Hardness Test

Subjects of interest

• Introduction/objectives
• Brinell hardness
• Meyer hardness
• Vickers hardness
• Rockwell hardness
• Microhardness tests
• Relationship between hardness and the flow curve
• Hardness-conversion relationships
• Hardness at elevated temperatures
Objectives

• This chapter provides fundamental knowledge of hardness of materials along with different methods of hardness measurements normally used.

• Relationships between hardness and tensile properties will be made and finally factors affecting hardness of metals will be discussed.
Introduction

**Definition**

*Hardness is a resistance to deformation.*

(for people who are concerned with mechanics of materials, hardness is more likely to mean the resistance to indentation)

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**Hardness impression**

Deeper or larger impression

Softer materials
Introduction

There are three general types of hardness measurements

1) Scratch hardness
   • The ability of material to scratch on one another
   • Important to mineralogists, using Mohs’ scale: 1 = talc, 10 = diamond
   • Not suited for metal → annealed copper = 3, martensite = 7.

2) Indentation hardness
   • Major important engineering interest for metals.
   • Different types: Brinell, Meyer, Vickers, Rockwell hardness tests.

3) Rebound or Dynamic hardness
   • The indentor is dropped onto the metal surface and the hardness is expressed as the energy of impact.
Introductions

- Hardness tests can be used for many engineering applications to achieve the basic requirement of mechanical property.

- **For examples**
  - surface treatments where surface hardness has been much improved.
  - Powder metallurgy
  - Fabricated parts: forgings, rolled plates, extrusions, machined parts.

[Image of a nitrided part]

[Graph showing hardness variation of nitrided part]

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Brinell hardness

- **J.A. Brinell** introduced the *first standardised indentation-hardness* test in 1900. The **Brinell hardness test** consists in indenting the metal surface with a **10-mm diameter steel ball** at a load range of 500-3000 kg, depending on hardness of particular materials.

- The load is applied for a standard time (~30 s), and the **diameter of the indentation is measured**. → giving an average value of two readings of the diameter of the indentation at right angle.

- The **Brinell hardness number (BHN or H_B)** is expressed as the load **P** divided by surface area of the indentation.

\[
BHN = \frac{P}{\left(\pi D / 2\right)\left(D - \sqrt{D^2 - d^2}\right)} = \frac{P}{\pi D t}
\]  

Eq.1

Where  
- **P** is applied load, kg  
- **D** is diameter of ball, mm  
- **d** is diameter of indentation, mm  
- **t** is depth of the impression, mm

Unit kgf.mm⁻² = 9.8 MPa
Advantages and disadvantages of Brinell hardness test

• Large indentation averages out local heterogeneities of microstructure.

• Different loads are used to cover a wide rage of hardness of commercial metals.

• Brinell hardness test is less influenced by surface scratches and roughness than other hardness tests.

• The test has limitations on small specimens or in critically stressed parts where indentation could be a possible site of failure.

Brinell hardness impression

\[
HB = \frac{2F}{\pi D (D - \sqrt{D^2 - d^2})}
\]
Brinell hardness test with nonstandard load or ball diameter

• From fig, \( d = D \sin \phi \), giving the alternative expression of Brinell hardness number as

\[
BHN = \frac{P}{(\pi / 2)D^2 (1 - \cos \phi)} \quad \text{Eq. 2}
\]

• In order to obtain the same \( BHN \) with a non-standard load or ball diameter, it is necessary to produce a geometrical similar indentations.

• The included angle \( 2\phi \) should remain constant and the load and the ball diameter must be varied in the ratio

\[
\frac{P_1}{D_1^2} = \frac{P_2}{D_2^2} = \frac{P_3}{D_3^2} \quad \text{Eq. 3}
\]

Basic parameter in Brinell test
• **Meyer** suggested that hardness should be expressed in terms of the *mean pressure between the surface of the indenter and the indentation*, which is equal to the load divided by the projected area of the indentation.

\[
\frac{P}{\pi r^2} \quad \text{Eq. 4}
\]

• **Meyer hardness** is therefore expressed as follows;

\[
\text{Meyer hardness} = \frac{4P}{\pi d^2} \quad \text{Eq. 5}
\]

**Note:**
- Meyer hardness is less sensitive to the applied load than Brinell hardness.
- Meyer hardness is a more fundamental measure of indentation hardness but it is rarely used for practical hardness measurement.
Vickers hardness

- **Vickers hardness test** uses a *square-base diamond pyramid* as the indenter with the included angle between opposite faces of the pyramid of 136°.

- The **Vickers hardness number** (*VHN*) is defined as the load divided by the surface area of the indentation.

\[
VHN = \frac{2P \sin(\theta/2)}{L^2} = \frac{1.854P}{L^2}
\]

Note: not widely used for routine check due to a slower process and requires careful surface preparation.

Where

- \( P \) is the applied load, kg
- \( L \) is the average length of diagonals, mm
- \( \theta \) is the angle between opposite faces of diamond = 136°.

**Note**: the unit can be VHN, DPH, H_

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Vickers hardness

- **Vickers hardness test** uses the loads ranging from 1-120 kgf, applied for between 10 and 15 seconds.
- Provide a fairly **wide acceptance for research work** because it provides a continuous scale of hardness, for a given load.
- **VHN = 5-1,500** can be obtained at the same load level → **easy for comparison**.
Impressions made by Vickers hardness

- **A perfect square indentation (a)** made with a perfect diamond-pyramid indenter would be a *square*.

- **The pincushion indentation (b)** is the result of sinking in of the metal around the flat faces of the pyramid. This gives an overestimate of the diagonal length (observed in *annealed metals*).

- **The barrel-shaped indentation (c)** is found in *cold-worked metals*, resulting from ridging or piling up of the metal around the faces of the indenter. Produce a low value of contact area → *giving too high value*.
Vickers hardness values of materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>$H_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin</td>
<td>5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>25</td>
</tr>
<tr>
<td>Gold</td>
<td>35</td>
</tr>
<tr>
<td>Copper</td>
<td>40</td>
</tr>
<tr>
<td>Iron</td>
<td>80</td>
</tr>
<tr>
<td>Mild steel</td>
<td>230</td>
</tr>
<tr>
<td>Full hard steel</td>
<td>1000</td>
</tr>
<tr>
<td>Tungsten carbide</td>
<td>2500</td>
</tr>
</tbody>
</table>

http://www.brycoat.com/hardness.htm
Rockwell hardness

- The most widely used hardness test in the US and generally accepted due to:
  1) Its speed
  2) Freedom from personal error.
  3) Ability to distinguish small hardness difference
  4) Small size of indentation.

- The hardness is measured according to the depth of indentation, under a constant load.
**Rockwell hardness test**

**Principal of the Rockwell Test**

- Position the surface area to be measured close to the indenter.
- Applied the *minor load* and a zero reference position is established.
- The *major load* is applied for a specified time period (dwell time) beyond zero.
- The *major load* is released leaving the minor load applied.

The dial contains 100 divisions, each division representing a penetration of 0.002 mm.

![Diagram of Rockwell hardness test]

The Rockwell number represents the difference in depth from the zero reference position as a result of the applied major load.
Rockwell hardness scale

- **Rockwell hardness number (RHN)** represents in different scale, A, B, C,... depending on types of indenters and major loads used.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Indenter</th>
<th>Load (kg.f)</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Brale</td>
<td>60</td>
<td>HRA</td>
</tr>
<tr>
<td>B</td>
<td>1/16” steel ball</td>
<td>100</td>
<td>HRB</td>
</tr>
<tr>
<td>C</td>
<td>Brale</td>
<td>150</td>
<td>HRC</td>
</tr>
</tbody>
</table>

EX: The scale is usable for materials from annealed brass to cemented carbides. Other scales are available for special purposes.

- The Hardened steel is tested on the **C scale** with \( R_c 20-70 \).
- Softer materials are tested on the **B scale** with \( R_b 30-100 \).
Rockwell hardness instruction

• Cleaned and well seated indenter and anvil.
• Surface which is clean and dry, smooth and free from oxide.
• **Flat surface**, which is perpendicular to the indenter.
• Cylindrical surface gives **low readings**, depending on the curvature.
• **Thickness** should be 10 times higher that the depth of the indenter.
• The **spacing between the indentations** should be 3 or 5 times the diameter of the indentation.
• **Loading speed** should be standardised.
Microhardness

• Determination of hardness over very small areas for example individual constituents, phases, requires hardness testing machines in micro or sub-micro scales.

• Vickers hardness can also be measured in a microscale, which is based on the same fundamental method as in a macroscale.

• The Knoop indenter (diamond-shape) is used for measuring in a small area, such as at the cross section of the heat-treated metal surface.

• The Knoop hardness number (KHN) is the applied load divided by the unrecovered projected area of the indentation.

\[
KHN = \frac{P}{A_p} = \frac{P}{L^2 C}
\]

Where

- \( P \) = applied load, kg
- \( A_p \) = unrecovered projected area of indentation, mm\(^2\)
- \( L \) = length of long diagonal, mm
- \( C \) = a constant for each indenter supplied by manufacturer.

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Plastic zone underneath an indenter

- The **plastic zone** underneath a **harness indentation** is surrounded with elastic material, which acts to **hinder plastic flow**.
- The material surrounding the deformed zone is rigid and **upward flow** of material compensates for the material displaced by the punch.
- The **compressive stress** required to cause **plastic flow** in the hardness test > that in the simple compression due to this **constraint**.
Relationship between hardness and the flow curve

- Tabor suggested a method by which the plastic region of the true stress-strain curve may be determined from indentation hardness measurement.

- This is under a condition such that the true strain was proportional to the $d/D$ ratio ($\varepsilon = 0.2d/D$).

\[ \sigma_o = \frac{VHN}{3}(0.1)^n \]  

Eq.8

Where $\sigma_o$ is the 0.2% offset yield strength, kgf.mm\(^{-2}\)(=9.81 MPa)

$VHN$ is the Vickers hardness number

$n$ is the work hardening exponent.
Relationship between hardness and the flow curve

• For Brinell hardness, a very useful correlation has been used for heat-treated plain-carbon and medium-alloy steels as follows:

\[ UTS(MPa) = 3.4(BHN) \]

Eq.9

• Furthermore, Young’s modulus can also be given from the nano-hardness test.
Hardness conversion relationships

- Hardness conversions are *empirical relationships* for Brinell, Rockwell and Vickers hardness values.
- This hardness conversions are applicable to heat-treated carbon and alloy steels in many heat treatment conditions. (or alloys with similar elastic moduli).
- For *soft metals*, indentation of hardness depends on the strain hardening behaviour of the materials.
- Special hardness-conversion tables for cold-worked aluminium, copper, and 18-8 stainless steel are given in the *ASM Metals Handbook*.
**Hardness at elevated temperatures**

- **Hot hardness** gives a good indication of potential usefulness of an alloy for *high-temperature strength applications*.
- Hot hardness testers use a **Vickers indenter** made of sapphire and with provisions for testing in either vacuum or an inert atmosphere.
- The temperature dependence of hardness could be expressed as follows;

\[ H = Ae^{-BT} \]

*Eq. 10*

Where  
- \( H \) = hardness, kgf.mm\(^{-2} \)  
- \( T \) = test temperature, K  
- \( A, B \) = constants
Hardness at elevated temperatures

Log H VS temperature curve provides two slopes, having the turning point about one-half of the melting point of the material.

- BCC metals are softer in an allotropic transformation where FCC and HCP metals have approximately the same strength.

Temperature dependence of the hardness of copper
References