Surface Hardening of Steels

Surface hardening is a process for obtaining desired characteristics on the exterior of a steel component.

Why Surface Hardening?
- To improve wear resistance
- To improve resistance to high contact stresses
- To improve fracture toughness
- To improve fatigue resistance, and, sometimes,
- To improve corrosion resistance

Components usually surface-hardened
- gears   - bearings   - valves   - shafts
- cams    - hand tools - rolls    - machine tools - sprockets

Methods
(a) Heat-treating processes
(b) Hardfacing processes

OR
(c) Processes that change surface composition
(d) Processes that preserve surface composition.

Heat-Treating Methods
Diffusional: carburizing, nitriding, carbonitriding, nitrocarburizing, boronizing, chromizing, ...
Selective Hardening: Flame hardening, induction hardening, laser and electron beam hardening

1. Carburizing
* A process of adding carbon to the surface of steels. This is done by exposing the part to a carbon-rich atmosphere at an elevated temperature and allowing diffusion to transfer the carbon atoms into steel.

Note: Diffusion will work only if the steel has low carbon content, because diffusion depends on concentration gradient at a given temperature. If, for example, high-carbon steel had is heated in a carbon-free furnace, such as air, the carbon will tend to diffuse out of the steel resulting in decarburization.

Types of Carburizing:
- Pack carburising
- Gas carburising
- Vacuum carburizing
- Plasma carburizing

Carbon content achieved: 0.7 to 1.2 wt.%
Suitable for: Low-carbon steels and alloy steels containing 0.08 to 0.2 wt.%C.
Carburizing temperature: 850-950 °C (1550-1750 °F) Carburizing Time: 4 to 72 h.
Mechanism (Pack): At carburizing temperatures, say 900 °C, the following reactions occur:

\[
\begin{align*}
C + O_2 &\rightarrow CO_2 & CO_2 + C &\rightarrow CO \\
Fe + 2CO &\rightarrow Fe(C in solution) + CO_2 & CO_2 + C &\rightarrow CO \\
BaCO_3 &\rightarrow BaO + CO_2 & CO_2 + C &\rightarrow CO \\
\end{align*}
\]

Surface hardness achieved: - 55 to 65 HRC
Case Depth: No technical limit. In practice, 0.5 to 1.5 mm
Applications: Gears, cams, shafts, bearings, piston rings, clutch plates, sprockets

Quenching:
After carburizing, the part is either slow cooled for later quench hardening, or quenched directly into various quenchants. The part is then tempered to the desired hardness.

2. Nitriding
* A process of diffusing nitrogen into the surface of steel. The nitrogen forms nitrides with elements such as aluminum, chromium, molybdenum, and vanadium. The parts are heat-treated and tempered before nitriding.

Suitable for: Low carbon alloy steels containing Al, Cr, Mo, V, Ni
Nitriding temperature: 500 to 600 °C (subcritical, below \(A_1\)).
Mechanism: \(NH_3 \leftrightarrow N + 3H\)

Surface hardness achieved: up to 1000 VHN
Case Depth: 0.1 to 0.6 mm
Applications: Gears, valves, cutters, sprockets, pump boring tools, fuel-injection pump parts.

3. Carbonitriding
* A process of adding carbon and nitrogen simultaneously into the surface of steels. The parts are heated (to austenite temperature) in an atmosphere of hydrocarbon (such as methane or propane) mixed with ammonia (NH\(_3\)). The process is a mix of carburizing and nitriding.

Suitable for: Mainly for low-carbon steels; medium-carbon steels sometimes.
Carbonitriding temperature: 700 to 800 °C; Carburizing Time: Less than carburizing.
Surface hardness achieved: 55 to 65 HRC
Case Depth: 0.07 to 0.5 mm
Typical Applications: Gears, bolts, nuts

4. Nitrocarburizing
* A thermochemical low-temperature process that diffuses both carbon and nitrogen into the surface of steels below the \(A_1\) transformation temperature. It is generally a short-cycle process that improves wear/friction resistance. The nitrocarburizing temperature range is about 482 to 593 °C. (900°F-1100°F).
Selective Hardening Methods

When is selective hardening necessary?

Selective hardening is applied because of one or more of the following reasons:
(1) Parts to be heat-treated are so large that conventional furnace heating and quenching become impractical and uneconomical - examples are large gears, large rolls and dies;
(2) Only a small segment, section, or area of the part needs to be heat-treated - typical examples are ends of valve stems and push rods, and the wearing surfaces of cams and levers;
(3) Better dimensional accuracy of a heat-treated part; and
(4) Overall cost savings by giving inexpensive steels the wear properties of alloyed steels.

1. Flame Hardening

Flame hardening is the process of selective hardening with a combustible gas flame as the source of heat for austenitizing. Water quenching is applied as soon as the transformation temperature is reached. The heating media can be oxygen acetylene, propane, or any other combination of fuel gases that will allow reasonable heating rates. For best results, the hardness depth is 3/16 inch.

There are three methods:
(1) Spot Flame Hardening: Flame is directed to the spot that needs to be heated and hardened.
(2) Spin Flame Hardening: The workpiece is rotated while in contact with the flame.
(3) Progressive Flame Hardening: The torch and the quenching medium move across the surface of the workpiece.

Suitable for: At least medium-carbon steels containing \( \geq 0.40 \) wt.% C, cast irons
Surface Hardness Achieved: 50 to 60 HRC
Case Depth: 0.7 to 6 mm
Typical Applications: Lathe beds and centers, crankshafts, piston rods, gear and sprocket teeth, axles, cams, shear blades

<table>
<thead>
<tr>
<th>Type of gas</th>
<th>Gas gravity</th>
<th>Calorific value (Btu/ft³, kcal/m³)</th>
<th>Gross Btu/ft³ of Std. Air</th>
<th>Gross kcal/m³ of Std. Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene, commercial</td>
<td>0.94</td>
<td>Gross 1410 Net 1360</td>
<td>12548 12105</td>
<td>115.4 1017</td>
</tr>
<tr>
<td>Butane, commercial, natural gas</td>
<td>2.04</td>
<td>Gross 3210 Net 2961</td>
<td>28066 26360</td>
<td>104.9 932.6</td>
</tr>
<tr>
<td>Butane, commercial, refinery gas</td>
<td>2.00</td>
<td>Gross 3184 Net 2935</td>
<td>26334 26119</td>
<td>106.1 944.2</td>
</tr>
<tr>
<td>Coke oven, by-product</td>
<td>0.40</td>
<td>Gross 569 Net 509</td>
<td>5064 4530</td>
<td>105.0 934</td>
</tr>
<tr>
<td>Natural, Alaska</td>
<td>0.55</td>
<td>Gross 998 Net 906</td>
<td>8879 8063</td>
<td>104.8 932.6</td>
</tr>
<tr>
<td>Natural, Birmingham, AL</td>
<td>0.60</td>
<td>Gross 1002 Net 904</td>
<td>8917 8045</td>
<td>106.1 945.1</td>
</tr>
<tr>
<td>Natural, Cleveland, OH</td>
<td>0.635</td>
<td>Gross 1059 Net 959</td>
<td>9424 8534</td>
<td>106.2 942.4</td>
</tr>
<tr>
<td>Natural, Kansas City, MO</td>
<td>0.63</td>
<td>Gross 974 Net 879</td>
<td>8668 7822</td>
<td>106.3 946.0</td>
</tr>
<tr>
<td>Natural, Pittsburgh, PA</td>
<td>0.61</td>
<td>Gross 1129 Net 1021</td>
<td>10047 9086</td>
<td>106.3 945.1</td>
</tr>
<tr>
<td>Propane, commercial, natural gas</td>
<td>1.55</td>
<td>Gross 2538 Net 2388</td>
<td>22764 20984</td>
<td>107.5 956.6</td>
</tr>
<tr>
<td>Propane, commercial, refinery gas</td>
<td>1.77</td>
<td>Gross 2504 Net 2316</td>
<td>22283 20610</td>
<td>108.0 961.1</td>
</tr>
</tbody>
</table>

**Flame Hardening Temperature:**
Characteristics of fuel gases used for flame hardening.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Heating Value (MJ/m³)</th>
<th>Flame Temperature (°C)</th>
<th>With Oxygen</th>
<th>With Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene</td>
<td>53.4</td>
<td>3105</td>
<td>2325</td>
<td></td>
</tr>
<tr>
<td>City gas</td>
<td>11.2-33.5</td>
<td>2540</td>
<td>1985</td>
<td></td>
</tr>
<tr>
<td>Natural gas (Methane)</td>
<td>37.3</td>
<td>2705</td>
<td>1875</td>
<td></td>
</tr>
<tr>
<td>Propane</td>
<td>93.9</td>
<td>2635</td>
<td>1925</td>
<td></td>
</tr>
</tbody>
</table>

2. **Induction Hardening**
Here, the steel part is placed inside copper induction coils and heated by high-frequency alternating current and then quenched. Depending on the frequency and amperage, the rate of heating as well as the depth of heating can be controlled.

**Suitable for:** Medium carbon steels (wt.% C ≥ 0.4), cast irons

**Hardening temperature:**
The induced current \( i \) within the steel then produces heat according to the relationship: Heat = \( i^2 R \), where \( R \) is the electrical resistance of the steel.

**Surface hardness achieved:** 50 to 60 HRC  
**Case Depth:** 0.7 to 6 mm  
**Typical Applications:** see flame hardening

**How to Select the Right Surface Hardening Method:**
(1) Carburizing is the best method for low carbon steels.
(2) Nitriding is a lower distortion process than carburizing but it can be used for certain type of steels such as chromium-molybdenum alloy steels or Nitralloy-type steels.
(3) Flame hardening is preferred for heavy cases or selective hardening of large machine components.
(4) Induction hardening works best on parts small enough and suitable in shape to be compatible with the induction coil.
(5) Electron beam and laser hardening are limited to the low alloy steels and plain carbon steels only.

![Figure: Pack carburizing process.](image-url)
Figure: Gas carburizing process.

Figure: Nitriding process

Figure: Carbonitriding process.
Figure: Flame hardening process.

Figure: Induction hardening process.
Surface Hardening Methods

Heat-treating processes

Selective hardening
- Flame
- Induction
- Electron beam
- Laser

Diffusion processes
- Carburizing
- Nitriding
- Carbonitriding
- Cyaniding
- Boronizing
- Chromizing
- Metalliding
- Ferritic nitrocarburizing

Thin-film coatings and surface modifications
- Thermal evaporation
- CVD
- Ion plating
- Sputter coating
- Ion implant
- Glazing

Plating
- Electroless
- Immersion electroplate
- Selective plating

Other processes
- Sleeves
- Wear plates
- Repair cements
- Spark deposition
- Braze coating
Carbon Concentration Gradients in Carburizing Steels

The carbon concentration gradient below the surface of the carburized part is affected mainly by temperature, time of carburizing, type of carburizing cycle, carbon concentration at the surface of the specimen, the size of the part and the original composition of the steel. For constant temperature, the Fick's Second Law of Diffusion (see Chapter 5 of Callister's book) enables us to estimate the carbon gradient from the surface to the inside of the steel part. The numerical solution of Fick's 2nd law for a flat surface yields the following equation:

\[
\frac{C_s - C_o}{C_s - C_o} = 1 - \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right)
\]  

(1)

Equation (1) can also be written as

\[
\frac{C_s - C_x}{C_s - C_o} = \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right)
\]  

(2)

where \( C_s \) = surface concentration of element in a gas diffusing into the surface
\( C_o \) = initial uniform concentration of element in the steel part
\( C_x \) = concentration of element at a distance \( x \) at time \( t \)
\( x \) = distance from the surface
\( t \) = time (in seconds)
\( D \) = diffusivity of diffusing solute element
\( \text{erf} \) = Gaussian error function

\[
\text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_{0}^{z} e^{-y^2} dy
\]

Equations (1) and (2) assume that \( D \) does not vary with the concentration of the diffusing species in the bulk sample, which may not be exactly the case. See Callister's book for some worked examples.

Decarburization

The reverse of carburization is decarburization. That is, instead of injecting carbon into the surface of the steel part, carbon is taken out of the surface of steel. This happens when the heat-treating atmosphere is not controlled. If the heat-treating is done in an oxidizing atmosphere, decarburization of the surface will occur and the desired effects of carburization will not be realized. For heat-treating shops, the atmosphere for heat treating is carefully controlled to avoid decarburization. The problem arises in plants with no facilities to control the atmosphere when steels are normalized, annealed, or heated to high temperatures.