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Evaluation of the mechanical properties of SS-316L thin foils by small punch testing and finite element analysis

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ABSTRACT

Thin foils having thickness values of 200 μm and less are commonly applied in the food industries, medical applications and more. Small punch technique (SPT) is a promising mechanical testing method for specimens thicker than 250 μm, in which a formulation correlating the measured parameters to standard tensile properties was previously reported. The current research is focused, for the first time, on the correlation between SPT and tensile mechanical properties of SS-316L thinner specimens in the range of 100–200 μm. It is demonstrated by finite-element-analysis, that the mechanical response of thin foils having thicknesses in the range of 25–500 μm can be divided into three categories. For specimens thicker than 300 μm, thin plate bending equations that were applied previously for thick specimens, are still valid, while for thinner specimens this theory fails to provide adequate correlation between SPT and tensile yield stress. For specimens thinner than 50 μm it was identified that equations derived from membrane solution should be employed rather than classical plate theory. For intermediate thickness values in the 50–300 μm range, a "transition-zone" was identified between plate and membrane-like mechanical responses. For the lower region, 50–100 μm, an analytical expression correlating the measured SPT parameters and the tensile yield stress is currently proposed.

1. Introduction

In the last few decades there is a continuing demand to characterize the mechanical properties of metals and alloys using small specimens due to limited material availability, for testing irradiated materials and more. The initial motivation for developing small specimen testing arose at the beginning of the 1980's in the nuclear industry. Overtime, due to the limited number of irradiated standard specimens, researchers started developing alternative testing methods based on non-standard small specimens. These non-standard small specimens could be extracted from the fragments of the already tested standard specimens. Small Punch Test (SPT)/Ball Punch Test (BPT) or Disk Bend Test (DBT) [1], as well as Shear Punch Test [2–7] and others, are techniques developed to characterize the mechanical behavior of small or thin specimens. The SPT concept is based on locking a thin sheet-like specimen between two dies and pushing against it a spherical cap punch up to failure. During the test, the load and the punch stroke are monitored simultaneously until the end test criterion (e.g., maximal or failure load, a certain stroke) is achieved. The ASTM E-643 standard and others [8] address specimen thickness between 200 and 2000 μm. Indeed, most of the studies reported were focused on alloys that have a thickness larger than 200 μm [9]. Thin foils having thickness values of 200 μm and less are used in a variety of applications such as Al for food service, shielding, vacuum chambers; Cu for electronics, batteries, circuit boards, cables wrap; and stainless steel for aerospace, surgical instruments, tool wrap, and heat exchangers. In medical applications, a cyclotron window that is 25 μm in thickness is required for fluorodeoxyglucose (FDG) production [10,11]. Irradiation of targets in cyclotron by proton and deuteron beams is carried out at variable energies and occasionally at high currents and long time durations up to few hours. During

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this period radiation damage is accumulated, its micro-structure may be changed and the mechanical properties may be significantly reduced. The damage and the temperature are not uniform due to the Gaussian shape of the beam intensity. At locations where higher temperature prevails the increased thermal atom diffusion (annealing) may reduce the damage. Therefore, it is important to be able to measure the local mechanical properties across the window. Although thin foil specimens under 200 μm are not considered in the ASTM E-643 standard, the SPT method has the best potential for estimating the mechanical properties of such small specimens.

The main challenge in SPT is to extract the mechanical properties of the material such as the yield stress and ultimate stress that are commonly the goal of standard tension tests. A schematic apparatus for SPT and a typical load displacement curve are shown in Fig. 1. The load displacement curve shown in Fig. 1b contains four regions described in [12–14]: I – elastic behavior, II – plastic behavior (strain hardening), III – plastic membrane stretching, and IV – plastic instability. In the vicinity of the maximal load, cracks are expected to develop in the specimen, followed by ductile propagation and fracture.

The zone between regions I and II is used to estimate the material yield stress while the ultimate stress and fracture strain are estimated from zone IV.

Unlike standard tension tests, the stress and strain that develop in the specimen during testing are not uniaxial and therefore the method of estimating the mechanical properties is not straight forward. For the initial elastic loading (region I), the classical thin plate bending theory is utilized for estimating the material's yield stress.

Classical thin plate bending theory is based on three main assumptions [14]:

1. Straight lines initially normal to the middle plane remain normal following the deformation.
2. Normal stresses are zero for each point in the middle plane.
3. Deflections of the middle plane are small with regard to the plate thickness.

Following these assumptions one can derive through static equilibrium the governing equations. In cylindrical coordinates, these equations take the following form [15]:

$$\left(\frac{d^2}{dr^2}+\frac{1}{r}\right)\left(\frac{d^2w}{dr^2}+\frac{\upsilon}{r}\frac{dw}{dr}\right)=\frac{P}{D} \quad ; \quad D=\frac{Et_0^3}{12(1-\upsilon^2)}. \tag{1}$$

Here w is the deflection of the middle plane of the plate, P – the applied load, and D – the plate's flexural rigidity, which is a function of the materials' elastic constants and the initial plate thickness (t_0). The solution of Lagrange's equilibrium equations for an edge-clamped thin circular plate results in stress components that depend linearly on the ratio between the applied force and the square of the thickness (P/t_0^2). By assuming that the solution to (1) accurately describes the stress state in region I, one can use the small punch experimental data to obtain the material yield stress. Estimation of the ultimate stress is more complicated but it is commonly assumed to be related to the maximal load and displacement at maximal load.

In [13] SPTs conducted on 250 μm sheets of SUS316, PCA, and HT-60 are reported. It is demonstrated that a good approximation to both the yield stress and ultimate stress can be obtained by taking the punch forces P_Y and $P_{\max}$ values from the SPT, divided by the square of the initial specimen thickness as expressed in (2).

$$\sigma_Y=\alpha_1\left(\frac{P_Y}{t_0^2}\right) \quad ; \quad \sigma_{ULT}=\alpha_2\left(\frac{P_{\max}}{t_0^2}\right)-320 \tag{2}$$

The unit-less slope parameters $\alpha_1 = 0.360$ and $\alpha_2 = 0.130$ were shown to provide a good approximation for all of the three tested materials.

In a recent study [9], different empirical correlation functions were used to analyze SPT conducted on a variety of metallic alloys having a wide range of mechanical properties. All specimens had a thickness of 500 μm. It was concluded that the best estimation for the yield and ultimate stress can be obtained by utilizing (3):

$$\sigma_Y=\alpha_1\left(\frac{P_Y^*}{t_0^2}\right); \quad \sigma_{ULT}=\alpha_2\left(\frac{P_{\max}}{\delta_m\cdot t_0}\right). \tag{3}$$

Here δ_m is the maximal punch deflection at maximal load and the method of extraction of P_Y^* differs from the method reported in [13]. The unit-less slope parameters in [9] were determined to be $\alpha_1 = 0.346$ and $\alpha_2 = 0.277$, providing a good approximation for all the tested materials. Although the experiments were conducted on 500 μm thick samples, finite element simulations of the SPT were used to check the sensitivity of (3) to specimen thickness variations. It was concluded that the proposed expressions for estimation of the yield and ultimate stress in (3) have low dependence on the specimen thickness [9].

The above correlations were obtained for specimens thicker than 250 μm and their applicability to thinner specimens of 200 μm or less is still an open question. The goal of this study is to examine the applicability of (2) and (3) to specimens thinner than 250 μm while proposing a new methodology for estimating the yield stress for such thin samples.

The novel findings of this study are (a) Standard correlations for estimating the yield and ultimate stress from SPT experiments fail for specimen's thinner than 200 μm. (b) A "transition zone" between plate bending and membrane stretching response of the specimen was identified using FE analysis. (c) A new analytical expression was established for estimating the yield stress from SPT experiments in the "transition zone".

The structure of the paper is as follows: In Section 2 our experimental setup and results for both tension and SPT are presented. In Section 3 it is demonstrated that classical correlations for estimation of mechanical behavior from SPT fail when applied to thin specimens. In Section 4 the numerical models for both tension and SPT tests are described in detail. Section 5 is devoted to computational investigation of small punch tests conducted on thin specimens. Summary and concluding remarks are given in Section 6.

2. Experimental setup and results

2.1. Experimental setup

Stainless Steel 316L sheets with thickness of 100 and 200 μm, in the annealed condition, were tested by tensile and SPT. The tensile specimens were cut from the as received foils by electrical discharge machining (EDM) according to ASTM standard E 8M-04 [16] (Fig. 2). The small punch specimens were cut by scissors to $W = L = 8$ mm dimensions (Fig. 1a). The tensile tests were performed in an Instron machine under stroke control at speeds of 1 and 2 mm/min and the strain was measured by a 50 × 2.5 mm clip on extensometer during the entire test. The tensile specimens were preloaded in the low elastic region before starting the test to eliminate any damage; the test was terminated at break criterion (Fig. 3).

The SPT was conducted using the apparatus shown in Fig. 4 by the following steps: (1) clamping of the specimen between the dies under 300 N, (2) pre load up to 5 N and balance the stoke transducer (Instron COD), and (3) pushing the ball into the specimen under stroke control at a speed of 0.2 mm/min up to failure; the