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Short communication

Novel techniques for estimating yield strength from loads measured using nearly-flat instrumented indenters

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ABSTRACT

Procedures to determine yield stress based on two loads from load-displacement curves obtained using nearly-flat, instrumented indenters are presented. Using measured loads in cavity expansion and slip-line theory, estimates of yield of steel and aluminum alloys were obtained. Magnitude of the relative error in the estimated yields is bounded by 16%.

1. Introduction

This article reports novel procedures to estimate the yield strength of metals using instrumented, micron-sized, nearly-flat indenters. Estimating the yield strength of a metal using a hardness value requires either a knowledge of the strain hardening response or statistical correlations. For instance, the relationships for yield stress presented by Tabor [1], Cahoon et al. [2], Cahoon [3] or Hawk et al. [4] rely on measurements of the Vickers Hardness, the strain hardening exponent (Meyer's coefficient), and an empirical, material-dependent constant. Requiring a knowledge of the strain hardening exponent renders the preceding relationships unusable for small regions such as the heat-affected zones adjacent to welds or surface treated regions, where the material cannot be extracted and tested in isolation by tensile testing. Examples of using correlations of yield with Brinell hardness are also put forth by Radmard et al. [5].

Instrumenting the indenter and measuring the force and displacement during indentation reduces some of the material-specific empiricism associated with yield strength estimation. However, to obtain yield stress by cyclic indentation using a spherical indenter as proposed by Haggag and Lucas [6] and Haggag [7] still requires knowledge of the strain-hardening exponent; see Pamnani et al. [8] for a recent application of this approach.

Coupling instrumented indentation with finite element computation allows estimation of the entire elasto-plastic response. In this regard, the work of Nix [9] and Giannakopoulos and Suresh [10] using sharp indenters and Alcalá et al. [11] using spherical indenters are noteworthy. Repeated indentation with spherical indenters and finite element computations may be found in Moussa et al. [12].

Accordingly, there is no simple, direct, procedure to obtain the yield strength of a metal using either hardness or indentation curves. Perforce, the user has to resort to either empirical relationships or computations. This is not surprising on account of only the load being known in hardness measurements. Lack of distinguishing features in the indentation curves obtained using sharp and spherical indenters is implicated when the indenter is instrumented. The curves are concave-upwards with no feature that can be used to discriminate a yield stress being exceeded near the indenter.

In contrast to sharp and spherical indenters, nearly-flat indenters obtain S-shaped indentation curves. See, for instance, Hu et al. [13] who idealized such indenters as rigid cylinders to analyze aluminum and steel alloys. Moreover, the indenter system's vendor provides software that analyzes the indentation curve to obtain a yield strength and a description may be found in the article by Leroux [14]; but the physical basis for the procedure is unclear.

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In this work, procedures to exploit the S-shape and identify two loads are presented. Arguing that the first load corresponds to the expansion a spherical cavity a formula to estimate yield strength is presented. The second load is shown to represent the indentation of a half space by a rigid cylinder and a second formula for the estimation of yield strength, based on slip-line theory, is given. It bears emphasis that conventional steel and aluminum alloys were tested in this work, and application of the cavity expansion and slip line theory is valid in so far as material yielding can be described by the von-Mises criterion.

2. Materials and indentation experiments

A Nanovea-M1 indentation tester was used. These indenters are axi-symmetric, with a truncated cone profile and have an approximately spherical contact tip; see Scanning Electron Microscope (SEM) image in Fig. 1(a). The height of the spherical portion is designated as δ_c and it is 1.3 μm for the 100-μm diameter indenter and 3.1 μm for the 200-μm diameter indenter.

Yield strengths of five engineering alloys were estimated in this work; sample thicknesses and alloys are listed in Table 1. Samples were prepared per ASTM E3-11 standard for optical microscopy.

Three samples for each material were cut and molded with hot mounting epoxy and ground using silica grit paper starting with 120 grade and ending with 1200 grade, then polished using cloth pad and alumina powder with water lubricant for 15 min. Automated diamond polishing was used to ensure high quality surface finish with different particle size starting by 9 μm, 3 μm, and then 1 μm.

Indented surfaces were perpendicular to the rolling direction. Indentation curves are shown in Fig. 1. At least 10 indentation experiments were carried out using the 100 μm- and 200 μm-diameter indenters; typical indentation curves using the 100 μm nearly flat tip indenter are shown in Fig. 1(b). In contrast to sharp and spherical indenters, these curves are approximately S-shaped.

Two forces, F_c and F_s were obtained from each indentation curve, as described below and the mean and 90% confidence intervals are listed in Table 1. Owing to a 40 N maximum loading capacity, the X80 steel was not loaded with the larger diameter indenter.

Conventional tensile tests per the ASTM-E8 standard were carried out to obtain yield strengths using the 0.2% offset method. Tensile tests were repeated at least 3 times for each material to assess repeatability. A displacement rate of 1 mm/min was used in all of the tests, and the loading direction was parallel to the indentation direction. The preceding choice of loading direction accounts for potential anisotropy of yield strength. Table 1 lists the mean and 90% confidence intervals for the 0.2% offset yields and also the grain sizes for each of the alloys.

3. Yield strength estimates

The first estimate is based on the assumption that when the dept of indentation is δ_c the hemispherical part of the tip has penetrated the substrate and there is full contact. The force F_c corresponding to δ_c is obtained from the indentation curve and used to compute the yield strength using

$$\sigma_y = \frac{1}{2.2}\frac{F_c}{\pi a^2}, \tag{1}$$

where a is the radius. The theory behind the factor of 2.2 is given in the next section.

The second estimate of yield is based on the observation that for indentation depth greater than δ_c, there is a point in the process, before the onset of pileup, when the highest plastic strain is concentrated at the edges of the indenter. Accordingly, at this point, the indenter can be treated as a rigid cylinder indenting a half space. The load corresponding to this point, F_s, can be identified by constructing a tangent to the curve as shown in the inset of Fig. 1(b). Shield [15] used slip-line theory to show that the pressure required to indent a semi-infinite substrate by a rigid

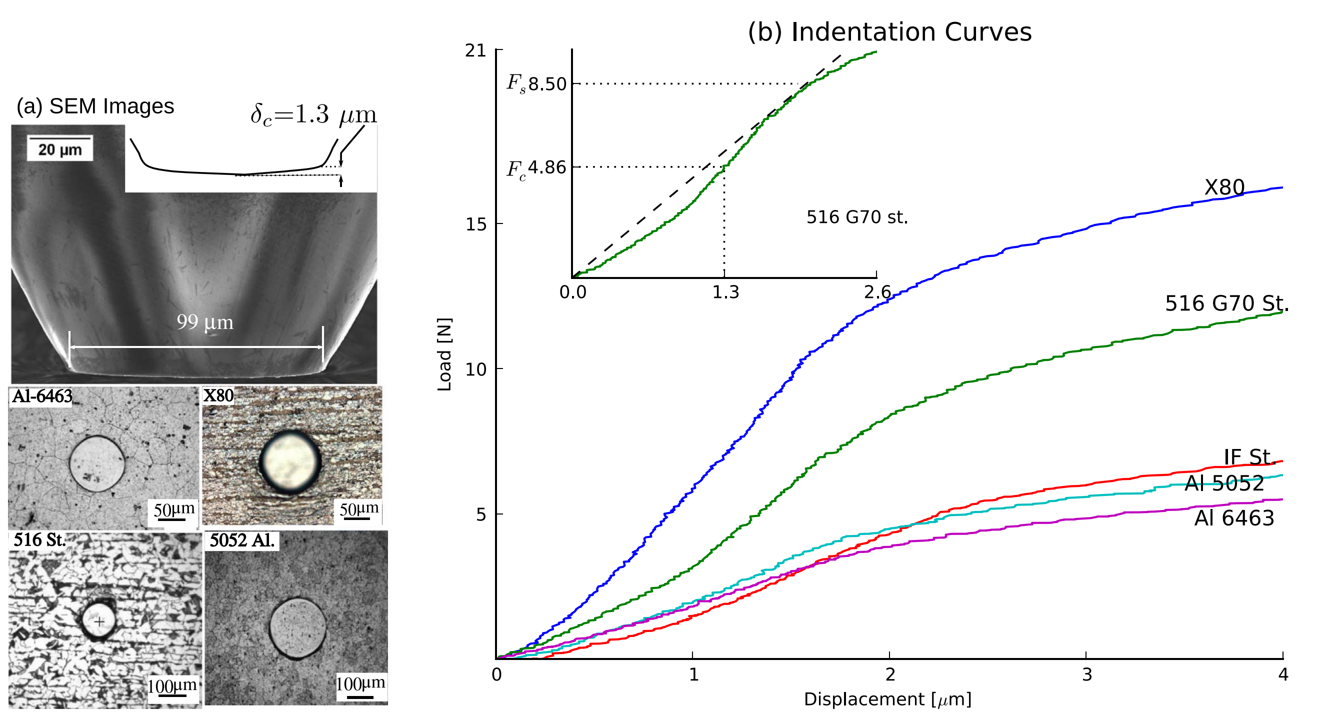

Fig. 1. (a) SEM image of the 100 μm-diameter indenter and post-indentation micrographs. (b) Indentation curves obtained using the indenter. Inset shows the construction used to obtain F_c and F_s; F_c corresponds to the displacement δ_c, and F_s is the force corresponding to the point where the line through the origin is a tangent to the indentation curve.

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