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SMALL SPECIMEN TECHNIQUE FOR ASSESSING THE MECHANICAL PROPERTIES OF METALLIC COMPONENTS

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ABSTRACT

Small punch test (SPT) is one of the most promising techniques of small specimen test, which was originally applied in testing of irradiated materials in nuclear engineering. Then it was introduced to other fields as an almost nondestructive method to measure the local mechanical properties that are difficult to be obtained using conventional mechanical tests. Most studies to date are focused on metallic materials, although SPT applications are recently spreading to other materials. The small punch test (SPT) employs small-sized specimens (for example, samples measuring 8 mm in diameter and 0.5 mm thick). The specimen is firmly clamped between two circular dies and is bi-axially strained until failure into a circular hole using a hemispherical punch. The 'load-punch displacement' record can be used to estimate the yield strength, the ultimate tensile strength, the tensile elongation, and the temperature of the ductile-to-brittle transition. Recently, some researchers are working on the use of miniature notched or pre-cracked specimens (denoted as p-SPT) to validate its geometry and dimensions for obtaining the fracture properties of metallic materials. In a first approach, the technique makes it possible to convert primary experimental data into conventional mechanical properties of a massive specimen. In this paper, a comprehensive review of the different STP applications it is presented with the aim of clarifying its usefulness.

1. INTRODUCTION

The evaluation of the mechanical properties of nuclear structural components and their degradation during service life due to neutron irradiation, thermal aging, etc. must be taken into account when assessing its structural integrity and expected residual lives. In general, large specimens are needed for standard mechanical characterization. In the case of irradiated materials, proper management of safety conditions make the use of standard specimens more difficult [1]. In these situations, it is very convenient to apply tests on miniaturized specimens for the mechanical characterization of materials, using samples which may be extracted from the components during their normal service life.

Several types of tests using small specimen are being used for ease of handling and experimental control. Small Punch Test (SPT) was developed in the 80's, is widely used in the nuclear industry primarily because of the volume of material involved that allows the analysis of post-irradiated materials with lower operational risk. This technique is also used in difficult-to-sample situations such as the heat-affected zone (HAZ) of welded joints or in thin coatings [2]. The tests are performed in samples with a large plastic deformation and the main goal is to find a correlation between the results obtained with SPT and those obtained by conventional techniques. SPT is generally applied as a nearly non-destructive method to obtain material properties. The thin SPT specimen has proven to induce less damage to the component in the practical application during service. In 2006, a European Code of Practice was published, which describes the methodology and the most reliable correlations used to estimate the mechanical properties through the punch test [3].

In this work it is presented the state of the art of the SPT technique, showing the possible variations in the format of the samples and the devices used to perform the tests, and how the mechanical properties are obtained with the aid of specific equations for each desired results and the use of finite elements methodology to simulate their results.

2. SMALL PUNCH TEST (SPT)

The small volume of the sample used in the SPT allows it to have different forms, as long as it is representative of the material to be analyzed. According to the ease of cutting, the samples are generally in the form of discs or square. The diameter of the disc-shaped samples varies from 4mm to 10mm, with an average thickness of about 0.5mm. The dimensions of the square samples are 10mm x 10mm x 0.5mm. These samples are attached to a device, which in general terms can be described as shown in Fig. 1.

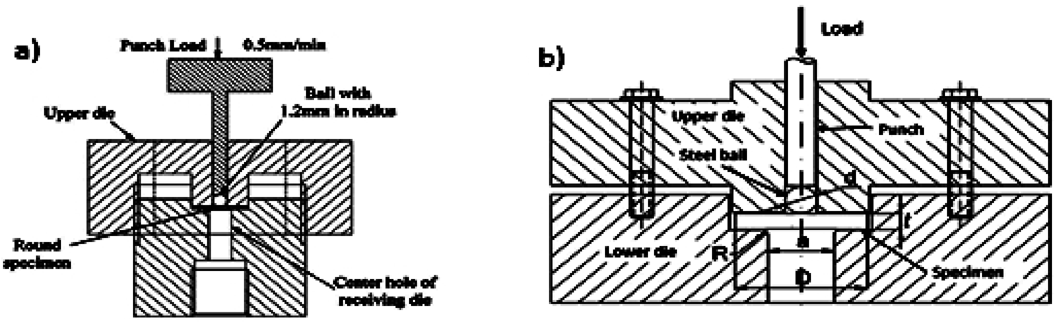

Figure 1: a)A scheme of the, loading and specimen supporting for performing SPT, as described by Yang et al.[4]; b) Another version for apparatus for SPT, shown by Song et al.[5].

The sample is attached to the device and the assembly is tested in a universal machine for mechanical testing. The load is applied in the center of the sample through a steel sphere, with a diameter of 2.4mm, with a constant deflection ratio. Small adaptations are possible for the test to be performed in a controlled environment such as temperature [6], pressure, atmosphere, etc. The miniaturized samples can be sanded and polished for observation of the microstructure and may also contain notches generally made with laser cut for evaluation of fracture toughness.

The result of the test punch is recorded by the test machine which stores the applied load values and the respective central deflection of the samples. The test can be carried out until the final failure with sample rupture or can be performed in steps to monitor the conditions of the samples at desired intervals. From the applied load x displacement curve of the sample it is possible to convert these data into conventional mechanical properties, compatible with the results of tests with standard samples. Some of the most studied properties are yield strength, ultimate tensile strength, tensile elongation, fracture energy, fracture toughness, the temperature of the ductile-to-brittle transition, etc [7].

A typical result of an SPT test is shown in Fig. 2 through the load x displacement curve for a metal alloy, where it is possible to distinguish four typical regions. According to Garcia et al.[8] in this graph: "Zone I corresponds to the elastic bending of the sample, along with the indentation produced on its surface by the contact of the head of the punch. Zone II describes the progressive extension of plastic bending to the entire sample. From a certain point onward, plastic bending leads to a membrane behavior which predominates in most of the curve, a phase which corresponds to zone III. On approaching the maximum load, the slope of the curve starts to decrease as failure micromechanisms develop (necking and internal cracking), giving rise to zone IV, where first necking and then a visible crack are finally produced, leading to a decrease in load until total failure of the specimen".

When comparing the graph obtained with the SPT and the one usually obtained with the conventional samples it is possible to deduce that in order to obtain the mechanical properties of a material, independent of the size of the sample, some adjustments are necessary in the mathematical formulas to calculate the values.

From the mechanical point of view, when analyzing the test in terms of elastic and plastic regime, it is possible to verify a perfect convergence and understanding of the researchers regarding the elastic part of the test. Although there are still some discussions about the methods of obtaining properties, the mathematical formulation is already well defined and accepted by the researchers [8,9,10].

In the discussions about the plastic regime of the SPT, the current researches focuses on determining the best adjustments to the mathematical formulation, taking into account the influence of the sample size on the mechanisms that lead to the final rupture of the material. Although some tests are performed with a single material, and the result applies to a particular [8] property, the final result shows the validity of the SPT by the accuracy of the values obtained, compared to those of conventional tests. The validation of the SPT results is also performed by finite element simulations (FE), which achieves results with greater accuracy and less processing time.

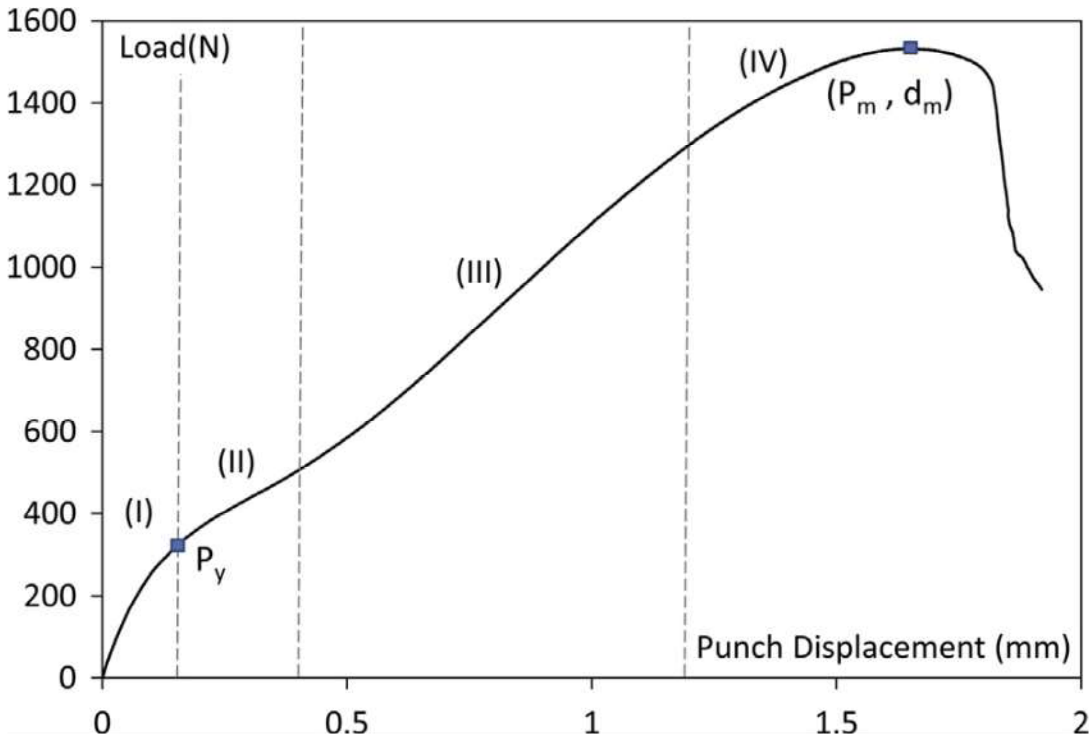

Figure 2: SPT load-displacement curve with different curve zones[8].

2.1. Equations and mechanical properties

The most well- established equation in the SPT tests is the one that shows a linearity between the tensile yield strength and the load (called Py) which separates the first region of the graph, denominated zone I, and zone II. The Equation 1 expresses this relation is given by:

$$\sigma_{YS} = \alpha_1 . \frac{P_Y}{t^2} + \alpha_2 \qquad (1)$$

Where σ_{YS} is the tensile yield strength; P_Y / t^2 at load divided by the square of the initial thickness (t) of the specimen and α_1 and α_2 are constants of the test [8].

The other properties still do not have a consensus as to the true expression that defines their values. Sometimes the debates go into small details as to whether the coefficient of the equation should be the value of the thickness or the value of the square of that thickness or even the product value of that thickness by the displacement at the maximum load, as in the case of the ultimate tensile strength [9]. Although it has not yet reached convergence, the values obtained (Table 1) are very close to the values found in the tests performed with the conventional samples [10].

To assist in the prediction of mechanical properties of SPT, computational simulation using finite elements (FE) is used. An example would be the finite element two-dimensional model, established based on the ABACUS software with the characteristic geometry of the SPT samples. Alegre et al.[9] used a three-dimensional model to simulate the symmetric half of the pre-cracked SPT specimens. This type of simulation uses less memory and less time of calculations. Due to the minimized size of the sample it is possible to do a modeling with a greater precision, increasing the number of nodes of the network. Even so, the volume of data to be processed is smaller compared to conventional samples, which results in a shorter processing time.

Table1: Values of mechanical characteristics of AISI 410 obtained from SPT[a]

Characteristic	Computed values
Load at the initial moment of yielding	220 N
Yield strength	317 MPa
Maximun load	2.300 N
Energy of the small-punch-induced strain	2.85

a. adapted from [10]

Several mechanical properties can be evaluated through SPT. Hassan [10] shows that it is possible to determine the mechanical properties like the ultimate rupture strength, the tensile yield strength, the fracture energy and the temperature of the ductile-to-brittle transition. According to the author, when studying mechanical properties in a stainless steel it verified that the values of the yield strength computed with the help of known semi empirical relations and determined by standard tensile tests differ by only 3%.

Fracture toughness characterization was studied by Martínez-Pañeda et al. [11] through notched specimens. The authors established a parallelism between the standard definition of the CTOD and the displacements of the notched faces in the SPT, while Jeon et al.[12] presented a method to predict the thermal ageing effect on fracture toughness (J–resistance curves).

Size effect (thickness-to-grain size ratio) [13], brittle to ductile transition regime as a function of temperature and irradiation [14], hydrogen embrittlement [15], estimation of residual stresses [16] are some of the properties studied by small punch test, guaranteeing the efficiency and correspondence of properties with conventional tests.

3. CONCLUSIONS

Through the results demonstrated in the several works on SPT, this technique can be used to characterize as a fast and powerful tool, several mechanical properties of materials with a reduced volume of sample. The use of finite element models helps to establish a good correlation with conventional tests. Due to the small volume of the sample it is possible to obtain more accurate results with a shorter processing time.

With a simple test, low cost and a small amount of material it is possible to obtain various mechanical properties, quickly and accurately. Some coefficient calculations are still being refined for a better fit with conventional test results but overall SPT is quite accurate and can be used in the nuclear industry to evaluate materials under special post-irradiated conditions.

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