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	- bearing races
- 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*** - Vacuum carburizing
- ***Gas 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:

$C + O_2 (initial\ air\ in\ charcoal) \rightarrow CO_2 \qquad CO_2 + C \rightarrow CO$ . . . . (1)

$Fe + 2CO \rightarrow Fe(C\ in\ \ solution) + CO_2 \qquad CO_2 + C \rightarrow CO$ . . . . (2)

$BaCO_3 \rightarrow BaO + CO_2 \qquad CO_2 + C \rightarrow CO$ . . . . (3)

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 ≥ 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

Properties of typical gaseous fuels

Type of gas	Gas gravity	Calorific value				Gross Btu/ft^3 of Std. Air	Gross kcal/m^3 of Std. Air
		Btu/ft^3		kcal/m^3			
		Gross	Net	Gross	Net		
Acetylene, commercial	0.94	1410	1360	12548	12105	115.4	1027
Butane, commercial, natural gas	2.04	3210	2961	28566	26350	104.9	932.6
Butane, commercial, refinery gas	2.00	3184	2935	28334	26119	106.1	944.2
Coke oven, by-product	0.40	569	509	5064	4530	105.0	934
Natural, Alaska	0.55	998	906	8879	8063	104.8	932.6
Natural, Birmingham, AL	0.60	1002	904	8917	8045	106.1	945.1
Natural, Cleveland, OH	0.635	1059	959	9424	8534	106.2	942.4
Natural, Kansas City, MO	0.63	974	879	8668	7822	106.3	946.0
Natural, Pittsburgh, PA	0.61	1129	1021	10047	9086	106.3	945.1
Propane, commercial, natural gas	1.55	2558	2358	22764	20984	107.5	956.6
Propane, commercial, refinery gas	1.77	2504	2316	22283	20610	108.0	961.1

Source: Industrial Thermal Processing Equipment Handbook, by Joseph H. Greenburg: ASM International, Materials Park, Ohio, 1994, p. 110.

Flame Hardening Temperature:

Characteristics of fuel gases used for flame hardening.

Gas	Heating Value (MJ/m^3)	Flame Temperature (°C)	
		With Oxygen	With Air
Acetylene	53.4	3105	2325
City gas	11.2-33.5	2540	1985
Natural gas (Methane)	37.3	2705	1875
Propane	93.9	2635	1925

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^2R, 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.

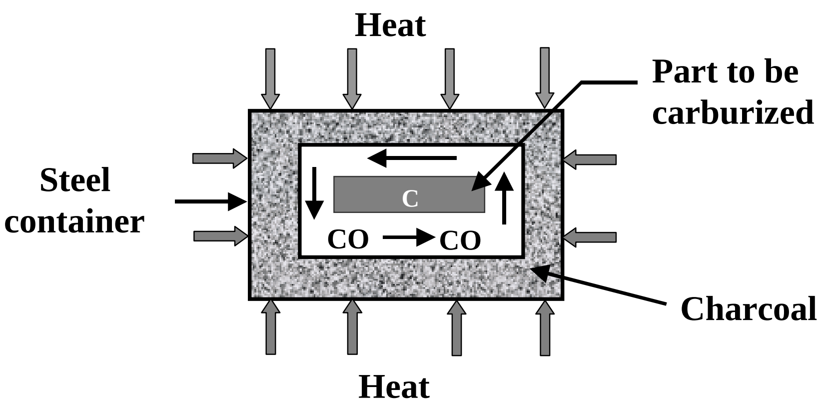


Figure: Pack carburizing process.

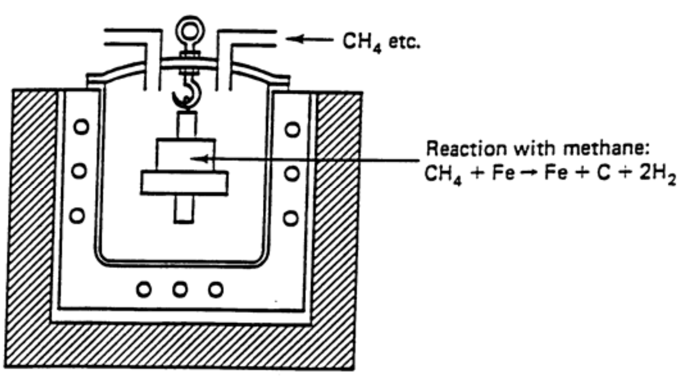


Figure: Gas carburizing process.

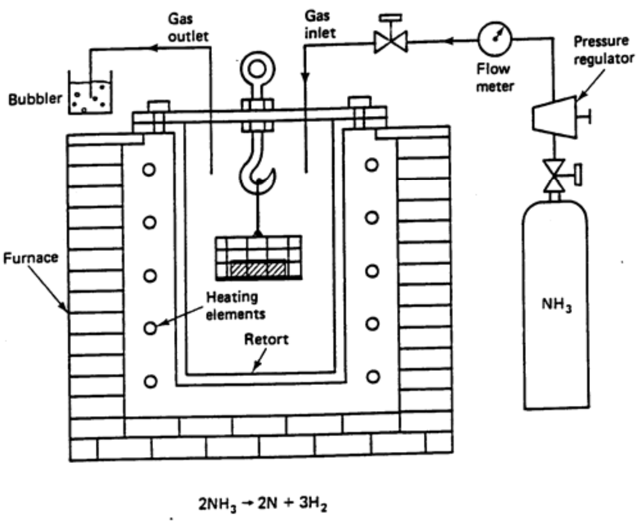


Figure: Nitriding process

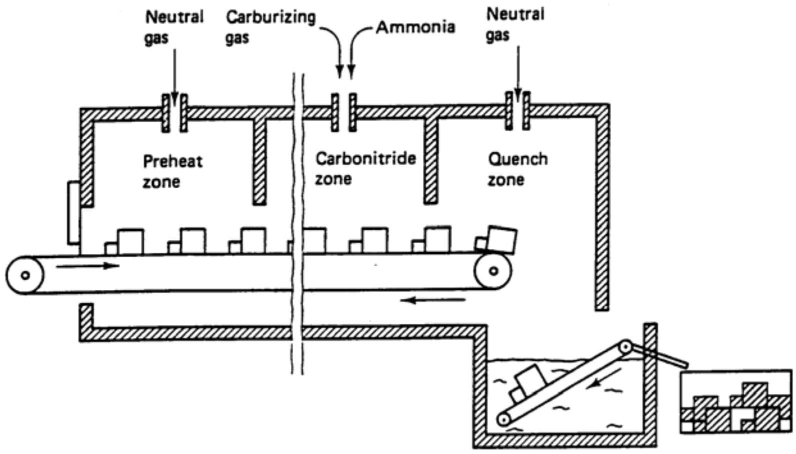


Figure: Carbonitriding process.

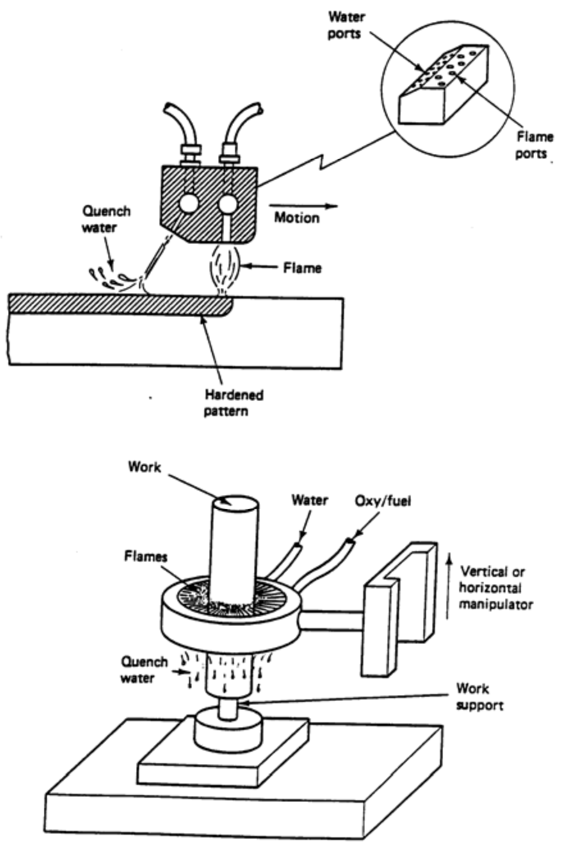


Figure: Flame hardening process.

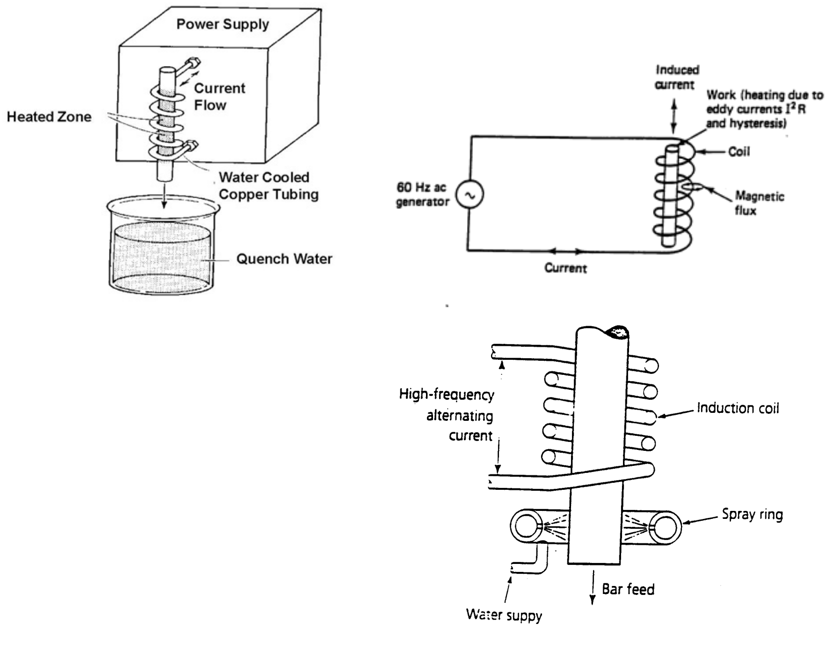
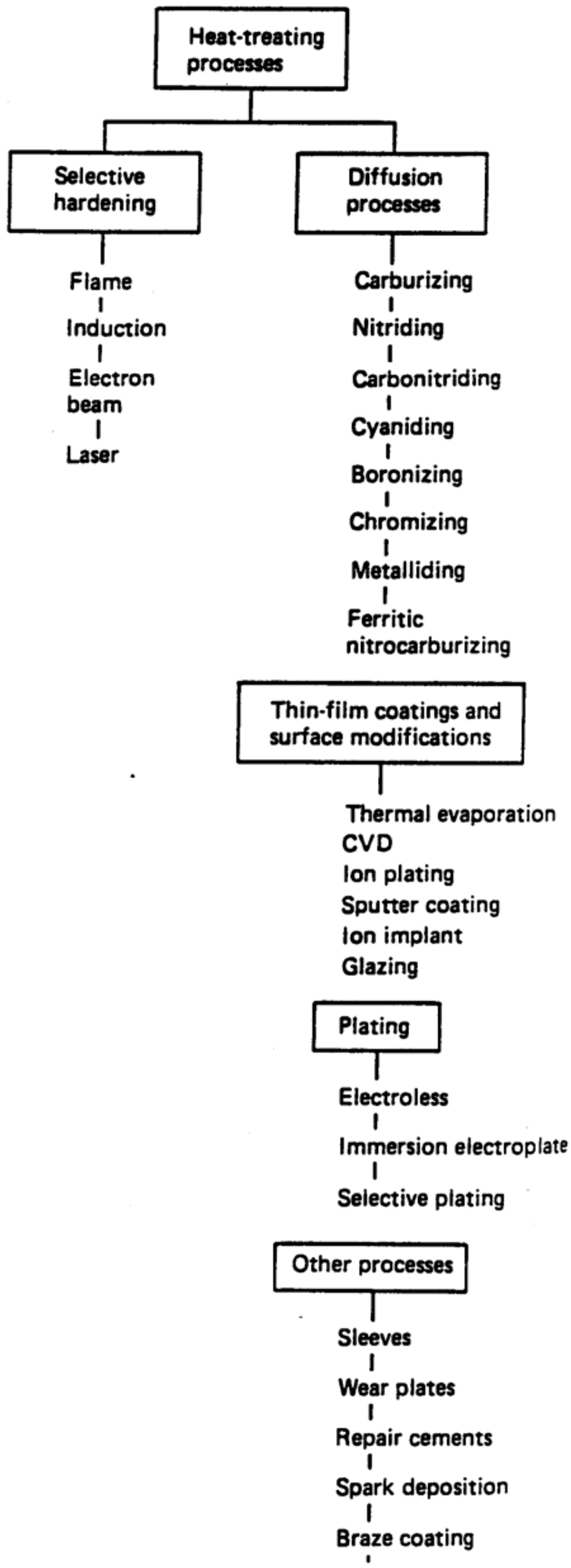


Figure: Induction hardening process.

Surface Hardening Methods



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:

$$\frac{C_x - C_o}{C_s - C_o} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \text{ (1)}$$

Equation (1) can also be written as

$$\frac{C_s - C_x}{C_s - C_o} = erf\left(\frac{x}{2\sqrt{Dt}}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \text{ (2)}$$

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
erf = Gaussian *error function*

erf is defined by $erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2}\, dy$

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.