	Aluar, Argentina	Alusuisse-Lonza	Alcoa, US	n/a	JFE Steel Corporation, Japan	Acindar, Argentina [25]
Shape	10 mm cylindric bar	Ingot	Squeezed cast block of 20 mm	12 mm bar	12 mm cold drawn bar	Pipe of 355.6 mm in diameter and 28 mm in thickness	32 mm bar