UNIVERSAL HARDNESS TEST APPLIED TO SINTERED AND/OR SIZED BRONZE BEARINGS

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Abstract
A new test method for characterising metallic materials, the so-called Universal Hardness (or depth-sensing indentation) is shortly described. The method enables to determine various properties, in addition to hardness, such as Young modulus, or splitting between plastic and elastic deformation work during the test. It has been applied successfully to iron-base sintered materials. This report presents the results of tests carried out on self-lubricating bronze bearings, manufactured by two top class European producers. As already observed on P/M steels, a linear correspondence links “plastic hardness” and HV and the correlation between elasticity moduli (“true” or based on HU) is fairly good. The observed microstructures are regular. The results indicate that the method can be positively applied to P/M bronze.

Keywords: bronze, hardness, instrumented hardness, P/M bearings, properties

THE SO-CALLED UNIVERSAL HARDNESS; SOME RECALLS OF THE MAIN ASPECTS

According to H. E. Boyer [1]: “There is probably no word in the English language for which so many definitions from so many sources have been offered as the term “hardness”. … Within the scientific community, hardness also represents different concepts: to a metallurgist, it represents resistance to penetration; to a lubrication engineer it means resistance to wear, whereas it denotes a measure of flow stress to a design engineer, resistance to scratching to a mineralogist, and resistance to cutting to a machinist. Although these actions appear to differ greatly in character, they are all related to the plastic flow stress of the material”. Metals Handbook, [2], defines the hardness as “Resistance of metals to plastic deformation, usually by indentation. However, the term may also refer to stiffness or temper, or to resistance to scratching, abrasion or cutting. Indentation hardness may be measured by various hardness tests, such as Brinell, Rockwell and Vickers”. As everybody knows, the Vickers and Brinell tests require the optical measurement of the indentation, while the Rockwell tests require the measurement of the indentation depth, after load removal, and may be carried out in a completely automatic way. The possibility of automatic testing is really an advantage, but, unfortunately, the range of testing loads is inadequate to measurements localized or focused on very small and selected areas. These requirements may be satisfied by the Vickers test, which presents the advantage of a constant penetration angle, so that hardness results are nearly independent on the used load. The short comparison between Rockwell and Vickers tests points out to a new method, which should include the different advantages of automatic testing and numerical results not influenced by level of load. This optimum solution is now a reality, because it is now
possible to carry out tests of instrumented hardness, by means of new machines, suitable to measure and record, continuously, the acting force and the corresponding penetration depth. Some selected papers on the subject are reported as references [3,4,19].

The DIN Standard 50359 recites: "With the so-called universal hardness test, the hardness is measured while the test force is still being applied". Over the last twenty years, progress in force application, depth measurement and data registration techniques have made it possible to develop this method to the point where it can finally be put into practice. One advantage of this method is that the indentation depth is not visually evaluated, but is automatically measured. As opposed to other optical methods, the subjectivity of the observer is thus eliminated. The ranges of test forces are:

- from 2 N to 1000 N for "standard" hardness ("apparent" hardness for P/M materials);
- less than 2 N for microhardness.

It is interesting to note that the microhardness range fits well to PM materials engineered for mechanical components and self-lubricating applications. For long time, repeated experiences demonstrated that the maximum load required excluding any influence of material porosity is between 1 and 2 N. The universal hardness value, HU, is given by the ratio of the test force, F, to the area A(h), which is the idealized sloping area of the indentation under the applied test force (see Tab.1). The typical course of load versus indentation depth during a test of universal hardness is plotted in Fig.1. Figure 2 shows the course of recorded data, versus time, when the test is carried out at constant force. An analogous scheme may be used to record data, always as a function of time, when the test is carried out at constant indentation depth. The DIN Standard requires also a minimum level of surface preparation, which depends on test load: to ensure that the surface roughness does not cause the actual uncertainty of measurement to exceed the limit of 10%.

Tab.1. Symbols and quantities.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Angle between opposite faces at vertex of pyramid indenter (136°)</td>
<td>°</td>
</tr>
<tr>
<td>F</td>
<td>Test force</td>
<td>N</td>
</tr>
<tr>
<td>h</td>
<td>Indentation depth while force is being applied</td>
<td>mm</td>
</tr>
<tr>
<td>HU</td>
<td>Universal hardness</td>
<td>N/mm²</td>
</tr>
</tbody>
</table>

\[
HU = \frac{F}{A(h)} = \frac{F}{26.43 \cdot \frac{h^2}{h^2}} \quad (1) \quad A(h) = \frac{4 \sin \left( \frac{\alpha}{2} \right)}{\cos^2 \left( \frac{\alpha}{2} \right)} \quad h^2 = 26.43 \cdot h^2 \quad (2)
\]

Plastic and elastic contributions to indentation work

The mechanical work produced during indentation, \(W_{\text{total}}\), is only partially consumed as plastic deformation work, \(W_{\text{plast}}\). The remainder is released as the work of elastic recovery, \(W_{\text{elast}}\). Taking into consideration the definition of mechanical work as \(W = \int Fdh\), these two contributions are represented by the two areas shown in Fig.3. The total work spent during the period of load increase is \(W_{\text{total}}\). Figure 3 shows that it is

\[
W_{\text{total}} = W_{\text{elast}} + W_{\text{plast}} \quad (3)
\]

Equation (3) contains information that allows a further characterisation of the tested material. It enables to separate two.
Fig. 1. Typical course of load versus indentation depth during a universal hardness test.

1. Increasing test force
2. Maximum test force maintained
3. Removal of test force
4. Zero test force
5. Increasing indentation depth
6. Maximum indentation depth maintained
7. Decreasing indentation depth
8. Creep under maximum test force
9. Creep at zero test force
10. Relaxation at maximum indentation depth

Fig. 2. Schematic representation of testing with controlled force, as a function of time contributions, one elastic and the other plastic given, respectively, by the expressions

\[
\eta_{HU} = \frac{W_{elast}}{W_{elast} + W_{plast}} \times 100 = \frac{W_{elast}}{W_{total}} \times 100[\%] \tag{4}
\]

\[
\eta_{plast} = \frac{W_{plast}}{W_{elast} + W_{plast}} \times 100 = \frac{W_{plast}}{W_{total}} \times 100[\%] \tag{5}
\]

Of course, it is also

\[
W_{plast} = W_{total} \left(1 - \frac{\eta_{HU}}{100}\right) \tag{6}
\]
Plastic hardness

Still according to DIN Standard 50359, plastic hardness is given by the ratio of the test force to an area calculated by extrapolation, as indicated in Fig.4:

\[ HU_{\text{plast}} = \frac{F_{\text{max}}}{26.43 \cdot h_{0}^2} \]  

(7)

where \( h_{0} \) [mm], is the point of intersection of the tangent of the curve at maximum force (at removal of test force) and the indentation depth axis (x-axis). A strong correlation between a plastic hardness value of \( HU_{\text{plast}} \), measured at 1 N load, and a Vickers microhardness \( HV_{0.1} \) has been observed on fully dense steels. It may be interesting to point out the formal analogy between the common expressions of Vickers hardness,

\[ HV = 2 \cdot F_{\text{max}} \cdot \sin\left(\frac{\alpha}{2}\right) = 1.8544 \cdot \frac{F_{\text{max}}}{d^2} \left[ \frac{kg}{mm^2} \right] \]  

or \[ \left[ \frac{N}{mm^2} \right] \]  

(8)

where \( d \) is the diagonal of the projected indentation area, and the expression of the plastic hardness. If we assume that the indentation geometry is perfect, it is \( d = 7.0006 \cdot h \), and the last equation can be transformed and made equal to (8).

Fig.3. Plastic and elastic contributions to indentation work.  
Fig.4. Determining plastic hardness and indentation modulus. The dashed line is the tangent to the curve of decreasing test load.

Indentation modulus

DIN Standard 50359 [3] states that: “The modulus of elasticity (Young’s modulus) for the indentation, \( Y_{HU} \), can be calculated from the slope of the tangent used to determine plastic hardness”, as shown in Fig.4. The indentation modulus is comparable to Young’s modulus for the material under test.

\[ Y_{HU} = \frac{1}{4 \cdot \tan\left(\frac{\alpha}{2}\right) \cdot h_{0} \cdot \frac{\Delta h}{\Delta F(h_{\text{max}})} \cdot (1 - v_{\text{dia}})} = \frac{1}{5.586 \cdot h_{0} \cdot \frac{\Delta h}{\Delta F(h_{\text{max}})} - 7.813 \cdot 10^{-7}} \]  

(9)

where: \( h_{0} \) is the point of intersection of the tangent of the curve at maximum force (at removal of test force) and the indentation depth axis (x-axis), in mm; \( \Delta h/\Delta F(h_{\text{max}}) \) is the reciprocal slope of
the tangent to the curve at maximum force (at removal of test force), in mm/N; \( \nu_{\text{dia}} \) is the Poisson’s ratio for diamond (0.25); \( E_{\text{dia}} \) is the Young’s modulus for diamond (1.2 MN/mm\(^2\)).

The literature reports the theoretical rationale of formula (9), and defines the overall (or system) modulus:

\[
E^* = \frac{1 - \nu^2}{E} + \frac{1 - \nu_w^2}{E_w} = \frac{1}{K} \left( \frac{dF}{dh} \right)^{\nu^2}
\]

(10)

APPLICATION OF THE METHOD TO SELF-LUBRICATING BRONZE BEARINGS

The universal hardness has been used with success to characterise iron-base sintered materials [17,18,19]. To proceed along a research line aimed at discovering the possible advantages of universal hardness applied to different sintered materials, also bronze has been investigated. The samples for this part of the research, self-lubricating bearings of current production, have been supplied by two of the top producers in Europe, that will be simply referred as A and B. It is common knowledge that the precision required by the applications implies a sizing operation, a sort of “controlled repressing” inside rigid tools. Sizing causes an extended plastic deformation, with work hardening involving the whole part.

Usually, the reduction of volume (and the corresponding density increase) ranges between 5 and 15%. On this ground, to unveil the effect of notable plastic deformation, the investigation has been carried out on:

- only sintered bearings,
- sintered and sized bearings (before oil-impregnation).

Several bodies have issued specifications on properties of materials for self-lubrication applications. The Standards most frequently applied are: ISO 5755 [20], MPIF St 35 [21], and ASTM B 438 [22]. Geometrical and physical data observed on various bearings are collected in table II, while the results of universal hardness test are collected in tab.3. Each value is the average from 7 measurements. Nearly in all cases, the standard deviation has been lower than one tenth of the average value.

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Ref.</th>
<th>State</th>
<th>d mm</th>
<th>D mm</th>
<th>D sphere mm</th>
<th>D flange mm</th>
<th>h mm</th>
<th>density g/cm(^3)</th>
<th>r.c.s.* MPa</th>
<th>HV5</th>
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<tbody>
<tr>
<td>A</td>
<td>1A</td>
<td>sized</td>
<td>10.07</td>
<td>12.030</td>
<td>-</td>
<td>-</td>
<td>9.41</td>
<td>7.35</td>
<td>300</td>
<td>73</td>
</tr>
<tr>
<td>A</td>
<td>2A</td>
<td>sintered</td>
<td>10.08</td>
<td>12.030</td>
<td>-</td>
<td>14.048</td>
<td>7.52</td>
<td>6.35</td>
<td>n.d.</td>
<td>58</td>
</tr>
<tr>
<td>A</td>
<td>3A</td>
<td>sintered</td>
<td>20.01</td>
<td>24.038</td>
<td>-</td>
<td>-</td>
<td>4.74</td>
<td>7.00</td>
<td>270</td>
<td>52</td>
</tr>
<tr>
<td>A</td>
<td>4A</td>
<td>sintered</td>
<td>7.00</td>
<td>10.055</td>
<td>-</td>
<td>-</td>
<td>6.52</td>
<td>6.25</td>
<td>240</td>
<td>42</td>
</tr>
<tr>
<td>A</td>
<td>5A</td>
<td>sized</td>
<td>7.02</td>
<td>10.035</td>
<td>-</td>
<td>-</td>
<td>6.34</td>
<td>6.55</td>
<td>255</td>
<td>43</td>
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<tr>
<td>B</td>
<td>1B</td>
<td>sintered</td>
<td>12.08</td>
<td>15.005</td>
<td>-</td>
<td>-</td>
<td>12.62</td>
<td>6.25</td>
<td>145</td>
<td>47</td>
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<tr>
<td>B</td>
<td>2B</td>
<td>sized</td>
<td>12.08</td>
<td>15.034</td>
<td>-</td>
<td>-</td>
<td>11.91</td>
<td>6.60</td>
<td>180</td>
<td>54</td>
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<td>3B</td>
<td>sintered</td>
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<td>6.010</td>
<td>-</td>
<td>-</td>
<td>8.45</td>
<td>6.60</td>
<td>205</td>
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<td>4B</td>
<td>sized</td>
<td>2.54</td>
<td>6.020</td>
<td>-</td>
<td>-</td>
<td>7.97</td>
<td>7.00</td>
<td>245</td>
<td>45</td>
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<td>11.607</td>
<td>12.232</td>
<td>-</td>
<td>8.53</td>
<td>6.00</td>
<td>n.d.</td>
<td>36</td>
</tr>
<tr>
<td>B</td>
<td>7B</td>
<td>sintered</td>
<td>4.08</td>
<td>10.910</td>
<td>-</td>
<td>-</td>
<td>6.32</td>
<td>6.65</td>
<td>175</td>
<td>35</td>
</tr>
<tr>
<td>B</td>
<td>8B</td>
<td>sized</td>
<td>4.03</td>
<td>10.825</td>
<td>-</td>
<td>-</td>
<td>6.03</td>
<td>7.00</td>
<td>200</td>
<td>42</td>
</tr>
</tbody>
</table>

*radial crushing strength
Tab.3. Results from universal hardness test.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>State</th>
<th>HU N/mm²</th>
<th>HUثلست N/mm²</th>
<th>YHU kN/mm²</th>
<th>Wₜ₀₈ Nmm</th>
<th>Wثلست Nmm</th>
<th>η W %</th>
<th>m(hr) kN/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>sized</td>
<td>623</td>
<td>719</td>
<td>47.2</td>
<td>0.896</td>
<td>0.072</td>
<td>8.09</td>
<td>12.91</td>
</tr>
<tr>
<td>2A</td>
<td>sintered</td>
<td>496</td>
<td>561</td>
<td>42.8</td>
<td>1.006</td>
<td>0.063</td>
<td>6.24</td>
<td>13.27</td>
</tr>
<tr>
<td>3A</td>
<td>sized</td>
<td>406</td>
<td>475</td>
<td>38.4</td>
<td>1.122</td>
<td>0.089</td>
<td>7.90</td>
<td>14.47</td>
</tr>
<tr>
<td>4A</td>
<td>sintered</td>
<td>354</td>
<td>391</td>
<td>36.7</td>
<td>1.186</td>
<td>0.049</td>
<td>4.11</td>
<td>13.75</td>
</tr>
<tr>
<td>5A</td>
<td>sized</td>
<td>364</td>
<td>397</td>
<td>42.4</td>
<td>1.171</td>
<td>0.030</td>
<td>2.58</td>
<td>15.63</td>
</tr>
<tr>
<td>1B</td>
<td>sintered</td>
<td>405</td>
<td>449</td>
<td>40.6</td>
<td>1.096</td>
<td>0.048</td>
<td>4.41</td>
<td>14.14</td>
</tr>
<tr>
<td>2B</td>
<td>sized</td>
<td>462</td>
<td>517</td>
<td>43.1</td>
<td>1.028</td>
<td>0.056</td>
<td>5.46</td>
<td>13.93</td>
</tr>
<tr>
<td>3B</td>
<td>sintered</td>
<td>361</td>
<td>396</td>
<td>40.0</td>
<td>1.193</td>
<td>0.042</td>
<td>3.50</td>
<td>14.82</td>
</tr>
<tr>
<td>4B</td>
<td>sized</td>
<td>386</td>
<td>424</td>
<td>42.0</td>
<td>1.150</td>
<td>0.047</td>
<td>4.04</td>
<td>15.03</td>
</tr>
<tr>
<td>5B</td>
<td>sintered</td>
<td>306</td>
<td>335</td>
<td>33.9</td>
<td>1.247</td>
<td>0.040</td>
<td>3.23</td>
<td>13.72</td>
</tr>
<tr>
<td>6B</td>
<td>sized</td>
<td>337</td>
<td>372</td>
<td>35.1</td>
<td>1.178</td>
<td>0.050</td>
<td>4.26</td>
<td>13.49</td>
</tr>
<tr>
<td>7B</td>
<td>sintered</td>
<td>304</td>
<td>330</td>
<td>37.3</td>
<td>1.288</td>
<td>0.028</td>
<td>2.14</td>
<td>15.15</td>
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<tr>
<td>8B</td>
<td>sized</td>
<td>356</td>
<td>390</td>
<td>40.1</td>
<td>1.166</td>
<td>0.034</td>
<td>2.90</td>
<td>14.99</td>
</tr>
</tbody>
</table>

Fig.5. Correspondence between HUثلست and HV, with regression equation and correlation coefficient.

The plot of HUثلست versus HV5, both in kg/mm², is presented in Fig.5. A straight line, which does not pass on the intersection between x-axis and y-axis, expresses the correspondence between the two quantities; the correlation index is very high, confirming the equivalence of indications from both the investigated scales. An analogous result was achieved on P/M steels [18]. Remembering that cylindrical bearings are located into their housing by shrink fitting, or by forced assembling, it is interesting to observe the values of Υ, proportional to the Young modulus. Design engineers involved in calculation of shrink fitting know that the modulus of elasticity, which characterise the rigidity (or “stiffness”) of a material, is a key parameter when establishing the safe interference. The data reported by the literature on fully dense bronze (Cu/Sn, 90/10) are:

- density: 8.8 g/cm³
modulus of elasticity: 90 kN/mm$^2$.

From the data, by the well-known formula

$$E_s = E_0 \cdot \rho^{3.4}$$

it has been possible to determine a reliable evaluation on the influence of density on the Young modulus of sintered bronze. For comparison, the values of $Y$ from universal hardness (on sized materials) and the curve of $E$ versus density are plotted in Fig.6.

It is interesting to observe that:

- the course of experimental results tendentially agrees with the curve based on technical literature;
- the two points more faraway from the curve (densities 6.55 and 6.60 g/cm$^3$) have been measured on the samples presenting the highest sizing ratio, given by the ratio between density after sizing and density before sizing.

### TYPICAL MICROSTRUCTURES

To complete the investigation, metallographic probes obtained from the various samples have been observed at the light optical microscope (LOM). Due to the importance of porosity pattern on self-lubricating properties, the probes have been observed also immediately after polishing, that is before etching. The results of LOM observations are plotted in Figs.7, 8, ..., 12. In both cases the pore distributions appear regular, with clear evidence of some surface densification caused by correct sizing. The distribution of pore size detectable on bearing from B seems bimodal, in both cases the pore rounding is at a typical stage of the so-called intermediate sintering, which is typical of most industrial products where a highly interconnected porosity, aimed at high internal permeability, is a basic functional property, as self-lubrication.

After etching in a solution of ferrous chloride, homogeneous alpha phase can be observed with the presence of twins, especially in the sized samples. Non-diffused tin residuals haven't been observed. There is no evidence of copper-tin intermetallic compounds in the microstructure. At higher magnification and occasionally there is some evidence of the prior-particle boundaries.

Fig.7. Porosity on sized bronze from A. 6.55 g/cm$^3$.
Fig.8. Porosity at the core of sized bronze from A.
Fig.9. Microstructure after etching of sized bronze from A.
CONCLUDING REMARKS

The experimental research showed that universal hardness testing (or “depth-sensing indentation”) can be successfully applied to sintered bronze bearings produced by highly qualified manufacturers. Also for this class of materials the method enables to get $Y_{HU}$, very next to Young modulus. The plot of experimental values presents a quite good correlation with the values achievable using a formula valid – on the average – for porous materials. It should be observed that the modulus of elasticity is a key quantity to set the correct interference between a cylindrical bearing and the corresponding housing. Some anomalies, if confirmed on larger size samples, should be adequately depthened, to avoid operating problems coming from weak fitting. At the end, it should be mentioned a very recent paper of Sanderow and Pease [23], on the same topic. Also our results, at least for bearings from supplier B, indicate a radial crushing strength lower than the minimum requested by MPIF standard, but fulfilling ISO 5755 standard. This point opens two possible lines for further investigations:
1. why different standards present so big differences?
2. for reliable operation of cylindrical bearings, with well developed porosity, is the radial crushing strength a really significant parameter to be measured?

REFERENCES
[10] Venkatesh, TA., Van Vliet, KJ., Giannakopoulos, AE., Suresh S.: Scripta Materialia,
vol. 42, 2000, p. 833