MSE-226 Engineering Materials

Lecture-5

“THERMAL PROCESSING OF METALS-3”
“Hardenability”
Hardenability is a term that is used to describe the ability of an alloy to be hardened by the formation of martensite as a result of given heat treatment (Ability to form martensite)

A steel that has high hardenability is one that hardens not only at the surface but throughout the entire interior.

HARDENABILITY TESTING METHODS

1) Grossman Method
2) Jominy End-Quench Test
JOMINNY END-QUENCH TEST

In this test, except for alloy composition, all factors that may influence the depth to which a piece hardens (i.e., specimen size and shape, and quenching treatment) are maintained constant.

**Procedure:**

1) Austenitize at a prescribed temperature and time
2) After removal from the furnace, quickly placed in a fixture
3) The lower end of specimen is queched by a jet of water of specified flow rate and temperature
JOMINNY END-QUENCH TEST

ASTM Standard A255-48T: Standard Test method for End-Quench Test for Hardenability of Steel

Jominny test specimen dimensions and test conditions

Specimen size: 1” in diameter, 4” long

Austenitization temperature: Determined according to carbon and alloy content of the material to get 100% austenite.

Quenching: Water is splashed at one end of the specimen
After the piece is cooled to room temperature, specimen surface is ground for 0.4 mm along the specimen length. Then, Rockwell Hardness (HRc) measurements are made along these surfaces up to 2.5 in. from the quench end.

Indents are applied for the first ~50 mm.

For the first 12.8 mm: hardness is taken at every 1.6 mm

For remaining part: hardness is taken at every 3.2 mm.

Hardness measurement
FACTORS EFFECTING HARDENABILITY

1) Chemical composition of the steel
   (carbon and alloy content)

2) Prior austenite grain size

3) Degree of homogeneity of alloys
FACTORS EFFECTING HARDENABILITY:

1- Chemical Composition

- With increasing carbon content and alloying elements shift the austenite to pearlite transformation lines to longer times. Alloying elements are more effective than carbon alone.

Hardenability increases!
(For alloy steels it becomes possible to form martensite phase throughout the specimen by cooling it even in air)

- "Alloy Steels" (4140, 4340, 5140, 8640)
  -- contain Ni, Cr, Mo (0.2 to 2wt%)
  -- these elements shift the "nose".
  -- martensite is easier to form.
Surface hardness depends on carbon content.

- Jominy end quench results, C = 0.4wt% C
FACTORS EFFECTING HARDENABILITY:

2-Prior Austenite Grain Size

The hardenability increases when the grain size is increased

- When the grain boundary area decreases, the nucleation site for ferrite, pearlite decreases. The transformation of these phases from austenite is slowed down, which can be seen in TTT-diagrams by shifting of austenite to pearlite transformation lines to the right. So, martensite transformation is favored even at slower cooling rates.
FACTORS EFFECTING HARDENABILITY:

3-Degree of Homogeneity

- The temperature and time for austenitization should be carefully chosen so that homogenous austenitic structure with homogenous composition can be obtained.

- Non-homogenous carbon distribution in austenite phase results in formation carbon rich and carbon depleted regions.
The quench-end has the maximum hardness (~100% martensite phase). Cooling rate decreases with distance from quench end. Formation of pearlite, bainite or mixture of martensite and those phases is possible.
In steels, there is always a slight, unavoidable variation in composition and average grain size which result in some scatter in measured hardenability data. Because of that hardenability band showing maximum and minimum hardness values at each distance is obtained.
FACTORS AFFECTING THE COOLING RATE IN QUENCHING

1) Type of quenching medium
2) Quenching Temperature
3) Agitation
4) Surface condition of the part
5) Specimen size and geometry
FACTORS AFFECTING THE COOLING RATE IN QUENCHING

1-Quenching Medium

Ideal quenching medium:
It would show a high initial cooling rate to avoid transformation in the nose region of the I-T diagram and then a slow cooling rate throughout the lower temperature range to minimize the distortion.

Industrial quenching media:
1) Water solution of 10% sodium chlorine (BRINE)
2) Tap water
3) Fused or liquid salts
4) Soluble oil and water solutions
5) Oil
6) Air

quenching severity decreases
FACTORS AFFECTING THE COOLING RATE IN QUENCHING

1-Quenching Medium

<table>
<thead>
<tr>
<th>Medium</th>
<th>Severity of Quench</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>oil</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>water</td>
<td>large</td>
<td>large</td>
</tr>
</tbody>
</table>

![Graph showing cooling rates for different mediums](image-url)
Cooling rate decreases as the temperature of the medium increases except for oil. As the temperature of the oil rises it also becomes more fluid (viscosity decreases), which increases the rate of heat conduction through the liquid.
FACTORS AFFECTING THE COOLING RATE IN QUENCHING

3-Agitation

- Circulation of the quenching medium reduces the length of the vapor-blanket stage formed during quenching stage, so that faster cooling rates will be achieved.

- Quenching severity of still water is 1.0

<table>
<thead>
<tr>
<th>Quench*</th>
<th>Oil</th>
<th>Water</th>
<th>Brine</th>
</tr>
</thead>
<tbody>
<tr>
<td>No circulation of liquid or agitation of piece</td>
<td>0.25–0.30</td>
<td>0.9–1.0</td>
<td>2</td>
</tr>
<tr>
<td>Mild circulation or agitation</td>
<td>0.30–0.35</td>
<td>1.0–1.1</td>
<td>2–2.2</td>
</tr>
<tr>
<td>Moderate circulation</td>
<td>0.35–0.40</td>
<td>1.2–1.3</td>
<td></td>
</tr>
<tr>
<td>Good circulation</td>
<td>0.40–0.50</td>
<td>1.4–1.5</td>
<td></td>
</tr>
<tr>
<td>Strong circulation</td>
<td>0.50–0.80</td>
<td>1.6–2.0</td>
<td></td>
</tr>
<tr>
<td>Violent circulation</td>
<td>0.80–1.10</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
FACTORS AFFECTING THE COOLING RATE IN QUENCHING

4-Surface condition of the part

- Thin layers of iron oxide formed on the steel surface are called “SCALE”.
- Thick layers retard cooling rate.
- Thin layers having thickness about less than 100 μm has no significant effect.
FACTORS AFFECTING THE COOLING RATE IN QUENCHING

5-Specimen size and geometry

- The cooling rate of a specimen depends on the rate of heat extraction.

- Heat energy must be transported to the surface before it can be dissipated into the quenching medium. Consequently, the cooling rate within and throughout the interior of a steel structure varies with position and depends on the geometry and size.

- Heat energy is dissipated to the quenching medium at the specimen surface, the rate of cooling for a particular quenching treatment depends on the ratio of surface area to the mass of the specimen. (SA/mass)

**When surface area-to-mass ratio increases:**
- cooling rate increases
- hardening in deeper sections
- irregular shapes with edges and corners have larger SA/mass ratio
Cooling rate as a function of diameter for cylindrical bars quenched in mildly agitated mediums

![Diagram of cooling rate at 700°C (1300°F) for water and oil mediums]
Example: Draw the radial hardness profile along the diameter of water quenched round SAE 1040 steel bar with 2" diameter.

- Bar Diameter (in)
- Hardness, HRC60
- Effective distance from quenched end (in)

- R = 54HRC
- R/2 = 30HRC
- Center = 27HRC

HRC 60

Hardness profile

20 → 2 in.
HARDNESS PENETRATION or RADIAL HARDNESS PROFILES:
Effect of alloying and Specimen size

EFFECT OF ALLOYING

Radial hardness profile for 50 mm diameter cylindrical 1040 and 4140 steels quenched in mildly agitated water

EFFECT OF SPECIMEN SIZE

Radial hardness profile for 50 mm and 100 mm diameter cylindrical 4140 steels quenched in mildly agitated water
Assume that a company is required to manufacture a steel shaft 2 in. diameter to a specified minimum hardness at the center after hardening of 42 HR_C. They plan to use oil quench and moderate agitation (H=0.35). They would like to use a bar of SAE 4140 steel whose hardenability curve is given. The problem is to determine whether that steel meet the above specification.
What will be the maximum allowable diameter of SAE 4140 steel bar, if the same company has decided to use same type of quenching medium and agitation to obtain a hardness value of 52.5 HRc at 1/2R.

~1.5 inches
A cylindrical piece of steel 2¼ in. (57.2 mm) diameter is to be austenitized and quenched so that a minimum hardness of 45 HRc is to be produced throughout the entire piece. Of the alloys 8660, 8640, 8630, and 8620, which will qualify if the quenching medium is (a) moderately agitated water, (b) moderately agitated oil:

- **If** moderately agitated water is used; SAE 8660 and 8640 steels meet requirements
- **If** moderately agitated oil is used; only SAE 8660 steel meets requirements

### Examples

![Graphs showing cooling rates and hardness vs. distance for different quenching media and steels.](image)

**Moderately agitated water**

**Moderately agitated oil**