Surface hardening by superficial heat treatments or diffusion treatments

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Heat treatments for carbon steels

General heat treatments
- Austenisation
- Annealing
- Normalization
- Quenching
- Tempering
- Isotherm decompositions

Thermochemical treatments
- Non-metals diffusion
  - Carburizing
  - Nitriding
  - Carbonitriding
- Diffusion treatments
  - Chromization
  - Calorization
  - Sherardization

Superficial heat treatments
- Induction hardening
- Flame hardening
- High energies
  - Laser
  - Electron beam
  - Arc Plasma

To enhance surface hardening
**Superficial heat treatments**

**Goal**
- Hard martensite on part surface
- No modification of steel chemical composition

**For steel containing wt.% C > 0.3**
- 0.4 to 0.6 wt.% C

**Heat treatments**
1. **Fast heating**
   - To avoid diffusion
   - Above $A_{c3} + 25-50^\circ C \rightarrow$ austenisation
2. **Quick cooling**
   - Water or oil quenching to obtain martensite
Superficial heat treatments

- Fast heating

Medium or high frequency **induction** heating

- Most common method
- Heating from a few 0.1 to a few mm deep
- Heating by Joule effect and thermal conduction

Heating with **flame**

- Very fast heating of the surface above Ac3 (a few seconds)
- Hardened depth between 1 mm and the full section of the part (up to 75 mm)

Immersion in a bath of **molten salts** (1000-1200°C)

- More rarely used
- For gear teeth
Superficial heat treatments

- Induction heating

## Advantages

- Short heating times, fast and economical processing
- Localized hardening
- Depth of heating controlled by frequency of the alternating current, power input, time, part coupling and quench delay
- Good wear resistance of hardened surfaces (due to high hardness)
- Fatigue resistance due to compressive surface stresses
- No decarburization or oxidation
- Low structural deformations because part core remains cold
- Core retains its initial mechanical characteristics
- Easy to automate
- Non-polluting

## Disadvantages

- High economic investment
- Need of a well shape design of the inductor to ensure correct distribution of the induced currents
- For a limited number of steel grades
- Need of a careful control of temperature and thermal gradients
Superficial heat treatments

• Applications

Improved properties

• Wear resistance by friction, by matting, by rolling
• Fatigue resistance by total or localized reinforcement at stress concentrations

Areas

• Automotive, railway, mechanical engineering, agricultural construction, public works, machine tools, steel industry, ...

Examples

• Axes, pistons, transmission shafts, road shafts, cylinders, slides, rollers, pulleys, tappets, crankshafts, cams, camshafts, rocker arms, transmission joints, ball joints, cutting tools, chain links, ...
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  - Non-metals diffusion treatments
    - Carburizing
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To enhance surface hardening
Thermochemical treatments

Based on the diffusion of chemical elements

- Non-metals : C, N $\rightarrow$ to enhance mechanical properties
- Metals : Cr, Al, Zn, Si $\rightarrow$ to enhance corrosion resistance

3 major treatments to enhance mechanical properties

1. Carburizing: diffusion of carbon (C)
2. Nitriding: diffusion of nitrogen (N)
3. Carbonitriding or nitrocarburizing: diffusion of C and N

2 hardening mechanisms

1. By quenching (carburizing, carbonitriding)
2. By precipitation, by solid solution effects and by chemical combination between substrate and diffusing element (nitriding, nitrocarburizing)
## Thermochemical treatments

<table>
<thead>
<tr>
<th>Active medium or diffusion medium used</th>
<th>Carburizing</th>
<th>Nitriding</th>
<th>Carbonitriding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid = pack (coal, coke, graphite, etc.)</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid = baths of molten cyanide salts</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Gaseous = gas mixture rich in C and/or N (CO or hydrocarbons of the $C_nH_m$ type, ammoniac NH$_3$)</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Plasma = ionic</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Low pression or vacuum = rarefied atmosphere</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Thermochemical treatments

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<tr>
<th>Carburizing</th>
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<tr>
<td>Diffusion of C in solid solution of insertion in Fe</td>
<td>Diffusion of N in solid solution of insertion in Fe</td>
</tr>
<tr>
<td>[2CO \rightarrow CO_2 + C_{at}]</td>
<td>[2NH_3 \rightarrow 3H_2 + 2N_{at}]</td>
</tr>
<tr>
<td>1. Heating at 815-980°C to obtain (\gamma) phase</td>
<td>1. Heating at about 500-550°C to obtain (\alpha) phase</td>
</tr>
<tr>
<td>2. Diffusion of C to obtain 0.7-0.9 wt.% C in surface</td>
<td>2. Diffusion of N</td>
</tr>
<tr>
<td>3. Water or oil quenching</td>
<td></td>
</tr>
<tr>
<td>4. Tempering (550°C-1 h)</td>
<td></td>
</tr>
<tr>
<td>Diffusion time: about 30 min</td>
<td>Duration: fct(t° of HT): 50-100 h</td>
</tr>
<tr>
<td>Hardening by <strong>martensite</strong> formation</td>
<td>Hardening by superposition of two layers (from the surface)</td>
</tr>
<tr>
<td>• Level of hardening depending on the carbon content of the martensite (800-850HV)</td>
<td>1. Thin <strong>compound layer</strong> made of Fe(<em>4)N ((\gamma')) and Fe(</em>{2-3})N ((\varepsilon)) nitrides = “white layer” ((\leq 30 \mu m))</td>
</tr>
<tr>
<td>• Hardened thickness between 0.2 to 2 (or more) mm depending on the application</td>
<td>2. <strong>Diffusion layer</strong> (0.1 to 1 mm): nitride-reinforced surface layer nitride precipitates of iron and of alloying elements + solid solution hardening</td>
</tr>
</tbody>
</table>
# Thermochemical treatments

<table>
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<tr>
<th>Carburizing</th>
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<tbody>
<tr>
<td>Other properties</td>
<td>Other properties</td>
</tr>
<tr>
<td>• High wear resistance</td>
<td>• Minimum distortion and excellent dimensional control</td>
</tr>
<tr>
<td>• Improved fatigue resistance due to compressive stresses on the surface</td>
<td>• High wear resistance</td>
</tr>
<tr>
<td>• High fatigue resistance in flexion and in torsion due to compressive</td>
<td>• High fatigue resistance</td>
</tr>
<tr>
<td>stresses on the surface</td>
<td>due to compressive stresses on the surface</td>
</tr>
<tr>
<td>• High resistance to seizing, adhesive bonding, wear due to small movements</td>
<td>• High resistance to seizing, adhesive bonding, wear due to small movements because of the</td>
</tr>
<tr>
<td>due to the presence of the compound layer (made of nitrides that are</td>
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</tr>
<tr>
<td>auto lubricious)</td>
<td>• Very high hot resistance</td>
</tr>
</tbody>
</table>

For mild steel with an initial carbon content < 0.25 wt.%                   For specific grades: mechanical engineering steels (medium-carbon (quenched and tempered) steels), tool steels, stainless steels, sintered steels
• Alloyed with elements that easily form nitrides (Cr, V, Al)
# Thermochemical treatments

<table>
<thead>
<tr>
<th>Carbonitriding</th>
<th>Nitrocarburizing</th>
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<tbody>
<tr>
<td>Diffusion of C and N in solid solution of insertion in Fe</td>
<td>Diffusion of C and N in solid solution of insertion in Fe</td>
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<tr>
<td>$2CO \Rightarrow CO_2 + C_{at}$</td>
<td>$2NH_3 \Rightarrow 3H_2 + 2N_{at}$</td>
</tr>
<tr>
<td>1. Heating at 760-870°C to obtain $\gamma$ phase</td>
<td>2 types of nitrocarburizing depending on the heat-treatment $t^\circ$</td>
</tr>
<tr>
<td>2. Water or oil quenching</td>
<td>1. ferritic</td>
</tr>
<tr>
<td>3. Tempering</td>
<td>2. austenitic</td>
</tr>
<tr>
<td>Diffusion time: 30 min to few hours</td>
<td>Higher levels of N with a compound layer</td>
</tr>
<tr>
<td>• Hardening by <strong>martensite</strong> formation</td>
<td></td>
</tr>
<tr>
<td>• In some cases: hardening by <strong>nitride</strong> formation</td>
<td></td>
</tr>
<tr>
<td>• Austenite may be retained after quenching</td>
<td></td>
</tr>
<tr>
<td>• N enhances hardenability and case hardness but inhibits the diffusion of C</td>
<td></td>
</tr>
<tr>
<td>$\Rightarrow$ Surface hardness equivalent to that of high-alloy carburized</td>
<td></td>
</tr>
<tr>
<td>steel without the need for drastic quenching</td>
<td></td>
</tr>
<tr>
<td>For low-carbon steels and stainless steels</td>
<td>For plain carbon steels</td>
</tr>
</tbody>
</table>
Carburizing

Steel containing 0.07 wt.% C and 2.3 wt.% Mn, treated at 950°C

Complete microstructure (from the surface to the core)

Martensite in surface

Very fine perlite/bainite in the core
Nitriding

- Compound layer (nitrides)
- Diffusion layer

Nital etching
Microscopic observation

Graph showing hardness (HRC) and depth below surface (mm) for nitriding steel, alloy steel, and stainless steel.
Case depth

Depth of diffusion

\[ \text{Case depth} = K \times \sqrt{\text{Time}} \]

K = diffusivity constant depending on temperature, chemical composition of the steel, concentration gradients of the hardening element

- K increases exponentially as a function of absolute temperature
- Concentration gradients depend on the surface kinetics and reactions of a particular process

Diffusion substrates
Carburizing or nitriding hardening depth

- Case depth allows to control the efficiency of the surface heat treatment
- 2 parameters
  - Total case depth
  - Effective case depth ➞ most interesting

![Diagram showing Carburizing and Nitriding](image-url)
Carburizing or nitriding hardening depth

- Thickness depending on
  - Duration of the hardening treatment
Carburizing or nitriding hardening depth

- Thickness depending on
  - Duration of the hardening treatment
  - Heat treatment temperature

![Carburizing graph](image1)

![Nitriding graph](image2)
Carburizing or nitriding hardening depth

- Thickness depending on
  - Duration of the hardening treatment
  - Heat treatment temperature
  - Chemical composition of the substrate because alloying elements are influencing the element diffusion rate

Nitriding
Carburizing or nitriding hardening depth

- Thickness depending on
  - Duration of the hardening treatment
  - Heat treatment temperature
  - Chemical composition of the substrate because alloying elements are influencing the element diffusion rate
  - Composition of the atmosphere (carburizing or nitriding potential)

Heat treatments

- **Carburizing**
  - After diffusion treatment
    - Quenching + tempering
- **Nitriding**
  - Before diffusion treatment
    - Quenching + tempering
Applications

Valve spring seat rings in St4 (left: untreated, right: carbonitrided, after hardening and tempering)

Tapered roller bearing in 20NiCrMo7F after carburizing, hardening and tempering

16MnCr5 bevel gears after carburizing, hardening and tempering
### Summary

- **Relative benefits for five common surface-hardening processes**

<table>
<thead>
<tr>
<th>Process</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical/tribological properties</strong></td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>Wear-resistance</td>
</tr>
<tr>
<td>Induction hardening</td>
<td>Hard</td>
</tr>
<tr>
<td>Flame hardening</td>
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Thank you for your attention

Questions?