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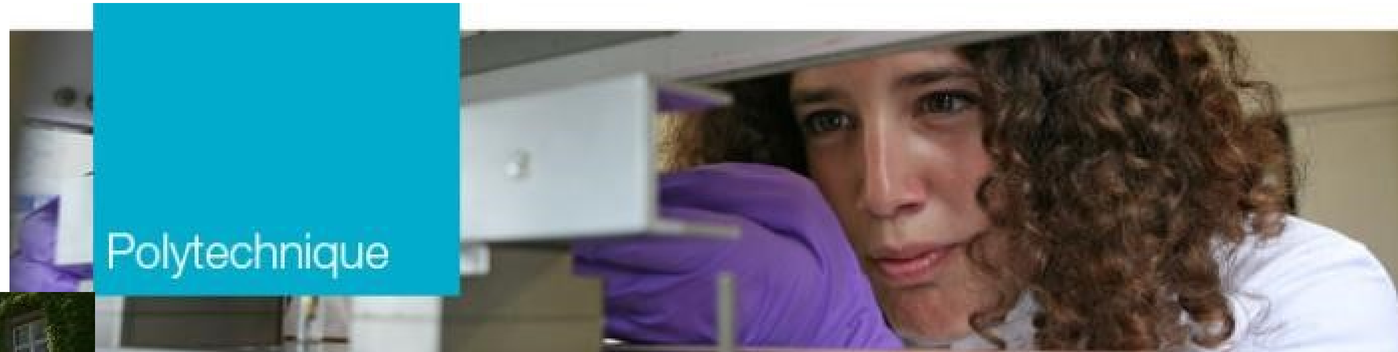

Surface hardening by superficial heat treatments or diffusion treatments

08 juin 2021

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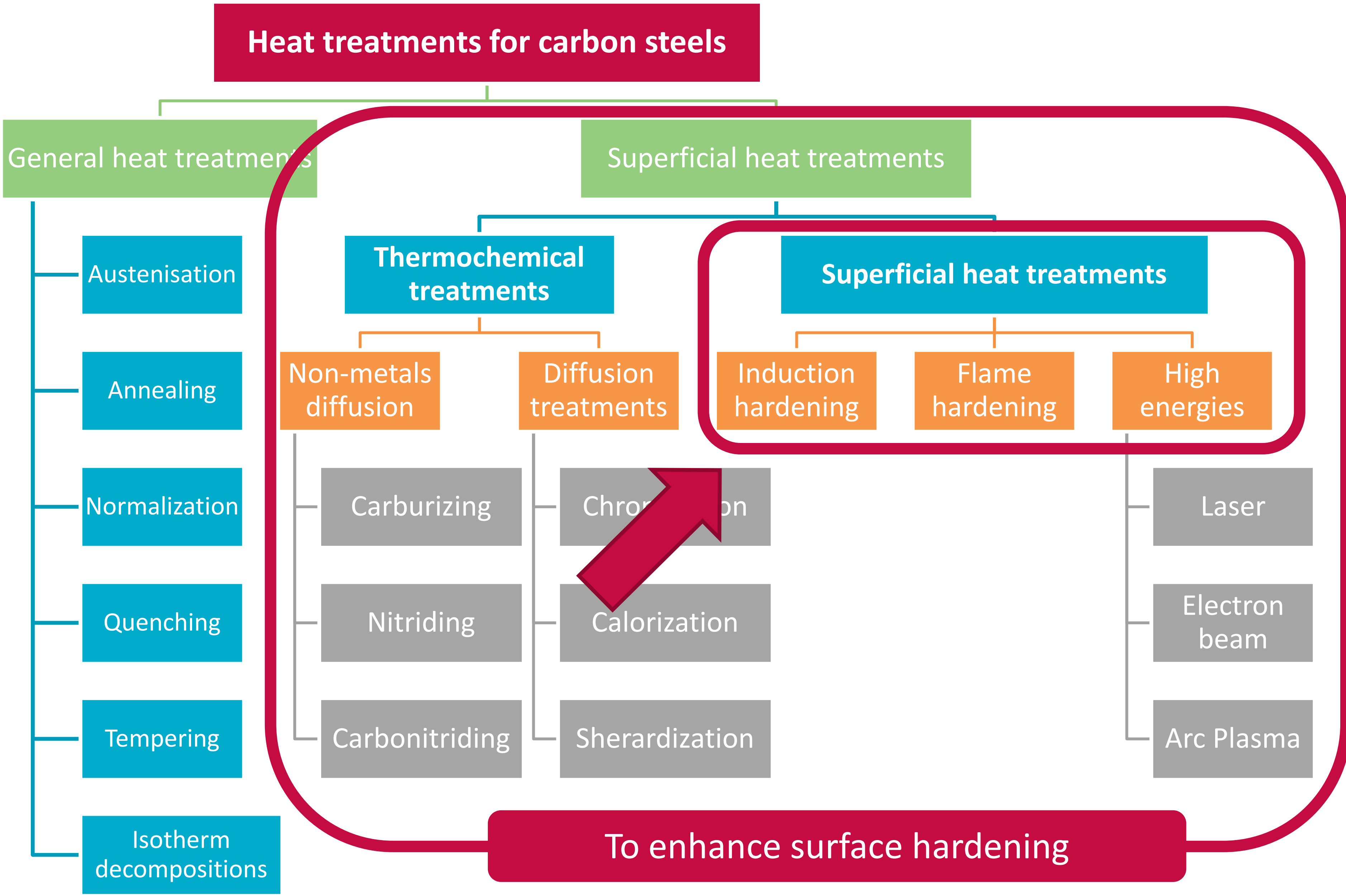

Heat treatments for carbon steels
General heat treatments
Superficial heat treatments
Austenisation
Annealing
Normalization
Quenching
Tempering
Isotherm decompositions
Thermochemical treatments
Superficial heat treatments
Non-metals diffusion
Diffusion treatments
Induction hardening
Flame hardening
High energies
Carburizing
Nitriding
Carbonitriding
Calorization
Sherardization
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°C → 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

- Applications

Improved properties

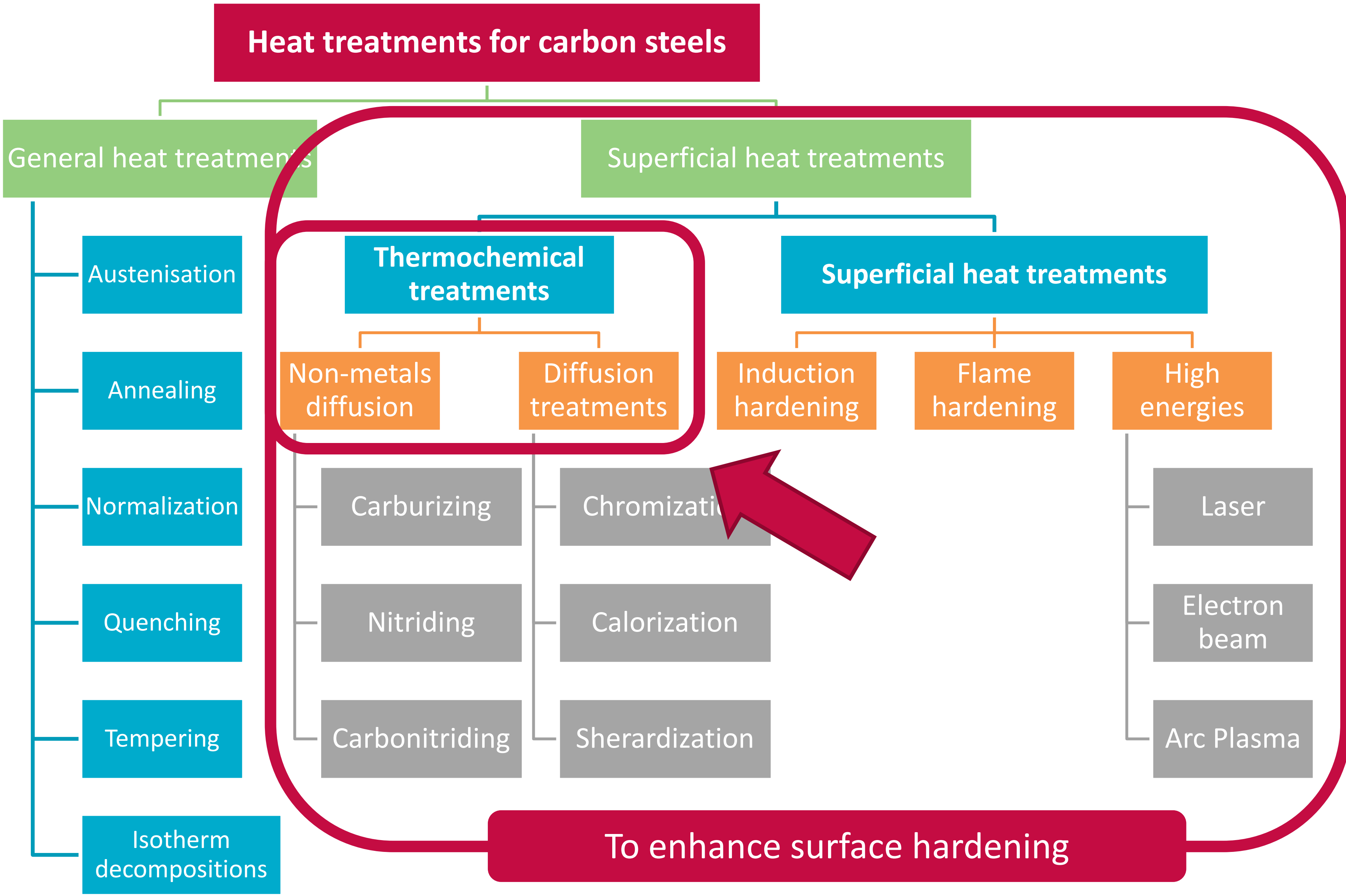
- Wear resistance by friction, by matting, by rolling
- Fatigue resistance by total or localized reinforcement at stress concentrations

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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Thermochemical treatments

Based on the diffusion of chemical elements

- Non-metals : C, N ➡ to enhance mechanical properties
- Metals : Cr, Al, Zn, Si ➡ 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

Active medium or diffusion medium used	Carburizing	Nitriding	Carbonitriding
Solid = pack (coal, coke, graphite, etc.)	☑		
Liquid = baths of molten cyanide salts	☑	☑	☑
Gaseous = gas mixture rich in C and/or N (CO or hydrocarbons of the C_nH_m type, ammoniac NH_3)	☑	☑	☑
Plasma = ionic	☑	☑	☑
Low pression or vacuum = rarefied atmosphere	☑		☑

Thermochemical treatments

Carburizing	Nitriding
Diffusion of C in solid solution of insertion in Fe	Diffusion of N in solid solution of insertion in Fe
$2CO \Rightarrow CO_2 + C_{at}$	$2NH_3 \Rightarrow 3H_2 + 2N_{at}$
1. Heating at 815-980°C to obtain γ phase 2. Diffusion of C to obtain 0.7-0.9 wt.% C in surface 3. Water or oil quenching 4. Tempering (550°C-1 h)	1. Heating at about 500-550°C to obtain α phase 2. Diffusion of N
Diffusion time: about 30 min	Duration: fct(t° of HT): 50-100 h
Hardening by **martensite** formation • Level of hardening depending on the carbon content of the martensite (800-850HV) • Hardened thickness between 0.2 to 2 (or more) mm depending on the application	Hardening by superposition of two layers (from the surface) 1. Thin **compound layer** made of Fe_4N (γ') and $Fe_{2\text{-}3}N$ (ε) nitrides= "white layer" (≤30 µm) 2. **Diffusion layer** (0.1 to 1 mm): nitride-reinforced surface layer nitride precipitates of iron and of alloying elements + solid solution hardening

Thermochemical treatments

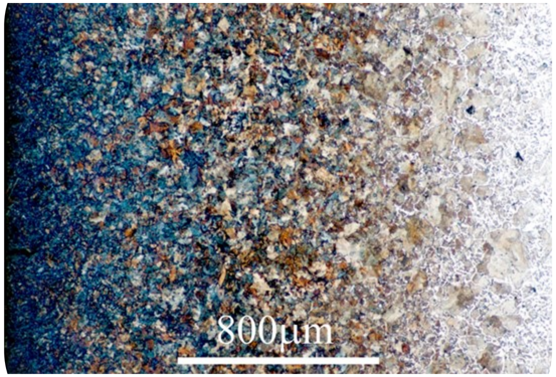
Carburizing	Nitriding
Other properties • High wear resistance • Improved fatigue resistance due to compressive stresses on the surface	Other properties • Minimum distortion and excellent dimensional control • High wear resistance • High fatigue resistance in flexion and in torsion due to compressive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

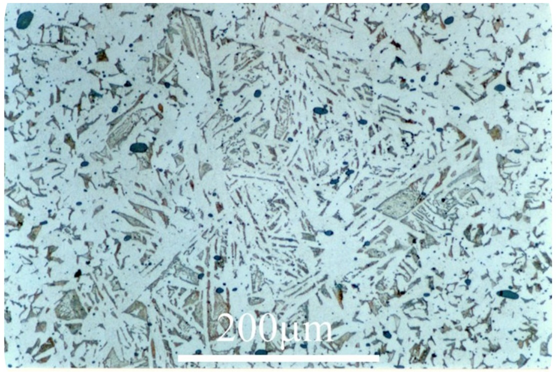
Carbonitriding	Nitrocarburizing
Diffusion of C and N in solid solution of insertion in Fe	Diffusion of C and N in solid solution of insertion in Fe
$2CO \Rightarrow CO_2 + C_{at}$ $2NH_3 \Rightarrow 3H_2 + 2N_{at}$	
1. Heating at 760-870°C to obtain γ phase 2. Water or oil quenching 3. Tempering	2 types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

Carburizing

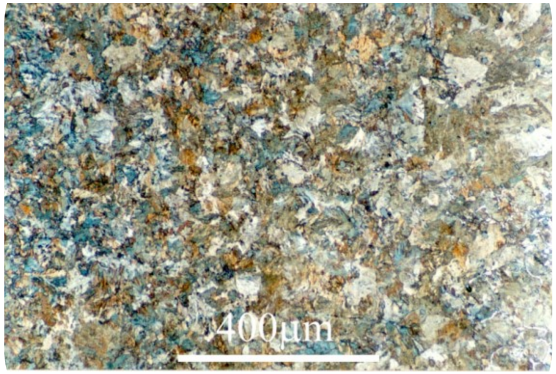
Steel containing 0.07 wt.% C and 2.3 wt.% Mn, treated at 950°C



Complete microstructure (from the surface to the core)

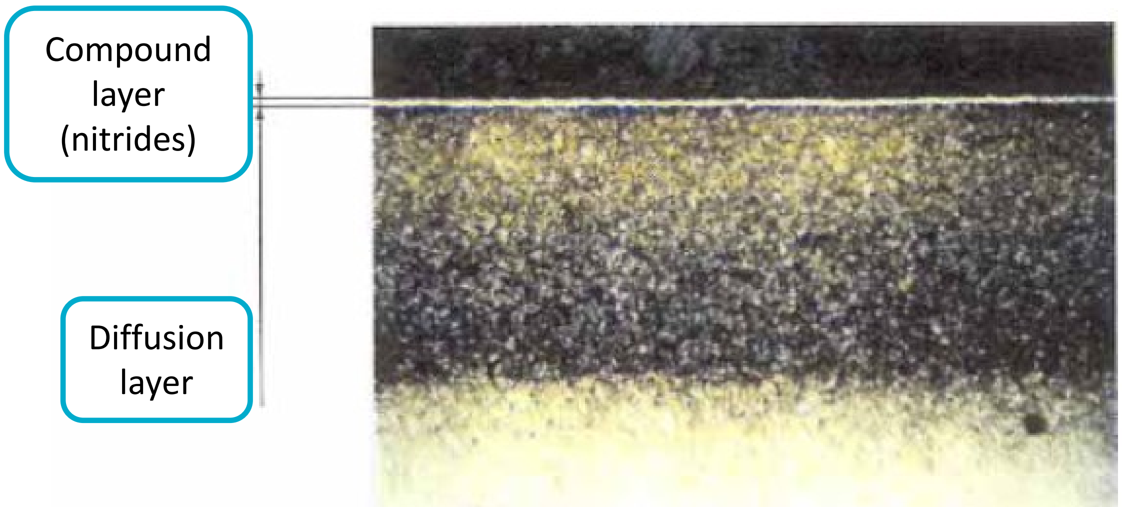


Martensite in surface

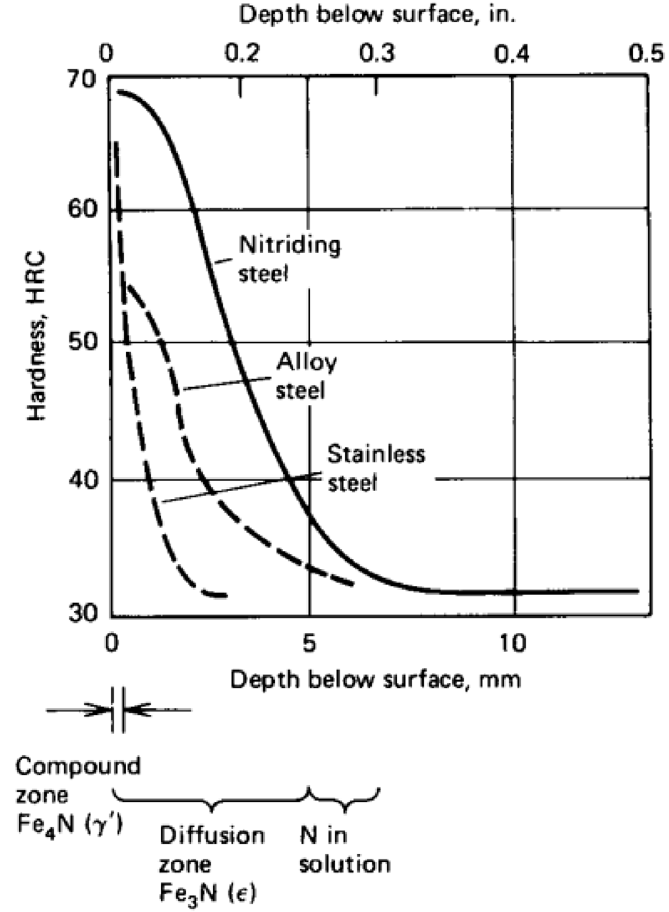


Very fine perlite/bainite in the core

Nitriding



Nital etching
Microscopic observation



Case depth

Depth of diffusion

$$Case\ depth = K \times \sqrt{Time}$$

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

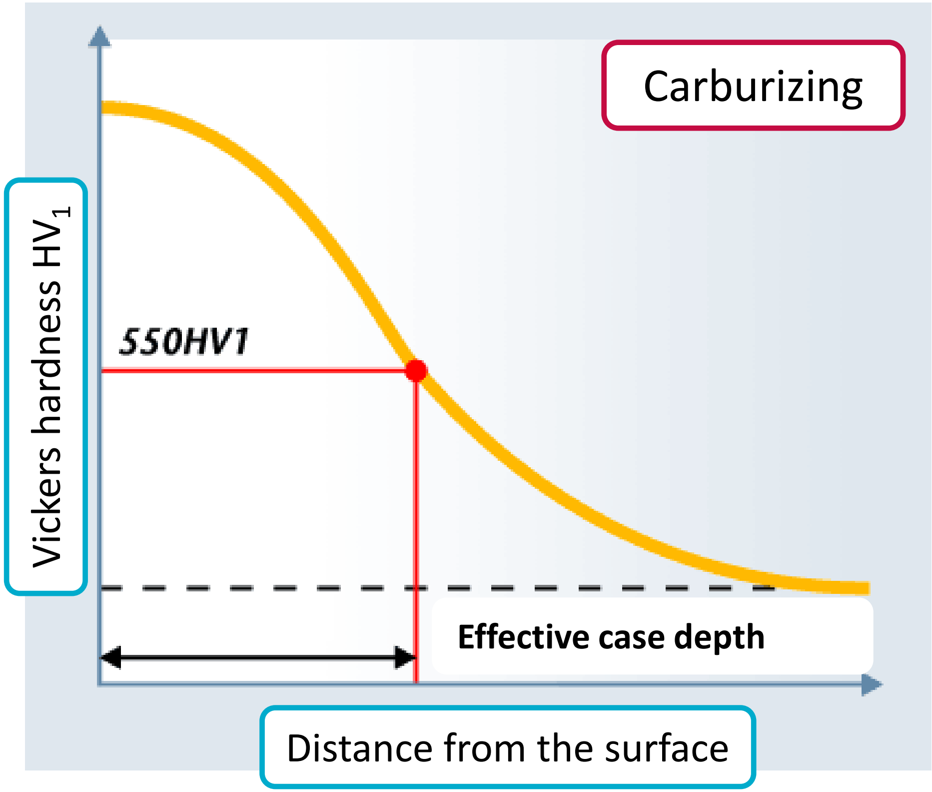
- K increases exponentially as a function of absolute temperature
- Concentration gradients depend on the surface kinetics and reactions of a particular process

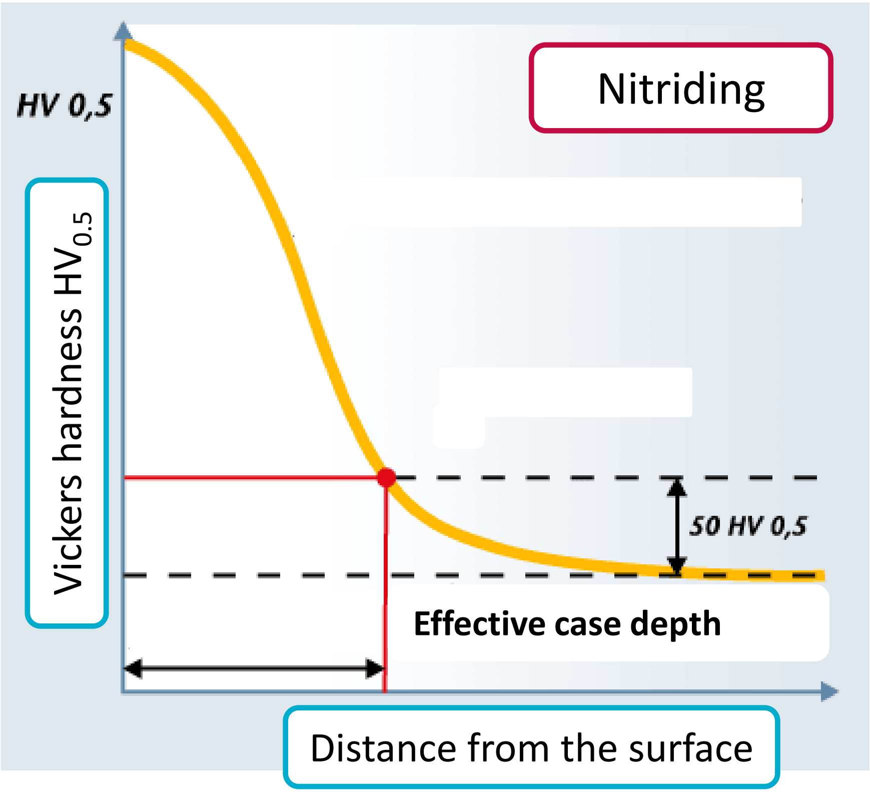
Diffusion substrates

Carburizing	Nitriding				Carbonitriding		Ferritic nitrocarburizing
Low-carbon steels	Alloyed steels	Stainless steels	Tools steels	Nitriding steels	Low-carbon steels	Stainless steels	Low-carbon steels

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

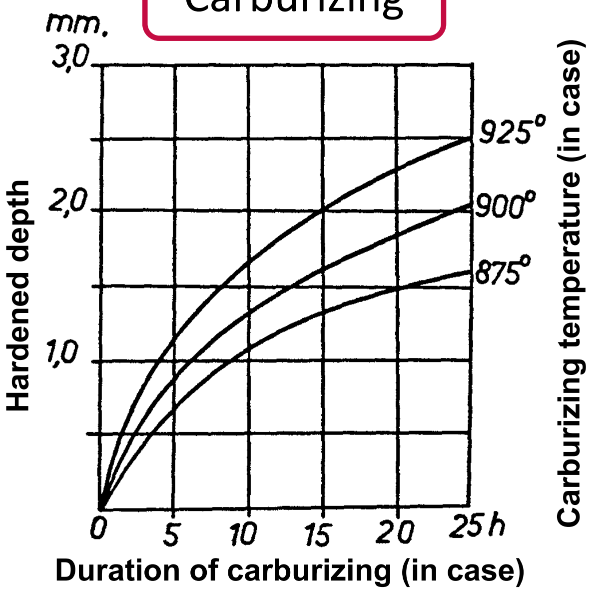




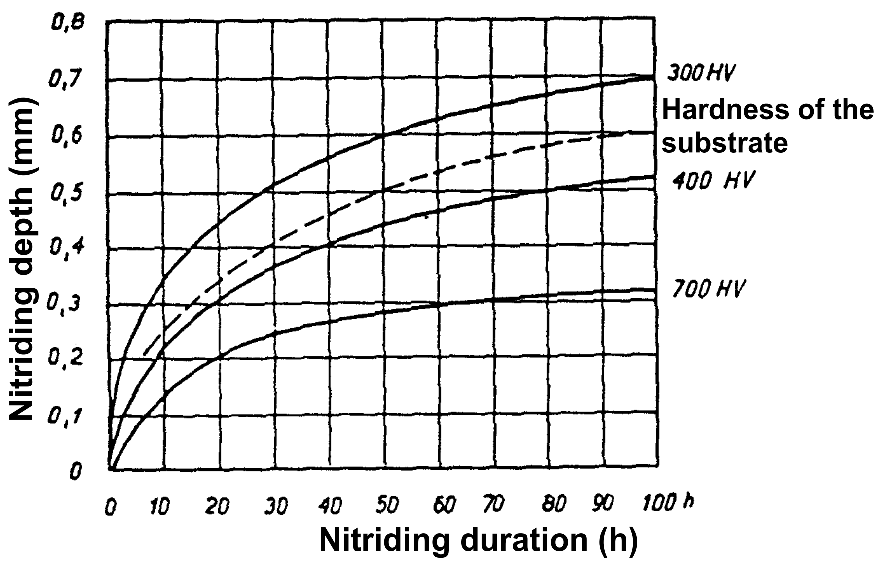
Carburizing or nitriding hardening depth

- Thickness depending on
  - Duration of the hardening treatment

Carburizing

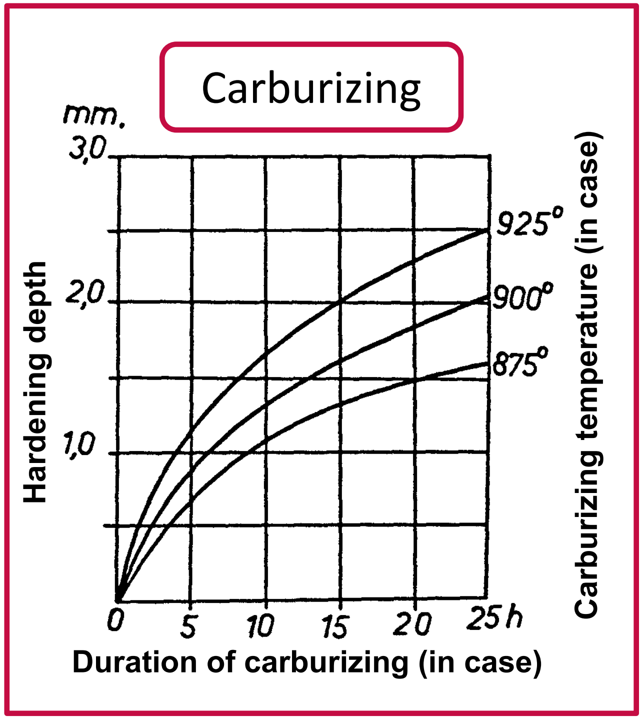


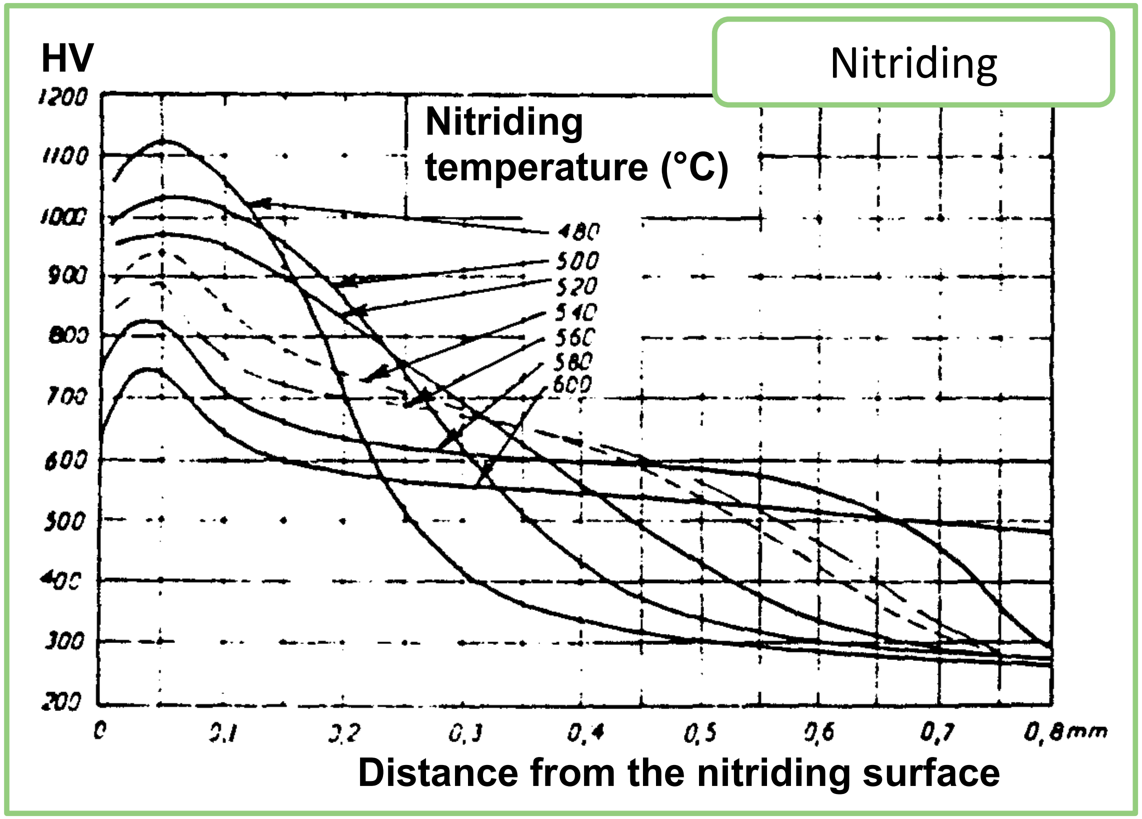
Nitriding



Carburizing or nitriding hardening depth

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

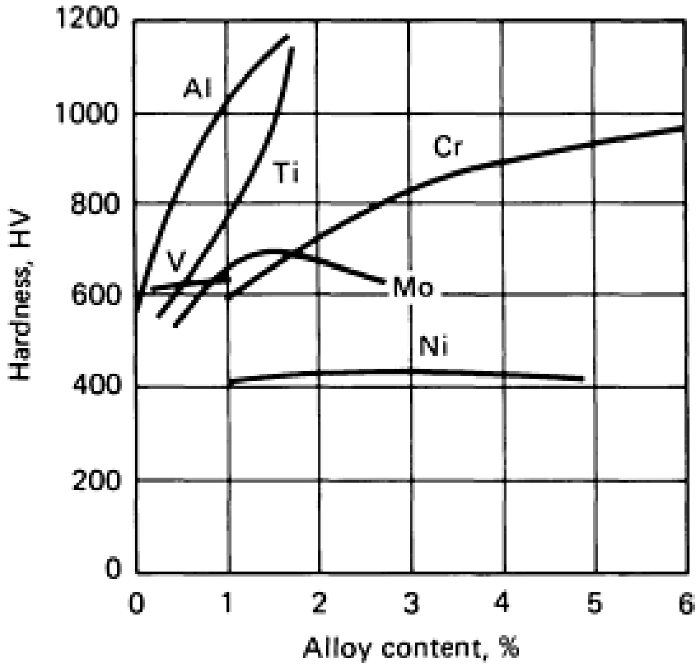


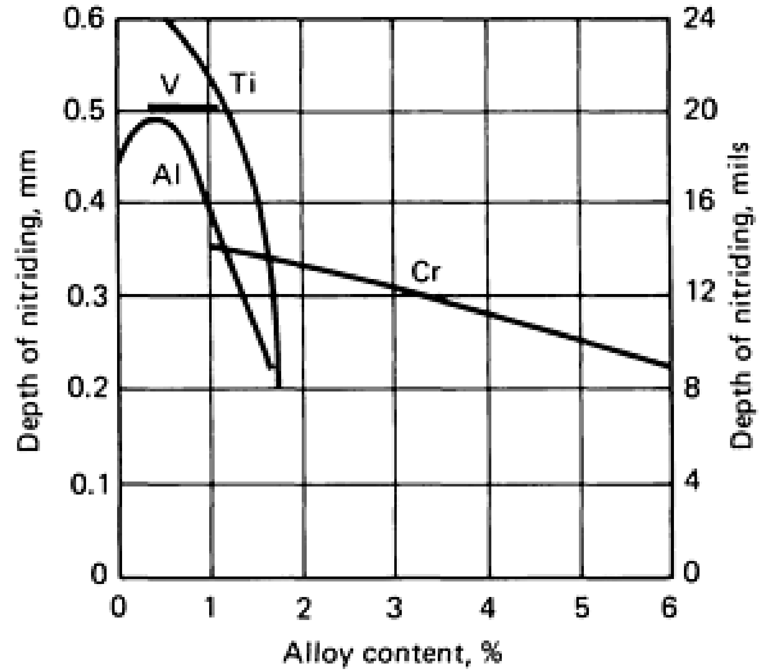


Carburizing or nitriding hardening depth

- 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**
  - <u>After</u> diffusion treatment
    - Quenching + tempering
- **Nitriding**
  - <u>Before</u> 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

Process		Benefits									
		Mechanical/tribological properties					Cost		Others		
		Hardness	Wear-resistance	Capacity for contact load	Bending fatigue	Resistance to seizure	Steel substrate	Capital investment	Freedom from quench cracking	Possible dimension-nal control	Salt corrosion resistance
Superficial heat treatments	Induction hardening	Hard	High (deep case depths)	good	good	fair	low-cost	medium		fair	
	Flame hardening	Hard	High (deep case depths)	good	good	fair	low-cost	low		fair	
Thermo-chemical heat treatments	Carburizing	Hard	High (medium case depths)	excellent	good	good	low-to-medium	high	excellent	fair	
	Nitriding	Hard	High (shallow case depths)	fair	good	excellent	medium-to-high	medium	good (during pretreat-ment)	excellent	improved
	Carbo-nitriding	Hard	High (shallow case depths)	fair	good	good	low-cost	medium	excellent	good	improved

Thank you for your attention

Questions?