Hardenability

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TMS / UDC / CWRU
Hardenability

• Hardenability – Ability to form martensite
  – A measure of the steel to be hardened when quenched from its austenitizing temperature
• Steels with high hardenability can form martensite with slower cooling rates
  – Measured as the depth at which martensite forms from the surface
• Hardenability is **NOT** hardness
  – Hardness = resistance to indentation
Hardenability Factors

• Function of:
  – Austenite grain size: grain size ↑, hardenability ↑
  – Alloying elements: alloying ↑, hardenability ↑

• Mechanism for austenite grain size:
  – Pearlite formation starts at austenite grain boundaries
  – Fewer grain boundaries = fewer pearlite nucleation sites
  – Easier to form martensite
  – Using austenite grain size to control hardenability is a poor practice

• Mechanism for alloying elements:
  – Solute atoms slow down diffusion-controlled processes (pearlite formation).
  – Different size atoms hinder diffusion.
Hardenability Calculations

- Alloying elements are not harder, but improve hardenability.
- Carbon in steel controls hardness and hardenability.
- Alloying elements control amount of martensite and how deep into a component martensite forms.
- Alloying improves $M_S$ and $M_F$ temperatures.
Exceptions to Alloying for Hardenability

• S = reduces hardenability by removing Mn from solution, forming MnS stringers
• Ti = reduces hardenability by removing C from solution, forming TiC
• Co = reduces hardenability by increasing nucleation rate of pearlite
Hardenability Calculations

- Grossman Method
- Jominy Method (ASTM A255)
Hardenability Calculations

Jominy Quench
Hardenability Calculations

Hardenability Calculations

- **Grossman Method**
  - Selecting a ‘reasonable’ steel
  - Obtain bars with 0.5 – 2.5 inch diameter
  - Austenitize, Q&T at various rates
  - Analyze microstructures
  - Determine critical diameter for minimum (50%) martensite at core
Hardenability Calculations

Grossman Method Variables
1. Determine “Ideal Diameter” (theoretical) based on grain size and composition
2. Determine an “Ideal Critical Diameter” (theoretical) based on alloy elements
   - Infinitely fast quench = an ‘ideal’ quench
   - Ideal diameter = maximum diameter a rod will have 50% martensite in the core when quenched ideally
3. Quench rate: water > oil > air (agitated > still)
   - Perfect quench: $H = \infty$
   - Still Oil: $H = 0.25$
   - Agitated Oil: $H = 0.50$
Hardenability Calculations

• Ideal diameter ($D_i$)
  – The maximum diameter of a rod where 50% of the core is martensite when quenched in an ideal quenchant

• Critical diameter ($D_c$)
  – The maximum diameter where a bar contains 50% martensite / 50% pearlite upon quenching
  – Can determine $D_i$ from $D_c$
  – High hardenability = High $D_c$
Di from %C and Grain Size
Alloy Element Multiplying Factors

Same data on different scales
# H Values

**Severity of Quench (H) for Various Quenching Media**

<table>
<thead>
<tr>
<th>Circulation Type</th>
<th>Air</th>
<th>Oil</th>
<th>Water</th>
<th>Brine</th>
</tr>
</thead>
<tbody>
<tr>
<td>No circulation of fluid or agitation of piece</td>
<td>0.02</td>
<td>0.25 to 0.30</td>
<td>0.9 to 1.0</td>
<td>2</td>
</tr>
<tr>
<td>Mild circulation (or agitation)</td>
<td>0.30 to 0.35</td>
<td>1.0 to 1.1</td>
<td>2 to 2.2</td>
<td></td>
</tr>
<tr>
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<td>1.2 to 1.3</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Good circulation</td>
<td>0.4 to 0.5</td>
<td>1.4 to 1.5</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Strong circulation</td>
<td>0.05</td>
<td>0.5</td>
<td>1.6 to 2.0</td>
<td>...</td>
</tr>
<tr>
<td>Violent circulation</td>
<td>0.8</td>
<td>1.1</td>
<td>4</td>
<td>5</td>
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</table>
Hardenability Calculations

• Several table and graphs have been developed to determine the affects: *(specific order)*
  – Carbon content and austenite grain size
  – Alloying
  – Quench media and method

• Example problem: Calculate the approximate hardenability (actual critical diameter) of an AISI/SAE-1040 steel with an ASTM grain size of 7 and using a mild water quench process. Assume the following chemistry: 0.40%C, 0.72%Mn, 0.030%P, and 0.020%S.
$D_i$ from %C and Grain Size
Alloy Element Multiplying Factors

Same data on different scales
# H Values

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$D_c$ from Quench Media (H-values)

Same data on different scales
Example Problem #1

- Example problem: Calculate the approximate hardenability (actual critical diameter) of an AISI/SAE-8640 steel with an ASTM grain size of 7 and using a mild water quench process. Assume the following chemistry: 0.40%C, 0.85%Mn, 0.50%Cr, 0.55%Ni, 0.20%Mo, 0.25%Si, 0.030%P, and 0.020%S.

- Compare hardenability of two alloys. Why does one have deeper hardenability? When would this be beneficial?

- Relating strength to hardness
$D_i$ from %C and Grain Size
Alloy Element Multiplying Factors

Same data on different scales
# Hardenability Calculations

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D_c from Quench Media (H-values)

Same data on different scales
Hardenability Calculations

Hardenability curves for different grade of steels
Hardenability Multiplying Factor

• Shows the rate at which the hardening depth is increased with the percentage of alloying elements

• Ideal critical diameter ($D_{ic}$):
  \[ D_{ic} = D_i \times f_{Mn} \times f_{Si} \times f_{Ni} \times f_{Cr} \times f_{Mo} \]
Hardenability Multiplying Factor

<table>
<thead>
<tr>
<th>Carbon %</th>
<th>No. 6</th>
<th>No. 7</th>
<th>No. 8</th>
<th>Manganese</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
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</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.0814</td>
<td>0.0750</td>
<td>0.0697</td>
<td>1.167</td>
<td>1.035</td>
<td>1.018</td>
<td>1.1080</td>
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<td>0.10</td>
<td>0.1153</td>
<td>0.1065</td>
<td>0.0995</td>
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<td>1.070</td>
<td>1.036</td>
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<td>1.30</td>
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<td>0.15</td>
<td>0.1413</td>
<td>0.1315</td>
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<td>1.105</td>
<td>1.055</td>
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<td>0.20</td>
<td>0.1623</td>
<td>0.1509</td>
<td>0.1400</td>
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<td>0.25</td>
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<td>1.175</td>
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<tr>
<td>0.45</td>
<td>0.2440</td>
<td>0.2259</td>
<td>0.2090</td>
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<td>1.315</td>
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<tr>
<td>0.50</td>
<td>0.2580</td>
<td>0.2380</td>
<td>0.2200</td>
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<td>1.350</td>
<td>1.182</td>
<td>2.0800</td>
<td>2.50</td>
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<tr>
<td>0.55</td>
<td>0.2730</td>
<td>0.2510</td>
<td>0.2310</td>
<td>2.833</td>
<td>1.385</td>
<td>1.201</td>
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<tr>
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<td>1.420</td>
<td>1.219</td>
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<td>1.455</td>
<td>1.237</td>
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<tr>
<td>0.70</td>
<td>0.306</td>
<td>0.283</td>
<td>0.260</td>
<td>3.333</td>
<td>1.490</td>
<td>1.255</td>
<td>2.5120</td>
<td>3.10</td>
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<tr>
<td>0.75</td>
<td>0.316</td>
<td>0.293</td>
<td>0.270</td>
<td>3.500</td>
<td>1.525</td>
<td>1.273</td>
<td>2.6200</td>
<td>3.25</td>
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<tr>
<td>0.80</td>
<td>0.326</td>
<td>0.303</td>
<td>0.278</td>
<td>3.667</td>
<td>1.560</td>
<td>1.291</td>
<td>2.7280</td>
<td>3.40</td>
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<tr>
<td>0.85</td>
<td>0.336</td>
<td>0.312</td>
<td>0.287</td>
<td>3.833</td>
<td>1.595</td>
<td>1.309</td>
<td>2.8360</td>
<td>3.55</td>
</tr>
<tr>
<td>0.90</td>
<td>0.346</td>
<td>0.321</td>
<td>0.296</td>
<td>4.000</td>
<td>1.630</td>
<td>1.321</td>
<td>2.9440</td>
<td>3.70</td>
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<tr>
<td>0.95</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.167</td>
<td>1.665</td>
<td>1.345</td>
<td>3.0520</td>
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<tr>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.333</td>
<td>1.700</td>
<td>1.364</td>
<td>3.1600</td>
<td>-</td>
</tr>
</tbody>
</table>
Example Problem #2

• Example problem: What is the diameter of an SAE-8630 steel with an ASTM grain size of 7 and using a moderately agitated oil quench process to get 50% martensite in the center?
  – Assume the following chemistry: 0.30%C, 0.85%Mn, 0.50%Cr, 0.55%Ni, 0.20%Mo, 0.25%Si, 0.030%P, and 0.020%S.

• Solution:
  – Find out base $D_i$ for 0.3% C at ASTM 7
  – Calculate multiplying factors for each element
  – Ideal critical diameter ($D_{ic}$) found by multiplying base diameter by the multiplying factors
  – Critical diameter found by incorporating severity of quench
Example Problem #2

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  – Assume the following chemistry: 0.30%C, 0.85%Mn, 0.50%Cr, 0.55%Ni, 0.20%Mo, 0.25%Si, 0.030%P, and 0.020%S.

• Example problem: Need a 1.75 inch diameter shaft (through hardened) ≥ 50% martensite at the center. (limit: 0.45% carbon maximum to maintain lath martensite for good toughness)
Timken Hardenability Charts

Courtesy: Timken Steel. Practical Data for Metallurgists, 18th ed. (2016)
Hardenability Calculations

• Determining Hardenability from Jominy Test Graph
  – After plotting the hardness vs. distance curve, determine the Jominy distance where the hardness is equal to 50% martensite.
  – The diameter of a rod having a cooling rate similar to the cooling rate at the Jominy was determined can be correlated to the Jominy distance of a rod having similar cooling rates for water quenching.
  – This diameter gives the hardenability of the steel in water quenching (where H value = 1)
  – Hardenability in any other quenchant can be determined from the same graph
  – Di (hardenability in ideal quench medium) can be determined in a similar manner
  – We can determine hardenability for any other amount of martensite in the core in any quenchant in a similar way.
III.F—Q2

A steel component is quenched from 1500F to 78F. Which media would you expect to have the lowest $h$ value?

(A) Oil, violent agitation  
(B) Water, strong agitation  
(C) Oil, no agitation  
(D) Water, no agitation
III.G—Q4

One manufacturer, concerned about quench-related distortion, decided to change to an alloy with higher chromium content. Why would that help?

(A) The chromium would increase hardenability, allowing the manufacturer to slow down the quench rate.
(B) Chromium in solution stiffens the iron matrix and minimizes distortion.
(C) Chromium competes with carbon for interstitial sites in the iron, causing a more uniform carbon case, and therefore less distortion.
(D) The increased chromium would offer no improvement in distortion.
III.J—Q2

What hardness range would you expect to see in a 1-inch bar of AISI 4340 after water quenching?

(A) 20-30 HRC  
(B) 30-40 HRC  
(C) 40-50 HRC  
(D) 50-60 HRC