2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

ISBN: 978-65-594-125

Small Punch Test Devices in Development at IPEN Aiming to Perform Tests in RMB Hot Cells

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1. Introduction

The correct knowledge of the mechanical properties of irradiated structural materials is an inherent need in the design and maintenance of nuclear facilities due to the high responsibility and risks. The risk in handling samples and specimens of such materials is higher the greater the involved mass is. From these comes the strong interest in the use of small specimens (SSP), which has given rise to studies and test proposals with an intense and growing development in the last ten years.

Among the techniques developed to obtain the mechanical properties of materials, using SSPs, we have the Small Punch Test (SPT). This test/assay is presented in the ASTM standard E3205/2020 [1].

The test basically consists of pressing a small sphere or semi-sphere against a plate of the investigated material until it ruptures. The applied force (F) and the displacement of the sphere (d) are recorded while the plate deforms. From the analysis of the F x d curve, which has certain characteristics, and from the analysis of the fracture surface of the ruptured sheet, and the shape of the macroscopic fracture itself, it is possible to obtain several mechanical properties of the tested material, such as, for example, the yield stress, tensile strength and fracture properties of the material such as its toughness.

The technique of testing miniaturized specimens, in particular the SPT, although still under development, is very promising. For instance, the disk-shaped sample of the SPT, in some cases, can be taken from a small chip removed from a component in service without affecting its performance. For this reason, the technique can also be considered as a non-destructive method.

In the Brazilian Multipurpose Reactor (RMB) project there is the prevision of a hot cell laboratory to characterize the degradation of irradiated structural components used in a nuclear reactor compared with the virgin material.

The Nuclear and Energy Research Institute (IPEN), a research institute located in São Paulo City, is managed by the Brazilian Nuclear Regulatory Commission (CNEN). One of its recent interdisciplinary project deals with the development of small punch test (SPT) devices aiming to be selected as a serious candidate to be used in the RMB surveillance programs.

This project aims to following goals: (i) design and manufacture of two mechanical devices to perform SPT tests at ambient as well as subzero temperatures; (ii) Carrying out SPT tests on standardized nuclear materials (ferritic and stainless steel), not irradiated for later correlation with conventional mechanical tests; (iii) Develop numerical simulations using the finite element method with ABAQUS and ANSYS programs to correlate them with experimental results and determine the parameters used to obtain the respective mechanical properties.

2. SPT Device, Test Specimen and Typical Result

Due to the risk in handling samples and specimens of irradiated materials it requires special laboratories even when the volume of material tested is in the order of a few cm^3 [2]. Hence, the strong interest in the use of small specimens (SSP) (volume < 10 mm^3) compared to traditional specimens, including those with Charpy geometry (10x10x55 mm^3), for example, which has given rise to studies and proposals for initial tests for about 30 years [3] but with an intense and growing development in the last ten years [4].

In the SPT test the specimen of the material to be tested typically is a disk with diameter d=8mm and thickness t=0.5mm, which has fixed edges, pressed by a sphere that has a diameter d=2.5mm (Figure 1, adapted from [6]. Thus, the test device is also very small as the specimen so that from a broken half of a post-impact Charpy test specimen it is possible to remove several SSPs for the SPT test. The involved material volume is about 25.1 mm^3 while a Charpy specimen has about 5,500 mm^3. A typical result is shown in Figure 2. This typical applied load vs. displacement (measured at the disc center) curve for ductile steels can be divided into several regions/zones: (i) elastic bending; (ii) transition from elastic bending to plastic bending (iii) plastic hardening; (iv) softening due to striction and damage initiation; and (v) crack growth and failure.

The test geometry and applied load imposes a complex stress field on the sample. The equivalent plastic deformation at certain locations of the perforated tested disc can reach values greater than the true uniform deformation. The correlations between the values determined from the SPT and the conventional mechanical properties are still under debate today [5].

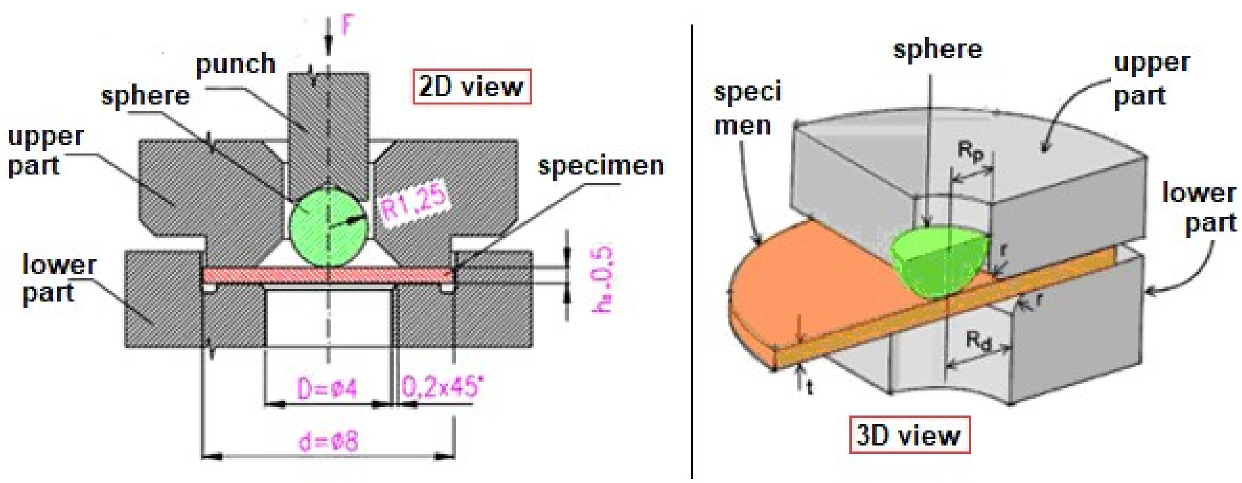

Figure 1: SPT device (Bolts not shown, schematic)

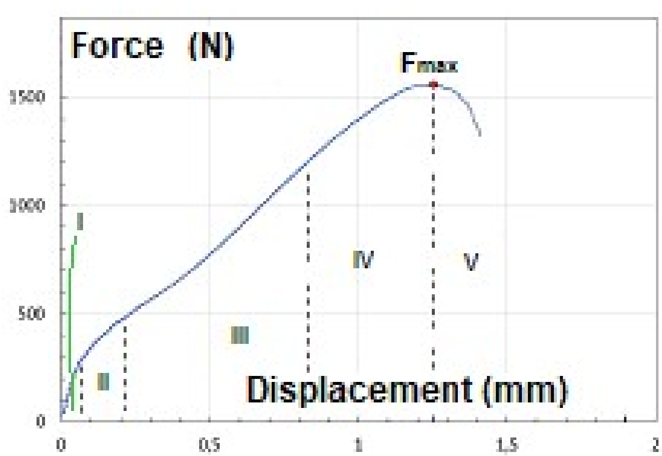

Figure 2: Typical SPT Experimental Curve: Applied Load x Displacement

A well-established relationship in SPT tests is one that shows a linearity between the tensile yield stress (σ_{YS}) and load (P_Y), that separates zones I and II in Figure 2, given by Eq. (1) [2] where t is the sample initial thickness α_1 and α_2 are test constants. Computational simulations using finite elements will also be used to aid in predicting mechanical properties of SPT samples. For this scope, an axisymmetric two- or three-dimensional finite element model can be used.

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

3. First Developed SPT Device and Acceptability Test Results

To reach one of the goals of the project, a first SPT device was designed to do tests at or near room temperature, shown in Figures 3.

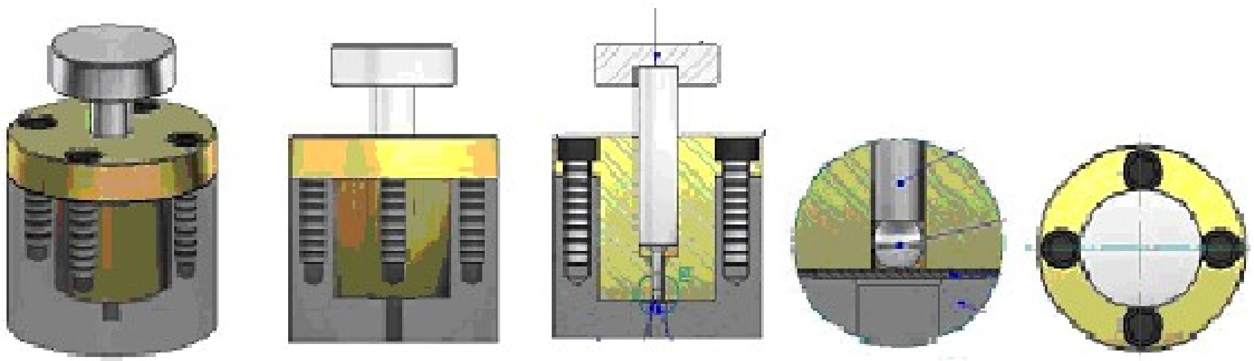

Figure 3 – The Developed SPT Device

After manufactured the device was tested using Carbon and Stainless steels specimens at room temperature. These specimens were manufactured with non-nuclear materials just to test this first device. The very first test on Carbon Steel (CARB-01) was not run until rupture on purpose. So, its corresponding Force x Displacement (*F x d*) curve, not shown, was a partial one barely reaching the maximum load.

In all other specimens, two Carbon steel and two Stainless steel specimens, the tests were conducted until their failure and the records of the F x d curves are complete for the application of several correlations with the conventional test curves and consequent obtaining of the /properties that characterize the tested material. The Carbon steel specimens CARB-01 and CARB-02 were from the same batch and were machined by electrical discharge machine (EDM). CARB-03 came from another batch and was machined in a conventional lathe. The CARB-02 and the CARB-03 specimens shown slightly different results. The stainless steel under study is a 300 series steel (austenitic). Figure 4 shows two typical curves obtained in these tests: one of Carbon steel (CARB-02) and other of Stainless steel (INOX-01). The curves behave as expected.

4. Conclusions

Numerical simulation of the SPT test is under development using the Finite Element Method to help understand the influence of various factors on the results. A non-linear modeling, with large displacements and large deformations, is being used, as well as friction between the sphere and the CP. Damage models is being studied also. In a future paper these results will be shown.

Also, a systematic study, with a nuclear carbon steel (an A508 Class 3 steel), firstly at room temperature, considering the influence of some parameters as specimen thickness, surface roughness, etc., is being planned to start soon together with the numerical simulations. In a few months a new device, now under development, to perform tests at sub-zero temperatures, will be used to obtain the toughness x temperature curve, for the A508 carbon steel, and its Ductile to Brittle Transition Temperature (DBTT), and compare all these results with previous other already obtained in past studies.

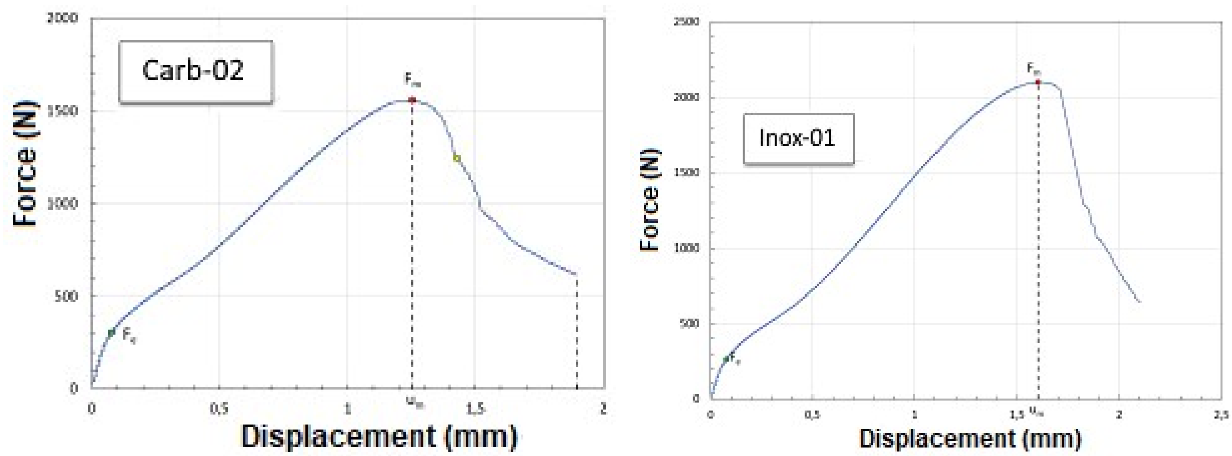

Figure 4 – Typical Test Results of the Developed SPT Device

Acknowledgements

The authors are grateful to IPEN for the support to this project.

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