JOURNAL OF MATERIALS SCIENCE 27 (1992) 3789 – 3792

Elastic modulus determined by Hertzian indentation

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A new method for determining the elastic modulus from Hertzian contact experiments has been developed. The test surfaces are polished and coated with a thin layer of gold/palladium and then indented with a small sphere. The contact removes the coating from the contact area and the size of this can, therefore, be readily measured in an optical microscope. A simple analysis based on Hertz equations is then used to derive the modulus. The elastic modulus of glass and several ceramics is reported.

1. Introduction

The elastic contact problem was first solved by Hertz [1] who gave the equations for the stresses and deformation in the contact zone for two bodies in contact. The equations for the stresses outside the contact area were first given by Huber [2] and a full three-dimensional solution for the stresses in two bodies in contact was given by Lundberg and Sjövall [3]. A review of the stress solutions and a description of the crack systems which develop during Hertzian indentation have recently been given by the present authors [4, 5]. Most of the studies of the Hertzian contact problem have concentrated on the development of the ring–cone crack system [6–8], and little attention has been paid to the contact problem before any cracks occur. In this paper we will use the elastic part of the indentation cycle to determine the elastic modulus of one of the two materials in contact.

A special case of the Hertzian problem is the indentation with a spherical indenter on a flat surface. The radius, a, of the contact area is, according to Hertz

$$a^3 = \frac{3PR}{4E^*} \qquad (1)$$

where P is the indentation load, R is the radius of the indenter and E^* is a composite modulus for the indenter/plate system given by

$$E^* = \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}\right]^{-1} \qquad (2)$$

where E is the elastic modulus and ν is Poisson's ratio, and the subscripts 1 and 2 refer to the indenter and the plate, respectively. By measuring the size of the contact area for a given indentation load, the elastic modulus of the plate can be obtained from Equation 1

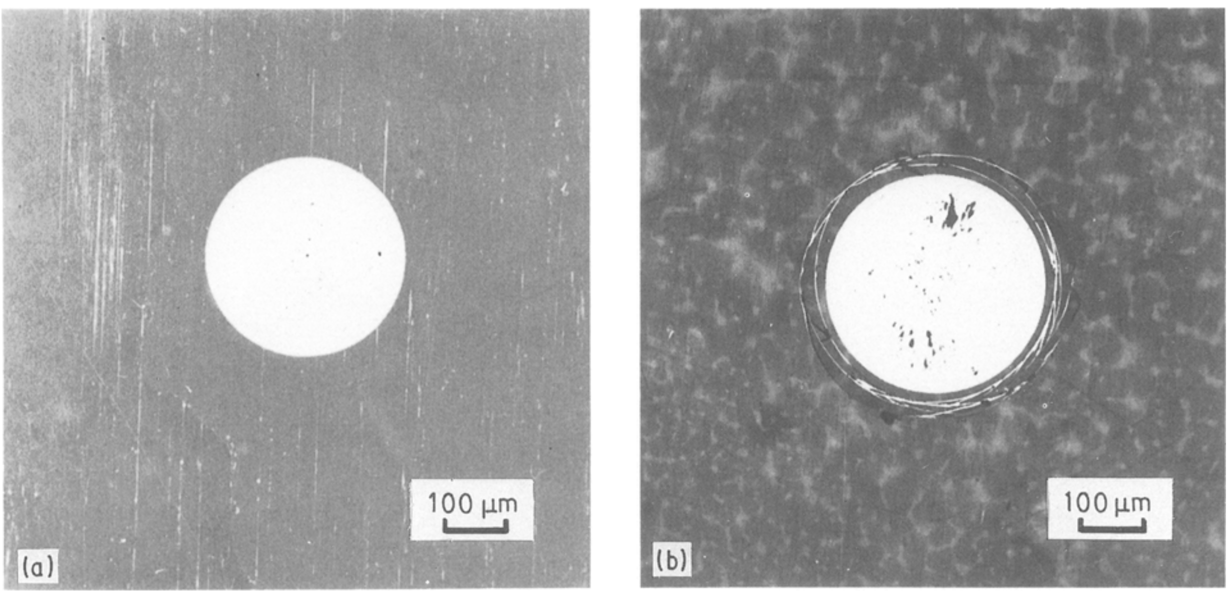


Figure 1 (a) The contact zone in glass at a load of 310 N. (b) The contact zone, primary and secondary ring cracks in glass at a load of 400 N. (c) The contact zone in Si_3N_4 at a load of 950 N. (d) The contact zone and a partial ring crack in Si_3N_4 at a load of 990 N.

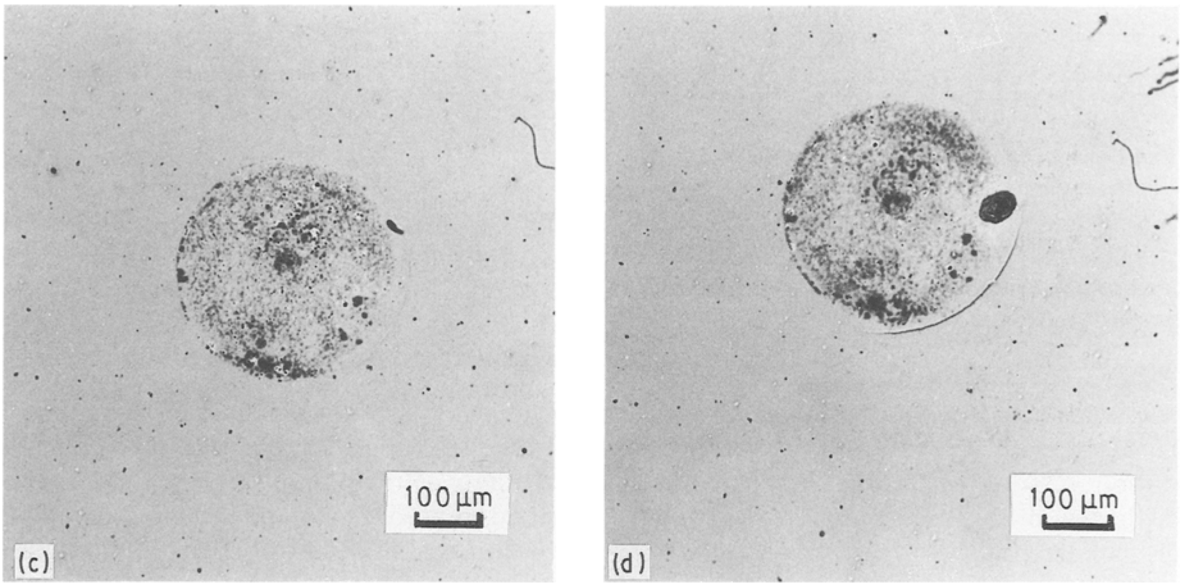


Figure 1 Continued.

when the modulus of the indenter and the Poisson's ratio of the two materials are known.

2. Experimental procedure

The following materials have been tested: soda–lime glass, two grades of Al_2O_3 (a cutting tool grade and a bioceramic grade), Si_3N_4 and SiC whisker-reinforced Al_2O_3. The indenter was a 2 mm diameter WC/6%Co ball with $E_1 = 614$ GPa and $\nu_1 = 0.22$. The indenter was attached to a universal testing machine (Instron 1361) and the indentation cycle was loading at 0.08 mm s^{-1}, holding at maximum load for 20 s and unloading at 0.08 mm s^{-1}. The specimens were diamond polished down to 1 µm and then the surface was sputter-coated with Au/Pd in a commercial SEM coating equipment. The indentation removed the coat ing in the contact zone and the size of this could be readily measured in an optical microscope.

The specimens were indented at loads from 10–1000 N for glass and from 10–1400 N for the ceramics in steps of 10 N, each time indenting an undamaged, coated area, resulting in more than 100 indents for each material. The size of the contact area as a function of indentation load was recorded. In addition, the load for initiation of various crack systems was recorded.

3. Results and discussion

Fig. 1a shows the contact area on the soda–lime glass sample at an indentation load of 310 N and Fig. 1b shows the contact area and ring cracks in soda–lime glass at an indentation load of 400 N. In Fig. 1c it is seen that a contact area in Si_3N_4 of comparable size to that in the glass is obtained at a load of 950 N, and partial ring cracks in Si_3N_4 do not occur until the load is close to 1000 N (Fig. 1d). From these micrographs it

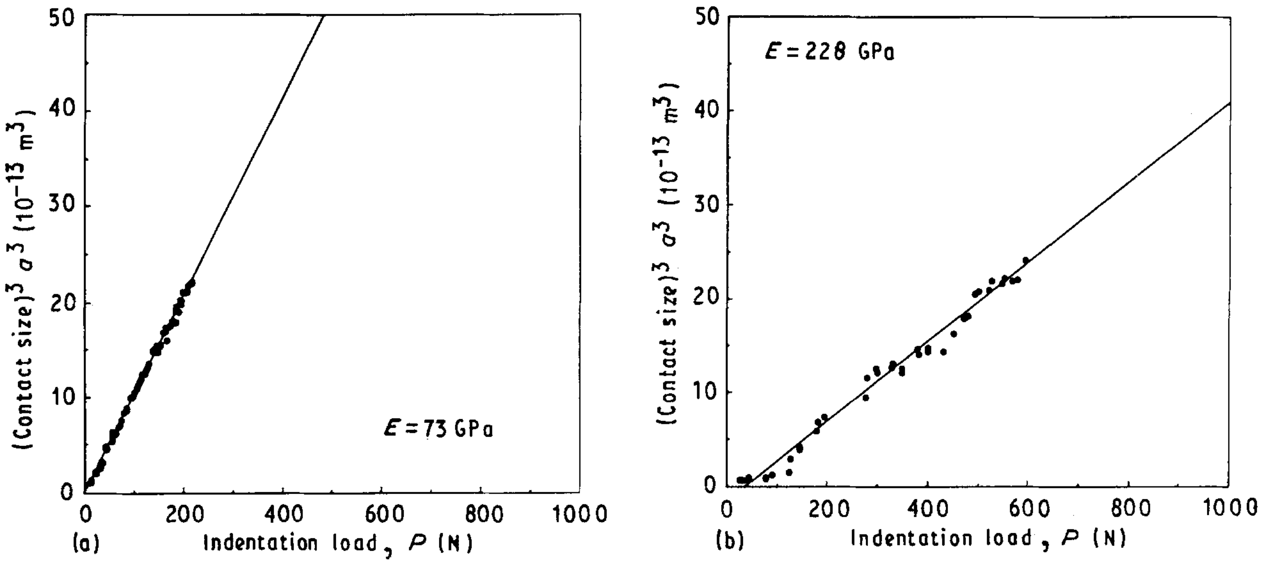
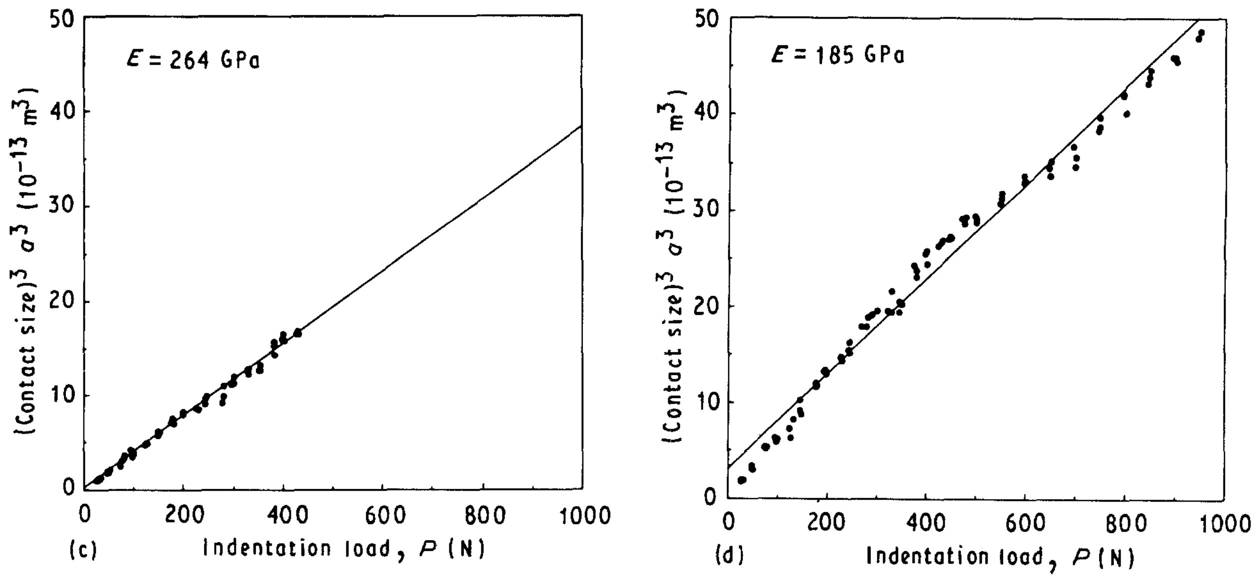


Figure 2 Radius of contact area as a function of indentation load in the elastic range. (a) Glass. (b) Al_2O_3 cutting tool grade. (c) Al_2O_3 bioceramic grade. (d) Si_3N_4. (e) $Al_2O_3/SiC_{whisker}$ measured on a plane parallel to the hot-pressing plane.



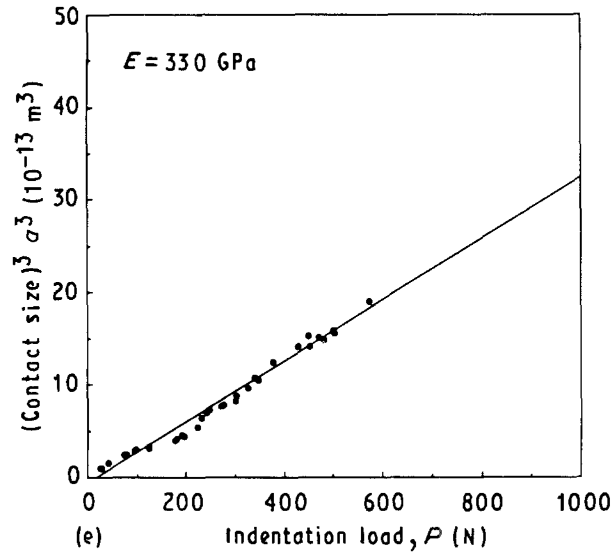


Figure 2 Continued

is seen that the contact area is well defined and easy to measure. The ring cracks occur at higher loads just outside the contact area and are of a size which agrees well with the theoretical stress analysis [4]. The results are summarized in Fig. 2a–e where the radius of the contact area, a, raised to the third power is plotted against the indentation load for load ranges where no cracking occurs. Regression of the data according to Equation 1 and using Equation 2 with $E_1 = 614$ GPa, $\nu_1 = 0.22$ and $\nu_2 = 0.25$, resulted in the values of elastic modulus given in Table I. Fig. 3a–e shows the size of the contact area over a wider load range, i.e. including the higher loads where various cracks occurred. These results show clearly that there is a change in the modulus after the initiation of the ring cracks, and in all the materials with the exception of the Si_3N_4 the cracked sample becomes more compliant than the uncracked material. It is worth noting that for Si_3N_4 the modulus changes well before any cracks are seen (Fig. 2d). The reason for this behaviour in Si_3N_4 is unknown at present, but it could be due to residual surface stresses or be an effect of the microstructure. The larger spread in the data at higher indentation loads reflects the fact that as the cracking increases,

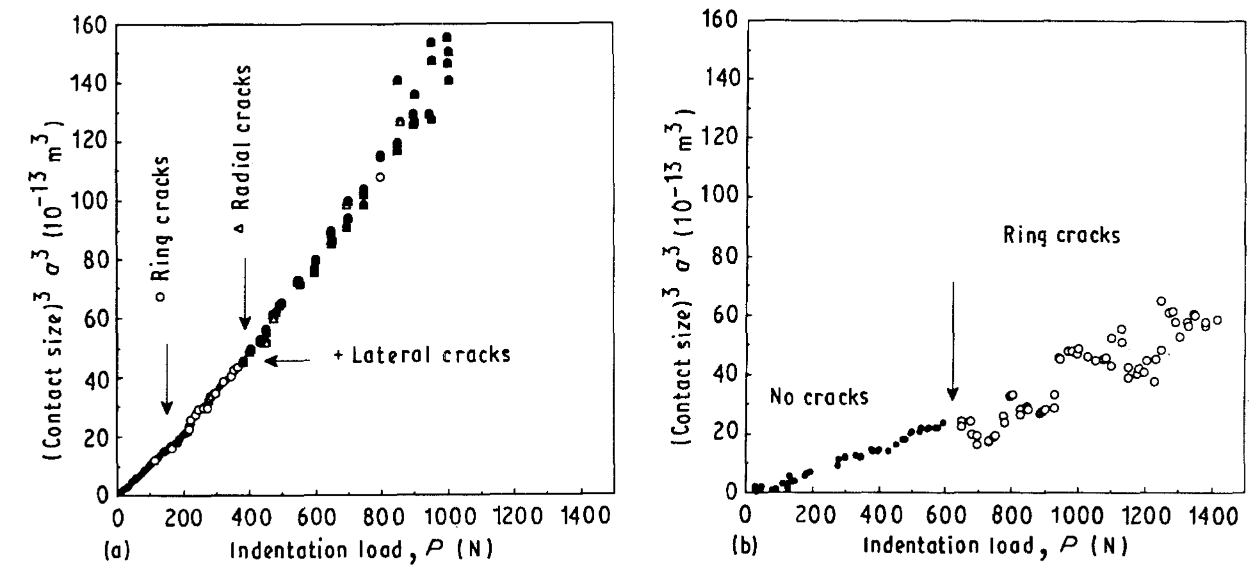
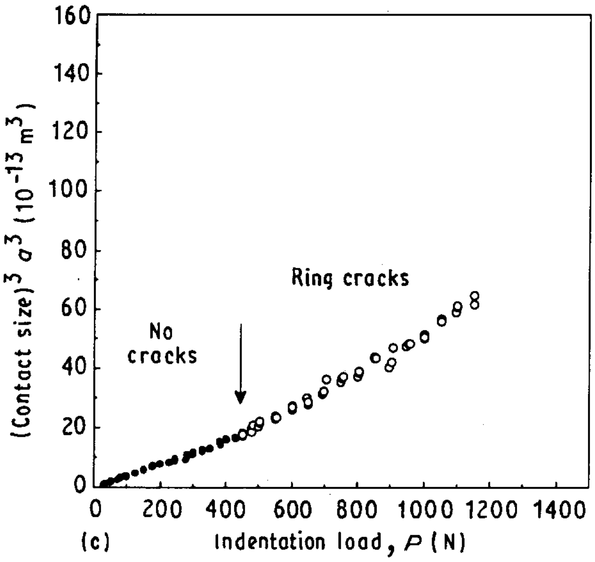
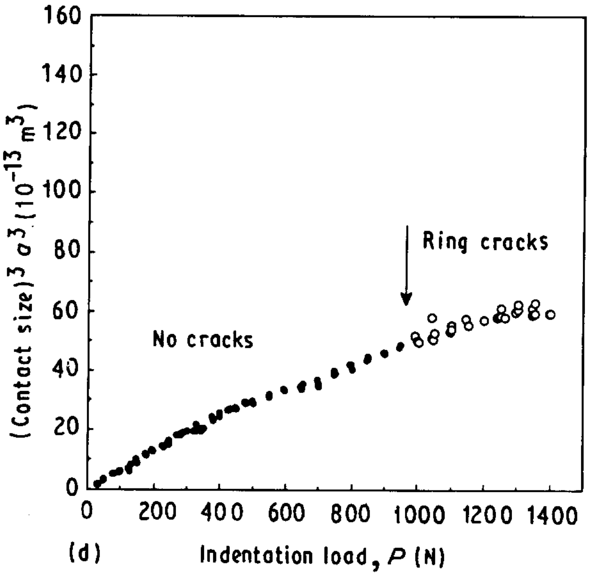


Figure 3 Radius of the contact area as a function of load with indication of the initiation of various crack systems. (a) Glass. (b) Al_2O_3 cutting tool grade. (c) Al_2O_3 bioceramic grade. (d) Si_3N_4. (e) $Al_2O_3/SiC_{whisker}$ measured on a plane parallel to the hot-pressing plane.





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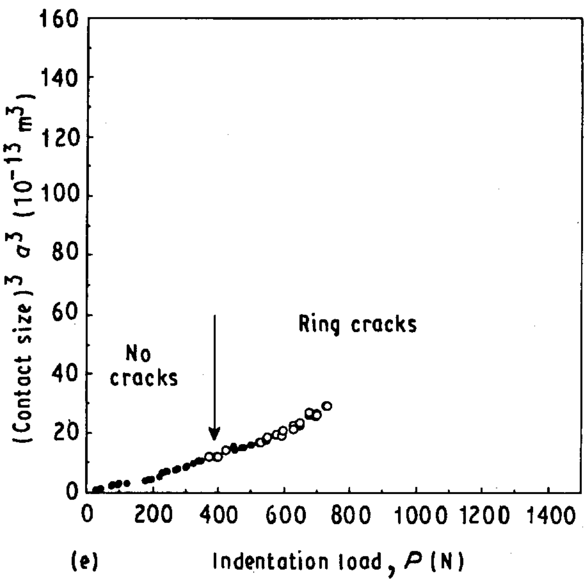

TABLE I Elastic modulus

Soda–lime glass	73 GPa
Al_2O_3 (cutting tool grade)	228 GPa
Al_2O_3 (bioceramic grade)	264 GPa
Si_3N_4 (sintered)	185 GPa
$Al_2O_3/SiC_{whiskers}$ // HP plane	330 GPa
$Al_2O_3/SiC_{whiskers}\perp$ HP plane	300 GPa

the contact area starts to overlap with the first ring crack, and it becomes difficult to determine the exact location of the edge of the contact zone. The results listed in Table I are in good agreement with values obtained by other methods [9–11], and as long as the indent is in the elastic range, i.e. no cracking has occurred, the method gives reproducible results. However, the method is only applicable to materials which exhibit elastic damage before any plastic deformation occurs. Experiments on WC–Co resulted in plastic deformation of the plate and then the given equations are not applicable.

4. Conclusions

We have shown that it is possible to determine the elastic modulus of hard, brittle materials by performing a Hertzian indentation experiment. The method is simple and only requires a well-polished sample with a thin sputtered metal coating and a hard spherical indenter. The results obtained are comparable to those obtained by other methods.

Acknowledgements

We thank Sandvik Hard Materials and Seco Tools for supplying the materials. This work has been supported by the Swedish National Board for Technical Development (STU) under grant no.8804286.

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Received 18 March
and accepted 1 July 1991