Extraction of Plasticity Parameters from Instrumented Indentation Data via Inverse FEM Modelling

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Introduction

Obtaning bulk mechanical properties from (instrumented) indentation data is a longstanding aim. The complexity of stress and strain fields beneath an indenter means that (apart from elastic constants) this cannot be done via analytical equations. However, if the properties (eg yield stress and work-hardening rate for plasticity) are known, then it is straightforward to input them into an FEM model and predict outcomes such as load-displacement plots and residual indent shapes. The challenge lies in the inverse problem - ie inferring the correct values of the property parameters from experimental outcomes.

Scale Effects

The (FEM-simulated) stress and strain fields beneath an indenter are independent of scale - they are the same, for example, under a sphere indented to a depth of 10% of its radius, whether that radius is 10 μm or 10 mm. Scale effects are nevertheless important, since the volume of material being mechanically interrogated must be large enough to be representative of the bulk.

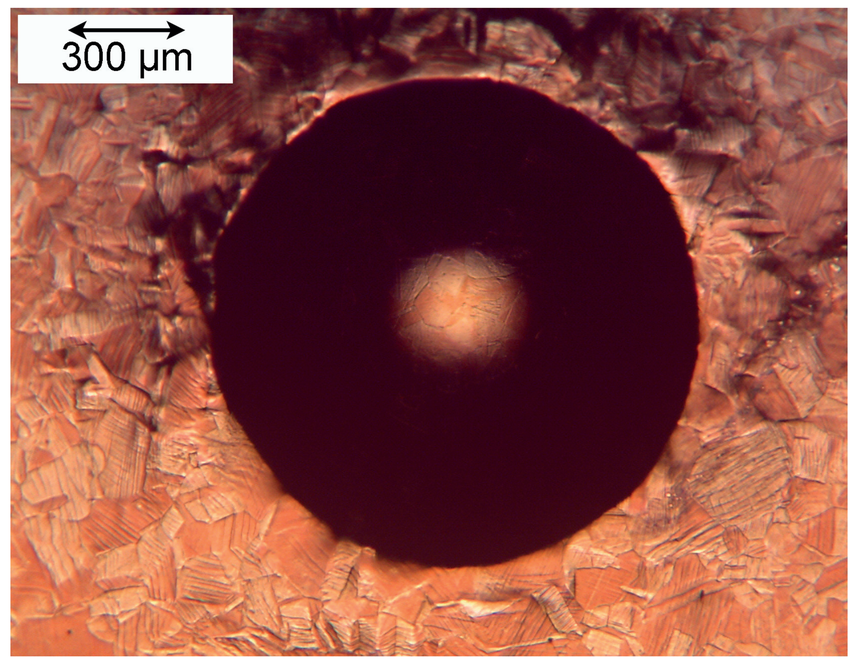

Fig.1: Optical micrograph of an indent in an extruded Cu bar, created by penetration of a 3 mm diameter sphere to a depth of about 100 μm.

In most cases, this requires the indent to straddle several grains - perhaps at least a dozen. Since grain sizes are commonly at least ~100 μm, indenters must be large for these purposes - eg in the mm range for the diameter of a sphere - see Fig.1. This also avoids the problems of surface roughness, oxide films, thermal drift etc that can plague fine scale indentation.

Shape Effects

A barrier to inferring plasticity (or other) properties from an experimental outcome (eg a load-displacement plot) is that it may be consistent with multiple combinations of the parameter values. However, extra degrees of freedom can be injected by using further indenter shapes, which create different strain fields. Fig.2 compares those beneath a sphere and a truncated cone. These exhibit different relationships between plasticity parameter values and indentation response.

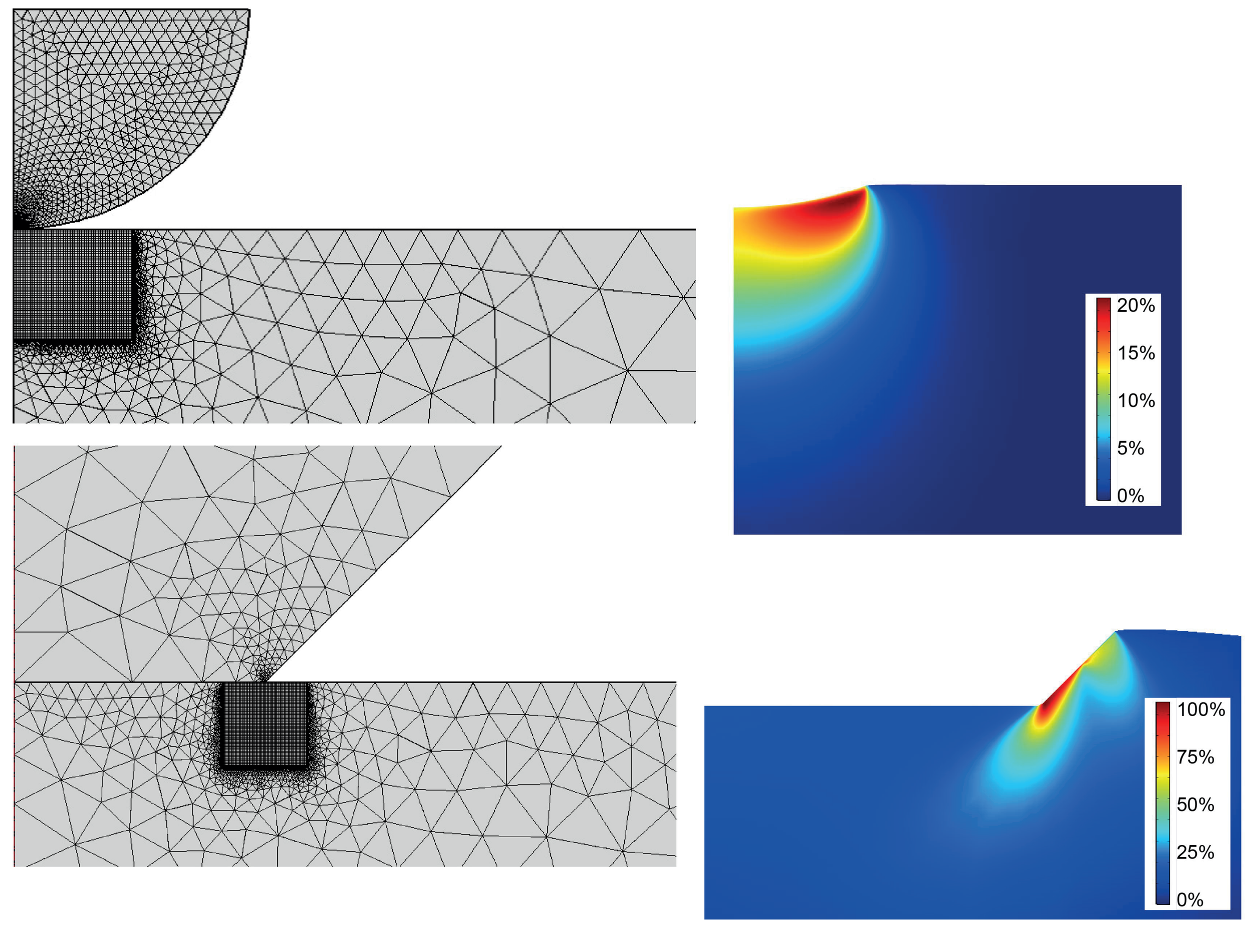

Fig.2: FEM meshes for indentation with a sphere and a truncated cone, together with predicted fields of (von Mises) plastic strain after some penetration. These are for a material having a yield stress of 300 MPa and a (linear) work hardening rate of 1,000 MPa.

Goodness-of-fit Parameter, *g*

Inverse FEM to infer property values requires characterising fit between experimental & predicted outcomes (eg $P(\delta)$ plots).

The definition used in the current work is illustrated in Fig.3.

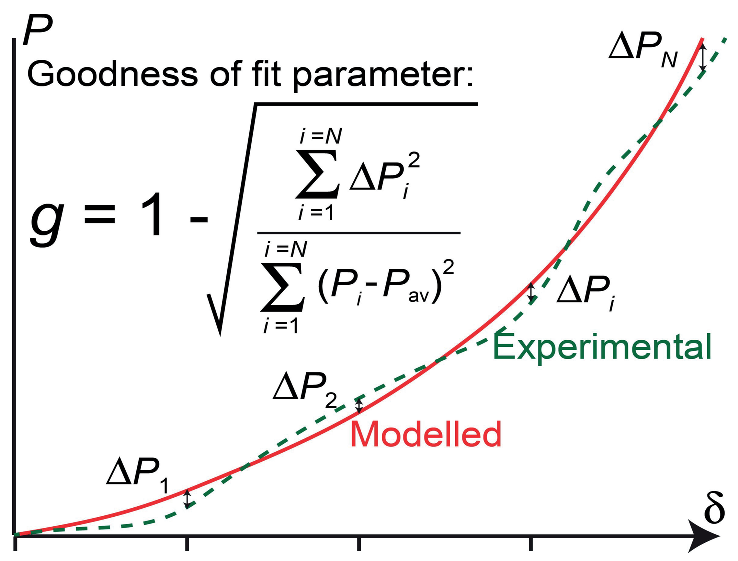

Fig.3: Experimental $P(\delta)$ plot, plus model prediction, and definition of g.

The "*g*-screening" Concept

For a given set of property parameter values, and indenter shape (and size), *g* values are obtained by comparing predicted and experimental outcomes ($P(\delta)$ plots). From the definition in Fig.3, the value could range from 1 (perfect fit) to 0 (no fit). The process involves creating a matrix of *g* values that will lead to a unique "solution" for the parameter values.

In general, except for a perfectly plastic material (no work hardening), more than one indenter shape should be used. This assists convergence on a unique solution. An example is shown in Fig.4, where it can be seen that the ambiguity associated with each of two indenter shapes in isolation is removed when they are considered together. In general, the procedure involves creating a "master cloud" of high-*g* points in parameter space, in which the solution corresponds to the point with the highest value.

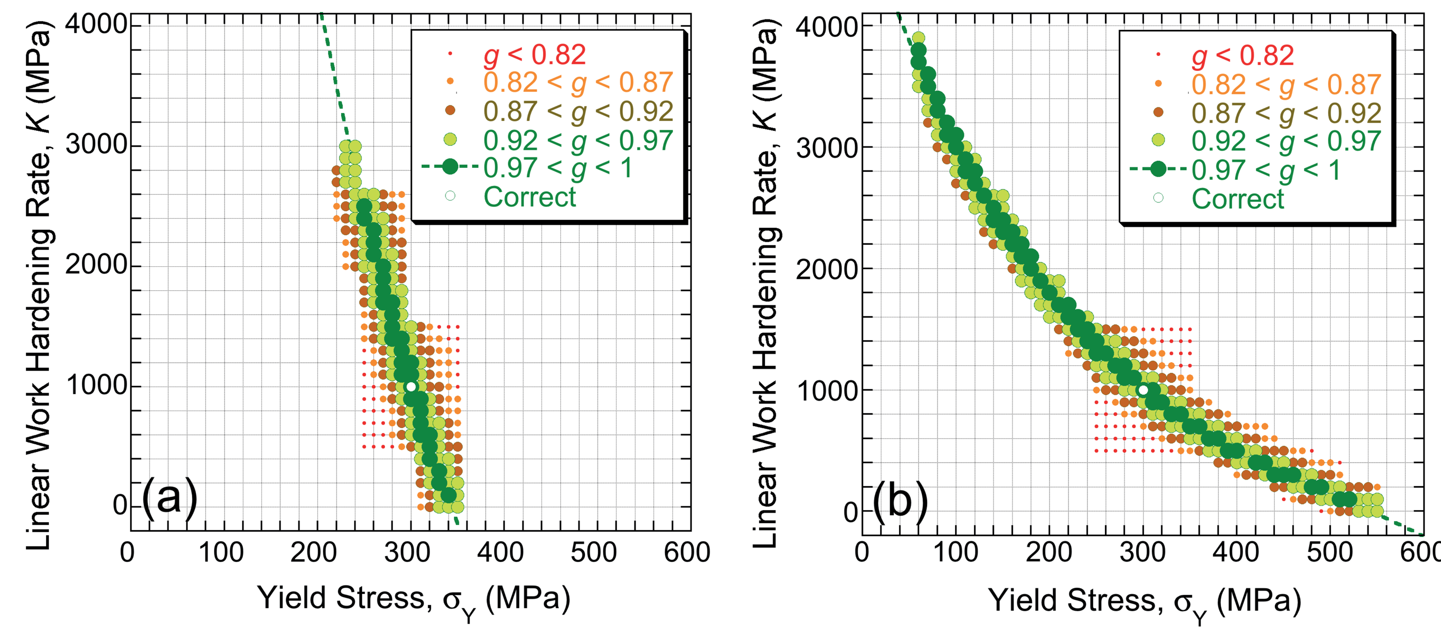

Fig.4: g-screening in σ_Y - K space, for "correct" values of 300 MPa and 1,000 MPa, showing the g range from each run, for (a) a sphere and (b) a cone. Dotted lines are best fits for points with g >0.97.

An Illustrative Example

Cu (Fig.1) was indented with a (4 mm diam.) sphere and a truncated cone (0.6 mm end diam., cone angle 90˚). Using these $P(\delta)$ data, *g*-scans were produced, as in Fig.4, and the "peak-*g*" point identified as (σ_Y=250 MPa, *K*=250 MPa). Fig.5 shows that these values fit well to the uniaxial stress-strain plot.

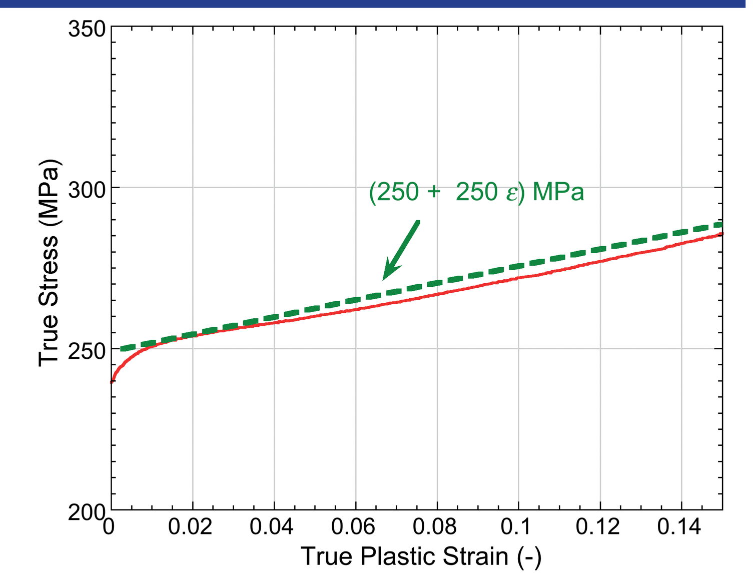

Fig.5: Uniaxial stress-strain plot, plus that for σ_Y and K values inferred from indentation data.