STAINLESS STEEL
Why is it stainless?

- The Cr react with O₂ form a tough, adherent, invisible, passive layer of Cr₂O₃ film on the steel surface.

- Pack neatly together, forming a stable layer about 130 Armstrong(Å) thick.

- If the surface is damaged and the passive film is disrupted, more oxide will quickly form and recover the exposed surface—protect it from oxidative corrosion.

- The steel looks bright because the thin film reflects light.
Types of stainless steel

- Ferritic
- Austenitic
- Martensitic
- Duplex (austenitic and ferritic)
- Precipitation Hardening
<table>
<thead>
<tr>
<th>Types</th>
<th>Composition (wt%)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Ni</td>
</tr>
<tr>
<td>Ferritic</td>
<td>0.06-0.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Austenitic</td>
<td>&lt;0.25</td>
<td>&lt;35</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Martensitic</td>
<td>0.1-1.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duplex</td>
<td>0.03-0.1</td>
<td>2.5-5</td>
</tr>
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<td></td>
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</tbody>
</table>
Ferritic Stainless Steel

α (ferrite) BCC crystal structures containing Cr (11%<Cr<30%) with ↓ C content (0.06-0.2 wt%C)

Composition: Fe-C(BCC)-Cr

Not Heat Treatable

Increases in mech. prop. can only be achieved by Cold Working
- 12-30% Cr, $\alpha$ at all T
- Typical microstructures:

```
ferrite
```

Group 1 (13-18%Cr) e.g.: 430
Group 2 (25-30%Cr) e.g.: 446
Mechanical properties – Ferritic SS

- Moderate corrosion resistance
- Resistance to stress-corrosion cracking (SCC)
  - ↑ Temp, chloride environment & H-induced Stress Corrosion
- Poor fabrication properties (improve : alloy modifications)
- Magnetic
- Good formability at low cost
- Corrosion in oxidizing aqueous media
- Oxidation at ↑ temperatures
- Pitting and crevice corrosion in chloride media
- Slightly higher $\sigma_y$ than austenitic steels
- High Cr ferritic S.S such as 446, sensible to the '475 C embrittlement', which is caused by the decomposition of the Fe-Cr solid solution in two phases, Fe and Cr-rich respectively.
## Graded of Ferritic Stainless Steel

<table>
<thead>
<tr>
<th>AISI grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>P</th>
<th>S</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>405</td>
<td>0.08</td>
<td>1.0</td>
<td>1.0</td>
<td>11.5-14.5</td>
<td>-</td>
<td>0.04</td>
<td>0.03</td>
<td>0.1-0.3 Al</td>
</tr>
<tr>
<td>409</td>
<td>0.08</td>
<td>1.0</td>
<td>1.0</td>
<td>10.5-11.75</td>
<td>-</td>
<td>0.045</td>
<td>0.045</td>
<td>(6xC) Ti min</td>
</tr>
<tr>
<td>429</td>
<td>0.12</td>
<td>1.0</td>
<td>1.0</td>
<td>14.0-16.0</td>
<td>-</td>
<td>0.04</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>430</td>
<td>0.12</td>
<td>1.0</td>
<td>1.0</td>
<td>16.0-18.0</td>
<td>-</td>
<td>0.04</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>446</td>
<td>0.20</td>
<td>1.5</td>
<td>1.0</td>
<td>23.0-27.0</td>
<td>-</td>
<td>0.04</td>
<td>0.03</td>
<td>0.25N</td>
</tr>
</tbody>
</table>
Applications

Architectural trim

household utensils;
Cooking utensils

Automotive exhaust components

heat exchanger tubing (high %Cr)

automotive trim

Automotive gaskets
Austenitic Stainless Steel

• Austenitic FCC crystal structure
• Composition: Cr(16 - 26%), Ni(<35%), C(<0.25)
• Non-magnetic solid solution of carbon exists in steel above the critical temperature of 1333°F (about 723°C).
• Can be hardened by only cold working
• Annealed to reduce residual stress
This alloy called austenitic, since its structure remains austenitic (FCC, \( \gamma \)) at all normal temperatures.

The presence of Ni, which has FCC structure, enables the FCC structure to be retained at room temperature.

Mechanical properties:

- Better high temperature strength
- Better corrosion resistant than ferritic and martensitic
- Excellent weldability
- Greater ductility than ferritic and martensitic SS

Austenitic microstructure
The AISI series of heat resistant austenitic stainless steel

<table>
<thead>
<tr>
<th>AISI grade</th>
<th>C max.</th>
<th>Si max.</th>
<th>Mn max.</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Nb</th>
<th>Al</th>
<th>V</th>
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<tbody>
<tr>
<td>301</td>
<td>0.15</td>
<td>1.00</td>
<td>2.00</td>
<td>16-18</td>
<td>6-8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>302</td>
<td>0.15</td>
<td>1.00</td>
<td>2.00</td>
<td>17-19</td>
<td>8-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>0.08</td>
<td>1.00</td>
<td>2.00</td>
<td>17.5-20</td>
<td>8-10.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>310</td>
<td>0.25</td>
<td>1.50</td>
<td>2.00</td>
<td>24-26</td>
<td>19-22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316</td>
<td>0.08</td>
<td>1.00</td>
<td>2.00</td>
<td>16-18</td>
<td>10-14</td>
<td>2.0-3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>321</td>
<td>0.08</td>
<td>1.00</td>
<td>2.00</td>
<td>17-19</td>
<td>9-12</td>
<td>5 x %C min.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>347</td>
<td>0.08</td>
<td>1.00</td>
<td>2.00</td>
<td>17-19</td>
<td>9-13</td>
<td>10 x %C min.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E 1250</td>
<td>0.1</td>
<td>0.5</td>
<td>6.0</td>
<td>15.0</td>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/25-Nb</td>
<td>0.05</td>
<td>1.0</td>
<td>1.0</td>
<td>20.0</td>
<td>25.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>A 286</td>
<td>0.05</td>
<td>1.0</td>
<td>1.0</td>
<td>26.0</td>
<td>1.2</td>
<td>~1.9</td>
<td>~0.18</td>
<td>~0.25</td>
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<td></td>
</tr>
<tr>
<td>254SMO</td>
<td>0.02</td>
<td>0.8</td>
<td>1.0</td>
<td>18.5-20.5</td>
<td>17.5-18.5</td>
<td>6-6.5</td>
<td>~1.9</td>
<td>~0.18</td>
<td>~0.25</td>
<td></td>
</tr>
</tbody>
</table>
Applications austenitic stainless steels

• Pumping and containment of oil, gasses and acids
• Food production and storage
• Cryogenic vessels
• Modern mass transit system
• Welding construction
Martensitic stainless steels

- Alloys of Cr and C that possess a BCC or BCT crystal structure in the hardened condition.
- 11.5-18 wt % Cr, and 0.1-1.2 wt % carbon
- Carbon content more than ferritic and austenitic SS
- They are ferromagnetic and hardenable by heat treatments.

Ferromagnet: any material that could exhibit spontaneous magnetization: a net magnetic moment in the absence of an external magnetic field.
Mechanical properties

- Corrosion resistance of martensitic s.s > ferritic s.s
- High strength and hardness levels (High carbon contents) induces to cracking.
- Poor weldability (they are brittle and difficult to form and weld)
- Magnetic
- Tensile yield strengths (≈ 275 Mpa)
- When is untempered, high hardness/yield strength lack of toughness and ductility.
• To optimize mechanical properties- **tempered** between 600°C and 750°C

• Martensitic stainless steels have the highest strength, the lowest corrosion resistance of the stainless steels.
## Graded of Martensitic stainless steels

<table>
<thead>
<tr>
<th>AISI grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>P</th>
<th>S</th>
<th>Comments/Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>410</td>
<td>0.15</td>
<td>1.0</td>
<td>0.5</td>
<td>11.5-13.0</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>0.03</td>
<td>The basic composition. Used for cutlery, steam and gas turbine blades and buckets, bushings.</td>
</tr>
<tr>
<td>416</td>
<td>0.15</td>
<td>1.25</td>
<td>1.0</td>
<td>12.0-14.0</td>
<td>-</td>
<td>0.60</td>
<td>0.04</td>
<td>0.15</td>
<td>Addition of sulphur for machinability, used for screws, gears etc. 416 Se replaces sulphur by selenium.</td>
</tr>
<tr>
<td>420</td>
<td>0.15-0.40</td>
<td>1.0</td>
<td>1.0</td>
<td>12.0-14.0</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>0.03</td>
<td>Dental and surgical instruments, cutlery</td>
</tr>
<tr>
<td>431</td>
<td>0.20</td>
<td>1.0</td>
<td>1.0</td>
<td>15.0-17.0</td>
<td>-</td>
<td>1.25-2.0</td>
<td>0.04</td>
<td>0.03</td>
<td>Enhanced corrosion resistance, high strength.</td>
</tr>
<tr>
<td>440A</td>
<td>0.60-0.75</td>
<td>1.0</td>
<td>1.0</td>
<td>16.0-18.0</td>
<td>-</td>
<td>0.75</td>
<td>0.04</td>
<td>0.03</td>
<td>Ball bearings and races, gage blocks, molds and dies, cutlery,</td>
</tr>
<tr>
<td>440B</td>
<td>0.75-0.95</td>
<td>1.0</td>
<td>1.0</td>
<td>16.0-18.0</td>
<td>-</td>
<td>0.75</td>
<td>0.04</td>
<td>0.03</td>
<td>As 440A, higher hardness</td>
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<tr>
<td>440C</td>
<td>0.95-1.20</td>
<td>1.0</td>
<td>1.0</td>
<td>16.0-18.0</td>
<td>-</td>
<td>0.75</td>
<td>0.04</td>
<td>0.03</td>
<td>As 440B, higher hardness</td>
</tr>
</tbody>
</table>
Applications

• Knife
• the chemical and oil industries
• surgical instruments.
• turbine blades, cutlery,
• razor blades,
  shafts spindle
Duplex Stainless Steel

- Mixed microstructure of BCC ferrite and FCC austenite.
- Comp: 23 - 28% Cr, 2.5 - 5.0% Ni, 1.0 - 2.0% Mo, 0.03 - 0.1% C
- Develop to reduce the intergranular corrosion problems in austenitic stainless steel.
  - Intergranular: Precipitation of $M_{23}C_6$ occurs in the austenite grain surfaces at temp $< 800^\circ$C cause grain decohesion. (M: mixture of metals atom)
  - Addition of Ni changes the microstructure from ferritic $\rightarrow$ duplex $\rightarrow$ austenitic
DUPLEX STAINLESS STEEL
(DARK PHASE FERRITE)
Mechanical Properties

• Twice the $\sigma_y$ of austenitic stainless steels. Allow designing engineer to decrease wall thickness.

• Elongation typically $> 25\%$.

• Ferritic s.s $< $ ductility and toughness $< $ Austenitic s.s

• Good Resistance to stress corrosion cracking in a chloride environment (high Cr), pitting corrosion and crevice corrosion.

• Low risk in intergranular attack

• Usable temperature range from -50 to 280°C (Danger of 475°C embrittlement of ferritic phase)
# Duplex stainless steel

<table>
<thead>
<tr>
<th>Designation</th>
<th>Cr</th>
<th>Ni</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Other</th>
<th>UTS / MPa</th>
<th>Elongation / %</th>
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</thead>
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<tr>
<td>Type 329</td>
<td>28.0</td>
<td>6.0</td>
<td>0.10</td>
<td>2.0</td>
<td>1.0</td>
<td>0.04</td>
<td>0.03</td>
<td>1.5 Mo</td>
<td>724</td>
<td>25</td>
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<tr>
<td>Type 326</td>
<td>26.0</td>
<td>6.5</td>
<td>0.05</td>
<td>1.0</td>
<td>0.6</td>
<td>0.01</td>
<td>0.01</td>
<td>0.25 Ti</td>
<td>689</td>
<td>35</td>
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<tr>
<td>2RE60</td>
<td>18.5</td>
<td>4.5</td>
<td>0.02</td>
<td>1.5</td>
<td>1.6</td>
<td>0.01</td>
<td>0.01</td>
<td>2.5 Mo</td>
<td>717</td>
<td>48</td>
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<tr>
<td>IC378</td>
<td>21.8</td>
<td>5.5</td>
<td>0.03</td>
<td>1.38</td>
<td>0.40</td>
<td>0.03</td>
<td>0.01</td>
<td>3.0 Mo 0.18 Cu</td>
<td>706</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.07 V 0.14 N</td>
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<tr>
<td>IC381</td>
<td>22.1</td>
<td>5.8</td>
<td>0.02</td>
<td>1.92</td>
<td>0.48</td>
<td>0.03</td>
<td>0.01</td>
<td>3.2 Mo 0.07 Cu</td>
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<td></td>
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<td></td>
<td>0.13 V 0.14 N</td>
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<td></td>
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<tr>
<td>A219</td>
<td>25.6</td>
<td>9.4</td>
<td>0.03</td>
<td>0.70</td>
<td>0.60</td>
<td>0.02</td>
<td>0.01</td>
<td>4.1 Mo 0.27 N</td>
<td>690</td>
<td></td>
</tr>
</tbody>
</table>
Storage tanks for forest product

Applications

- Brewery pipes and tanks
- Power generation: feedwater heaters, fuel gas scrubbers
- Tank trailers for hot chemical
- Oil and gas industries
- Chemical engineering
- Tank on a marine chemical tanker

Flanges
Precipitation-hardening martensitic stainless steels have corrosion resistance comparable to austenitic varieties, but can be precipitation hardened to even higher strengths than the other martensitic grades.

The most common, 17-4PH, uses about 17% chromium and 4% nickel.

There is a rising trend in defense budgets to optimise for an ultra-high-strength stainless steel when possible in new projects, as it is estimated that 2% of the US GDP is spent dealing with corrosion. The Lockheed-Martin Joint Strike Fighter is the first aircraft to use a precipitation-hardenable stainless steel—Carpenter Custom 465—in its airframe.
Applications: precipitation hardened martensitic stainless steel

Gears,
cams,
shafting,
aircraft and turbine parts
The SAE steel grades are the most commonly used grading system in the US for stainless steel.

100 Series—austenitic chromium-nickel-manganese alloys
200 Series—austenitic chromium-nickel-manganese alloys
300 Series—austenitic chromium-nickel alloys
400 Series—ferritic and martensitic chromium alloys
500 Series—heat-resisting chromium alloys
600 Series—martensitic precipitation hardening alloys
## Comparison: Properties of Stainless Steel

<table>
<thead>
<tr>
<th>Alloy Group</th>
<th>Magnetic Response(^1)</th>
<th>Work Hardening Rate</th>
<th>Corrosion Resistance(^2)</th>
<th>Hardenable</th>
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</thead>
<tbody>
<tr>
<td>Austenitic</td>
<td>Generally No</td>
<td>Very High</td>
<td>High</td>
<td>By Cold Work</td>
</tr>
<tr>
<td>Duplex</td>
<td>Yes</td>
<td>Medium</td>
<td>Very High</td>
<td>No</td>
</tr>
<tr>
<td>Ferritic</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>By Cold Work</td>
</tr>
<tr>
<td>Martensitic</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>Quench &amp; Temper</td>
</tr>
<tr>
<td>Precipitation Hardening</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>Age Harden</td>
</tr>
</tbody>
</table>
Surface Hardening
Surface Hardening

- Many engineering must be very hard to resist surface indentation or wear and yet possess adequate toughness to resist impact damage.

- Surface Hardening is a process by which a steel is given a hard, wear resistant surface, while retaining a ductile but tougher interior.

- Surface hardening is usually done for the following reasons:
  - 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 that usually require surface hardening include:

- gears
- bearings
- valves
- cams
- hand tools
- rolls
- shafts
- machine tools
- bearing races

Surface hardening techniques can be classified into two major categories:

1. Processes that change the surface chemical composition (case hardening or thermochemical processes)
2. Processes that do not change the surface chemical composition (selective surface hardening or local thermal surface hardening)
1. **Case Hardening**

- Case hardening methods include:
  1. Carburising
  2. Nitriding
  3. Carbo-nitriding
  4. Cyaniding
Carburising

Carburising is a hardening process in which carbon is introduced into the surface layer of the steel.

1. The steel is heated in contact with a substance that has a high carbon content.
2. The steel is held at a temperature above the UCT (850 – 950 °C) for a suitable period of time.
3. Then quenched rapidly to produce a hardened surface layer or “case” over a softer and tougher core.
4. The steel is then tempered to the desired hardness.
Carburising is done on low C steel (< 0.25 %)

- The carburising time varies between 4 – 70 hours
- The length to time the steel is left in the furnace determines the *depth of carburising*
- Case depths ranging from 0.08 mm - 6.4 mm may be specified, depending on the service requirements of the product
- The carburising process does not harden the steel, it only increases the carbon content to a desired depth below the surface
1. **Pack Carburising**

- In pack carburising, the steel piece is packed in a steel container and completely surrounded with charcoal.

- The charcoal is treated with $\text{BaCO}_3$, which promotes the formation of $\text{CO}_2$.

- $\text{CO}$ reacts with the low carbon steel surface to form atomic C, which diffuses into the steel.

- Quenching is difficult in pack carburising. Usually the part is allowed to cool slowly and then hardened and tempered.

- **Carburising time:** 4 – 10 hours
- **Carburising depth:** no limit (< 1.3 mm)
2. **Gas Carburising**

- Carburising is done with carbonaceous gases, such as: methane, ethane, natural gas or propane at around 930 °C.
- The advantage of gas carburising is that the steel can be quenched directly from the carburising temperature.

3. **Liquid Carburising**

- Carburising is done in liquid salts, which contain cyanide compounds such as NaCN.
- Shorter carburising time compared to pack and gas carburising.
- Environmental hazards of the salts used.
Nitriding

- Another process by which a case of hardened steel can be achieved
- In nitriding, the steel piece is heated in a furnace between 500 – 600 °C and at the same time is exposed to ammonia gas (NH₃)
- The heat from the furnace causes the ammonia to decompose into hydrogen (H₂) and nitrogen (N₂)
- Nitrogen reacts with elements in the steel to form nitrides in the outer layer of the steel providing high hardness and wear resistance
- Nitriding times range between 1–100 hours depending on steel composition and depth of hardening desired
- Since nitriding does not involve austenitizing the steel and subsequent quenching to form martensite, it can be carried out at comparatively low temperatures and thus produce less distortion and deformation
Nitriding

\[ 2\text{NH}_3 \rightarrow 2\text{N} + 3\text{H}_2 \]
This process involves both the diffusion of C and N into the steel surface.

Nitriding is performed in a gas atmosphere furnace using a carburising gas such as propane or methane (source of C) mixed with several vol% of ammonia (NH₃) (source of N).

Carbonitriding is performed at temperatures above the UCT (700 – 800 °C).

Quenching is done in a gas which is not as severe as water quench (the result is less distortion on the material to be treated).
Carbonitriding

Diagram showing the process of carbonitriding with labeled zones:
- Preheat zone
- Carburizing zone
- Carbonitriding zone
- Quench zone
- Neutral gas
- Carburizing gas
- Ammonia
- Neutral gas

Faculty of Mechanical Engineering
Cyaniding

- This process also involves both the diffusion of C and N into the surface layers of the steel.

- In cyaniding, the steel is heated in a liquid bath of cyanide – carbonate – chloride salts and then quenched in brine, water or oil.
These processes are also called localised heat treatment because only the surface is austenitised and quenched to produce martensite.

The basic requirement for these processes is that the steel must have sufficient carbon and hardenability to achieve the required hardness at the surface (medium carbon steels are usually suited for these processes).

Selective surface hardening are classified according to the heating source into:

1. Flame hardening
2. Induction hardening
3. Laser hardening
4. Electron-beam heat-treating
Selective Surface Hardening

Selective hardening is applied because of one or more of the following reasons:

1. Parts to be heat-treated are so large as to make conventional furnace heating and quenching 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.
4. Overall cost savings by using inexpensive steels to have the wear properties of alloyed steels.
Flame Hardening

Induction Hardening
<table>
<thead>
<tr>
<th></th>
<th>Heat treatment</th>
<th>Case hardening</th>
</tr>
</thead>
<tbody>
<tr>
<td>%C Austenized</td>
<td>0.4-0.6 surface</td>
<td>0.2 all</td>
</tr>
<tr>
<td>Speed of procedure</td>
<td>Fast (secs)</td>
<td>Slow (~10hrs)</td>
</tr>
<tr>
<td>Surface chemistry</td>
<td>No change</td>
<td>0.8-1.0% C (or N)</td>
</tr>
<tr>
<td>Depth</td>
<td>1-10mm</td>
<td>0.5-2mm</td>
</tr>
<tr>
<td>Surface hardness</td>
<td>$R_c$ 57-60</td>
<td>$R_c$ 65</td>
</tr>
<tr>
<td>Microstructure</td>
<td>martensite</td>
<td>surface martensite;</td>
</tr>
<tr>
<td></td>
<td>(may be through part)</td>
<td>centre pearlite;</td>
</tr>
<tr>
<td>Control</td>
<td>difficult</td>
<td>easy</td>
</tr>
<tr>
<td>Residual stress</td>
<td>Surface compressive</td>
<td>Surface compressive</td>
</tr>
<tr>
<td>Core toughness</td>
<td>Medium (high C)</td>
<td>Good (low C)</td>
</tr>
<tr>
<td>Cost</td>
<td>Cheap $/part</td>
<td></td>
</tr>
</tbody>
</table>
INDUCTION HARDENING

Process:
- Induced current.
- Metal will be surrounded in a quickly changing magnetic field.
- Heating temperature: 750°C – 850°C
- Quench in water.

Advantages:
- No scaling effect.
- Reduce distortion.
- Consistent surface texture.

Disadvantages:
- High cost

Applications:
- Crankshafts.
- Gears.
- Automotive components which require high core strength.
**FLAME HARDENING**

**Process:**
Heated to $\gamma$ region with ‘oxyacetylene’ flame.
Quenching.
Thin surface hardening.
Thickness control by temp. and time.

**Advantages:**
- No scaling effect.
- Cheap and portable.

**Disadvantages:**
- ‘Overheating’ can damage components.

**Applications:**
- Crankshafts.
- Gears.
- Automotive components which require high core strength.
<table>
<thead>
<tr>
<th>PROCESS</th>
<th>TEMP. °C</th>
<th>DIFFUSING ELEMENTS</th>
<th>PROCESS MEDIA</th>
<th>STEELS</th>
<th>CASE CHARACTERISTICS</th>
<th>PROCESS CHARACTERISTICS</th>
<th>APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARBURISING</td>
<td>900-1000</td>
<td>Carbon</td>
<td>Pack</td>
<td>Low-carbon steels, mild and low-alloy</td>
<td>• Medium to deep cases</td>
<td>• Care required to minimise distortion</td>
<td>• High surface stress conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Salt</td>
<td></td>
<td>• Oil quenched</td>
<td></td>
<td>• Alloy steels – large sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gas</td>
<td></td>
<td>• Typical surface hardness 57-62 HRC (650-800 HV) after low-temperature tempering.</td>
<td></td>
<td>• Mild steels – small sections (&lt;12.5mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fluidised bed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CARBONITRIDING</td>
<td>800-880</td>
<td>Carbon + Nitrogen</td>
<td>Salt</td>
<td>Low-carbon steels, mainly mild steels</td>
<td>• Shallow to medium cases</td>
<td>• Less distortion than carburising</td>
<td>• High surface stress conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Carbon predominates)</td>
<td>Gas</td>
<td></td>
<td>• Oil quenched</td>
<td></td>
<td>• Mild steels – to section sizes above 12.5mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Plasma</td>
<td></td>
<td>• Typical surface hardness 57-62 HRC (650-800 HV) after low-temperature tempering.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fluidised bed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NITRIDING</td>
<td>500-550</td>
<td>Nitrogen</td>
<td>Gas</td>
<td>Alloy steels, and some tool steels, with</td>
<td>• Shallow to medium cases</td>
<td>• Very low distortion</td>
<td>• Severe surface stress conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Plasma</td>
<td>appropriate levels of nitride-forming</td>
<td>• No quenching required</td>
<td></td>
<td>• Gives highest hardness and temperature resistance (up to 200-300°C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fluidised bed</td>
<td>elements</td>
<td>• Surface hardness in range 650-1100HV depending on steel.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NITROCARBURISING*</td>
<td>560-570</td>
<td>Nitrogen + Carbon</td>
<td>Salt</td>
<td>Wide range of steels, from low-</td>
<td>• Thin (10-20μm) hard surface compound layer</td>
<td>• Very low distortion</td>
<td>• Low to medium surface stress conditions</td>
</tr>
<tr>
<td>(“Ferritic”)</td>
<td></td>
<td>(Nitrogen</td>
<td>Gas</td>
<td>carbon/non-alloy to tool steels</td>
<td>• Underlying nitrogen diffusion zone</td>
<td></td>
<td>• Good wear resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>predominates)</td>
<td>Fluidised bed</td>
<td></td>
<td>• Surface hardness depends on steel type and process route. Can range from 350-550HV1</td>
<td></td>
<td>• Post oxidation/impregnation gives salt corrosion resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>on low-carbon/non-alloy steels to 1000 + HV1 on some tool steels</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Nitrocarburising treatments above 590°C (“Austenitic”) can produce a variety of deeper underlying hardened cases.
<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induction Hardening</td>
<td>Does not change chem. comp. For medium carbon steel &amp; alloy steel.</td>
</tr>
<tr>
<td>Flame Hardening</td>
<td>Does not change chem. comp. For carbon steel (0.3-0.6%C).</td>
</tr>
<tr>
<td>Carburising</td>
<td>Changed chem. comp. Additions of C on the surface. Oldest, cheapest technique. For low carbon steel</td>
</tr>
<tr>
<td>Nitriding</td>
<td>Changed chem. comp. Additions of N through NH$_3$ gas.</td>
</tr>
</tbody>
</table>
How to select the right surface hardening method

- Carburizing is the best method for low carbon steel

- Nitriding is a lower distortion process than carburizing but it can be used for certain type of steel such as chromium-molybdenum alloy steel

- Flame hardening is preferred for heavy cases or selective hardening of large machine components.

- Induction hardening works best on parts small enough and suitable in shape to be compatible with the induction coil

- Electron beam and laser hardening are limited to the low alloy steels and plain carbon steels