Stress-strain curve for aluminium from a continuous indentation test

W. H. ROBINSON, 
Materials Science Section, Physics & Engineering Laboratory, D.S.I.R. Lower Hutt, New Zealand

S. D. TRUMAN 
Department of Chemical and Materials Engineering, University of Auckland, Auckland, New Zealand

Continuous indentation tests using a 6.35 mm diameter steel ball were carried out on polycrystalline aluminium (99.995%) at forces up to 942 N (96 kg) and a total displacement of 65 μm. On loading the results were observed to follow the classical Hertz equation until the elastic limit was reached at 4.6 ± 0.2 N (0.47 kg), 1.02 ± 0.05 μm. The unloading results after plastic indentation were found to fit the Hertz solution for an indenter in a spherical hole. Using the Hertz theory it was possible from the unloading results to determine the mean stress and strain under the ball, together with the indentation diameter, plastic strain, Meyer stress and ratio of elastic to total strain, enabling a stress–strain curve for hardness to be drawn. The elastic limit of aluminium occurred at a stress of 4.7 ± 0.2 × 10⁸ Pa (46 kg mm⁻²) and a strain of 1.27 ± 0.05%. At a total strain of 11.25% the stress was 11.7 ± 0.2 × 10⁸ Pa (115 kg mm⁻²).

1. Introduction
The continuous indentation test has been used by a number of researchers to study hardness. Bunshah and Armstrong [1] measured the hardness of brass from a continuous test and expressed their results in terms of the Meyer stress. Armstrong and Robinson [2, 3] observed the elastic and plastic deformation of KCl and from their results formed a stress–strain curve (by the addition of elastic and plastic areas) which in the elastic region agreed with the Hertz solution for the mean stress under the indenter and in the plastic region approached the Meyer stress. Cousins et al. [4] successfully followed the elastic deformation of lignin, a component of wood, and were, from their results, able to form an elastic stress–strain curve and determine the Young’s modulus of lignin. In this paper we present results for the elastic and plastic deformation of aluminium obtained at higher sensitivity (±0.02 μm) than used previously and using the Hertz theory we determine a stress–strain curve for hardness together with curves for the Meyer stress, indentation diameter and ratio of elastic to total strain. These stress–strain curves differ from our previous work in that in the plastic region they were determined solely from the elastic unloading curves rather than by the less rigorous addition of elastic and plastic areas.

2. Test procedure
The test end of the 99.995% aluminium specimen (grain size < 1 μm) was polished to a mirror finish with Buehler micropolish C (<1 μm) alpha alumina. The opposite end of the 20 mm diameter by 30 mm cylindrical specimen was ground flat with 400 paper. The steel ball (6.35 mm diameter) assembly was attached directly to the 100 to 5000 N load cell of a 250 kN Instron testing machine (model TT-KM). The specimen was placed on a 10 cm × 10 cm × 3 cm thick flat steel plate and the specimen plus ball displacement was measured using a Hewlett Packard 24DCDT-050 displace-
ment transducer attached directly to the ball assembly with its core extension resting on the steel plate. The force displacement curves were recorded on a fast response (<1 sec for fsd) X–Y recorder with the force measured from the load cell. The amplification of the load and displacement was such that on the X–Y recorder 1 cm could represent a load ranging from 0.05 to 50 N and a displacement ranging from 0.13 to 2.6 μm. With this configuration there was no need to take the machine deflection or hysteresis into account, although before it was possible to get the required stability to begin the test it was necessary to run the Instron, load cell amplifier, transducer and recorder for 8 h with the test room completely closed.

3. Results

If the elastic displacement, $h(e)$, of the specimen plus ball followed the elastic solution, then from Hertz [5] (see also [6])

$$h(e) = \left[ \frac{(1 - \nu(1)^2)/E(1) + (1 - \nu(2)^2)/E(2)}{E(1)} \right]^{2/3} \times \left[ \frac{9(D(1)^{-1} - D(2)^{-1})}{8} \right]^{1/3} F^{2/3}$$

(1)

where $\nu(i)$ is Poisson’s ratio, $E(i)$ is Young’s modulus, “1” refers to the ball and “2” to the specimen, $D(1)$ is the ball diameter and $D(2)$ the diameter of curvature of the indented hole and $F$ is the applied force. The results for the initial loading at a cross head speed of 10 μm min$^{-1}$ are shown on a $F^{2/3}$ versus $h(t)$ plot in Fig. 1, $h(t)$ being the total displacement $h(e) + h(p)$ where $h(p)$ is the plastic displacement. The dashed line is given by Equation 1 with $D(2) = \infty$ and $E(1) = 2.11 \times 10^{11}$ Pa, $\nu(1) = 0.28$, $E(2) = 7.03 \times 10^{10}$ Pa and $\nu(2) = 0.34$, values for steel and aluminium. Except for the first point at 0.25 N (25 g) the results fit this straight line until the elastic limit is reached at a load of 4.6 ± 0.2 N (0.47 kg) and displacement of 1.02 ± 0.05 μm. On unloading from 10.3 N an $F^{2/3}$ straight line is followed, though in this case it is steeper than the initial loading curve and gave a plastic deformation $h(p) = 0.22$ μm. The force was then increased in a series of loadings and unloadings to a maximum of 94 N before the results shown in Fig. 2 to a maximum of 942 N were obtained. The reloading curves followed the unloading results up to the maximum previous force, and the unloading curves followed the elastic behaviour, but with a steeper slope than for $D(2) = \infty$, consistent with a decrease in $D(2)$ with increasing plastic deformation.

These results are in agreement with the suggestion of Tabor [7] that the indented hole can, on unloading, be treated as the cap of a sphere of radius of curvature greater than that of the indenter. By rearranging Equation 1

$$D(2)^{-1} = D(1)^{-1} - 8 \left[ (1 - \nu(1)^2)/E(1) + (1 - \nu(2)^2)/E(2) \right]^{-2} h(e)^3 / 9 F^2$$

(2)