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Calculation of the ABI® Plastic Indentation Diameter from the Plastic Indentation Depth – An Innovation Feature of the Partial-Unloading Technique of the ABI® Test Method

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Accurate determination of the true-plastic-strain requires precise calculation of the plastic indentation diameter from the associated plastic indentation depth. The plastic depth depends on the elastic recovery and the amount of pile-up or sink-in behavior of the test material. Plastic indentation diameters calculated from the partial-unloadings of the ABI test show excellent comparison with optical measurements made on steel test blocks used in the 2003 Round Robin of the Automated Ball Indentation® or ABI test method. Examples of these results (using the last unloading cycle from two ABI tests on 4142 steel block), shown below in Table 1 and Figures 1-3, are evidence that the innovative procedure of using the partial unloading technique to calculate the plastic indentation diameters provides excellent agreement with the optical measurements for all indentation pile-up conditions of metallic materials.

\[ d_p = 3 \sqrt{\frac{(2.735PD)(4h_p^2 + d_p^2)}{E_r(4h_p^2 + d_p^2 - 4h_pD)}} \]  

(1)

Where \( d_p \) is the plastic indentation diameter, \( h_p \) is the indentation plastic depth, \( P \) is the indentation force, \( D \) is the indenter diameter, and \( E_r \) is the effective elastic modulus of the indenter and the test specimen.

Calculating the plastic indentation diameter (\( d_p \)) is based on Hertz’s equation. Equation (1) above is solved by iteration and can be expressed as a polynomial of degree five. This equation has three negative roots that have no physical meaning and two positive roots. One of the two positive roots represents a small diameter that lies within the ball indenter when submerged into the test specimen. Therefore the remaining fifth positive root accurately predicts the plastic indentation diameter from the plastic indentation depth as shown in Figures 1-3 below. The calculated final plastic diameters from two ABI tests on a 4142 steel specimen have less than 1.5% difference with those from the optical measurements shown in Table 1 and Figures 2 and 3. Values of the plastic indentation depth and associated plastic indentation diameter are shown in Columns 3 and 5 of Figure 1.

For further examples of ABI test data and results see Figure 4 and in Appendix X1 of the Haggag Tensile and Toughness Method (HTTM) (also known as ABI).

Table 1 Comparison between ABI-Calculated (using the innovative partial-unloading technique) and Optically-Measured (at 25X magnification) Plastic Indentation Diameter (\( d_p \)) using a 1.575-mm (\( D = 0.062 \)-in) diameter tungsten carbide indenter on a 4142 Steel sample of the ABI Round Robin

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Calculated Diameter (µm)</th>
<th>Measured Diameter (µm) 25X</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR-4142-62G-1</td>
<td>922</td>
<td>935</td>
<td>1.4</td>
</tr>
<tr>
<td>RR-4142-62G-2</td>
<td>935</td>
<td>945</td>
<td>1.1</td>
</tr>
</tbody>
</table>
ABI\textsuperscript{®} test results of these two tests show the detailed plastic diameter associated with each partial unloading cycle (Column No. 5). The final plastic indentation diameter associated with the last cycle (Number 10) is shown at the last raw of Column 5. Note that all partial elastic unloadings have excellent linearity as demonstrated by their regression values ($R^2$ should be very close to the theoretical value of 1.000) shown in column 10 of the two tables below (Figure 1) and Figures 2 and 3.

![ABI Analysis Results by Cycle](image)

Figure 1 ABI test results at two test locations of a 4142 steel specimen.
Figure 2 Test No. 1 (Test name: RR-4142-62G-1) on 4142 steel, 25X, ABI-Calculated Diameter is 922 μm. Average of two optical measurements is 935 μm.

Figure 3 Test No. 2 (Test Name: RR-62G-4142-2) on 4142 steel, 25X, ABI-Calculated Diameter is 935 μm. Average of two optical measurements is 945 μm.
Figure 4 Overlay of ABI force-depth data and true-stress/true-plastic-strain curves from the two ABI tests

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