

# Introduction to Surface Hardening of Steels\*

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**SURFACE HARDENING**, a process that includes a wide variety of techniques (Table 1), is used to improve the wear resistance of parts without affecting the more soft, tough interior of the part. This combination of hard surface and resistance to breakage upon impact is useful in parts such as a cam or ring gear, bearings or shafts, turbine applications, and automotive components that must have a very hard surface to resist wear, along with a tough interior to resist the impact that occurs during operation. Most surface treatments result in compressive residual stresses at the surface that reduce the probability of crack initiation and help arrest crack propagation at the case-core interface. Further, the surface hardening of steel

can have an advantage over through hardening because less expensive low-carbon and medium-carbon steels can be surface hardened with minimal problems of distortion and cracking associated with the through hardening of thick sections.

There are two distinctly different approaches to the various methods for surface hardening (Table 1):

- Methods that involve an intentional buildup or addition of a new layer
- Methods that involve surface and subsurface modification without any intentional buildup or increase in part dimensions

The first group of surface-hardening methods includes the use of thin films, coatings, or weld overlays (hardfacings). Films, coatings, and overlays generally become less cost-effective as production quantities increase, especially when the entire surface of workpieces must be hardened. The fatigue performance of films, coatings, and overlays may also be a limiting factor, depending on the bond strength between the substrate and the added layer. Fusion-welded overlays have strong bonds, but the primary surface-hardened steels used in wear applications with fatigue loads include heavy case-hardened steels and flame- or induction-hardened steels. Nonetheless, coatings and overlays can be effective in some applications. With tool steels, for example, TiN and Al<sub>2</sub>O<sub>3</sub> coatings are effective not only because of their hardness but also because their chemical inertness reduces crater wear and the welding of chips to the tool. Some overlays can impart corrosion-resistant properties. Overlays can be effective when the selective hardening of large areas is required.

This introductory article on surface hardening focuses exclusively on the second group of methods, which is further divided into diffusion methods and selective-hardening methods (Table 1). Diffusion methods modify the

chemical composition of the surface with hardening species such as carbon, nitrogen, or boron. Diffusion methods may allow effective hardening of the entire surface of a part and are generally used when a large number of parts are to be surface hardened. In contrast, selective surface-hardening methods allow localized hardening. Selective hardening generally involves transformation hardening (from heating and quenching), but some selective-hardening methods (selective nitriding, ion implantation, and ion beam mixing) are based solely on compositional modification. Factors affecting the choice of these surface-hardening methods are discussed in the section "Process Selection" in this article.

## Diffusion Methods of Surface Hardening

As previously mentioned, surface hardening by diffusion involves the chemical modification of a surface. The basic process used is thermochemical because some heat is needed to enhance the diffusion of hardening elements into the surface and subsurface regions of a part. The depth of diffusion exhibits a time-temperature dependence such that:

$$\text{Case depth} = K\sqrt{\text{Time}} \quad (\text{Eq 1})$$

where the diffusivity constant,  $K$ , depends on temperature, the chemical composition of the steel, and the concentration gradient of a given hardening element. In terms of temperature, the diffusivity constant increases exponentially as a function of absolute temperature. Concentration gradients depend on the surface kinetics and reactions of a particular process.

Methods of hardening by diffusion include several variations of hardening elements (such as carbon, nitrogen, or boron) and of the

**Table 1 Engineering methods for surface hardening of steels**

### Layer additions

- **Hardfacing:**
  - Fusion hardfacing (welded overlay)
  - Thermal spray (nonfusion-bonded overlay)
- **Coatings:**
  - Electrochemical plating
  - Chemical vapor deposition (electroless plating)
  - Thin films (physical vapor deposition, sputtering, ion plating)
  - Ion mixing

### Substrate treatment

- **Diffusion methods:**
  - Carburizing
  - Nitriding
  - Carbonitriding
  - Nitrocarburizing
  - Boriding
  - Titanium-carbon diffusion
  - Toyota diffusion process
- **Selective-hardening methods:**
  - Flame hardening
  - Induction hardening
  - Laser hardening
  - Electron beam hardening
  - Ion implantation
  - Selective carburizing and nitriding
  - Use of arc lamps

\* Revised from S. Lampman, Introduction to Surface Hardening of Steels, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 259–267

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process method used to handle and transport the hardening elements to the surface of the part. Process methods for exposure involve the handling of hardening species in forms such as gas, liquid, or ions. These process variations naturally produce differences in typical case depth and hardness (Table 2). Factors influencing the suitability of a particular diffusion method include the type of steel (Fig. 1), the desired case hardness (Fig. 2), case depth (Fig. 3), the desired case profile, and cost.

It is also important to distinguish between total case depth and effective case depth. The effective case depth is typically about two-thirds to three-fourths the total case depth. (In some cases, the depth to the hardness value of 50 HRC or five points lower than the surface hardness is also specified.) The required

effective depth and the measurement technique must be specified so that the heat treater can process the parts for the correct time at the proper temperature.

### Carburizing and Carbonitriding

Carburizing is the addition of carbon to the surface of low-carbon steels at temperatures (generally between 850 and 980 °C, or 1560 and 1800 °F) at which austenite, with its high solubility for carbon, is the stable crystal structure. With grades of steel engineered to resist grain coarsening at high temperatures and properly designed furnaces such as vacuum furnaces, carburizing above 980 °C (1800 °F) is practical to dramatically reduce carburizing time.

Hardening is accomplished when the high-carbon surface layer is quenched to form martensitic case with good wear and fatigue resistance superimposed on a tough, low-carbon steel core. Of the various diffusion methods (Table 2), gas carburization is the most widely used, followed by gas nitriding and carbonitriding.

Case hardness of carburized steels is primarily a function of carbon content. When the carbon content of the steel exceeds approximately 0.65%, additional carbon has no effect on hardness but does enhance hardenability. Carbon in excess of 0.65% may not be dissolved, which would require high temperatures to ensure carbon-austenite solid solution. Higher levels of carbon in the case will impact microstructural properties that can enhance performance characteristics such as wear, sliding contact fatigue,

**Table 2 Typical characteristics of diffusion treatments**

Process	Nature of case	Process temperature		Typical case depth	Case hardness, HRC	Typical base metals	Process characteristics
		°C	°F				
<b>Carburizing</b>							
Pack	Diffused carbon	815–1090	1500–2000	125 µm–1.5 mm (5–60 mils)	50–63(a)	Low-carbon steels, low-carbon alloy steel	Low equipment costs; difficult to control case depth accurately
Gas	Diffused carbon	815–980	1500–1800	75 µm–1.5 mm (3–60 mils)	50–63(a)	Low-carbon steels, low-carbon alloy steels	Good control of case depth; suitable for continuous operation; good gas controls required; can be dangerous
Liquid	Diffused carbon and possibly nitrogen	815–980	1500–1800	50 µm–1.5 mm (2–60 mils)	50–65(a)	Low-carbon steels, low-carbon alloy steels	Faster than pack and gas processes; can pose salt disposal problem; salt baths require frequent maintenance
Vacuum/LPC	Diffused carbon	815–1090	1500–2000	75 µm–1.5 mm (3–60 mils)	50–63(a)	Low-carbon steels, low-carbon alloy steels	Excellent process control; bright parts; faster than gas carburizing; high equipment costs
<b>Nitriding</b>							
Gas/LPN	Diffused nitrogen, nitrogen compounds	480–590	900–1100	125 µm–0.75 mm (5–30 mils)	50–70	Alloy steels, nitriding steels, stainless steels	Hardest cases from nitriding steels; quenching not required; low distortion; process is slow; is usually a batch process
Salt	Diffused nitrogen, nitrogen compounds	510–565	950–1050	2.5 µm–0.75 mm (0.1–30 mils)	50–70	Most ferrous metals including cast irons	Usually used for thin hard cases < 25 µm (1 mil); no continuous white layer; most are proprietary processes
Ion	Diffused nitrogen, nitrogen compounds	340–565	650–1050	75 µm–0.75 mm (3–30 mils)	50–70	Alloy steels, nitriding steels, stainless steels	Faster than gas nitriding; no white layer; high equipment costs; close case control
<b>Carbonitriding</b>							
Gas	Diffused carbon and nitrogen	760–870	1400–1600	75 µm–0.75 mm (3–30 mils)	50–65(a)	Low-carbon steels, low-carbon alloy steels, stainless steels	Lower temperature than carburizing (less distortion); slightly harder case than carburizing; gas control critical
Liquid (cyaniding)	Diffused carbon and nitrogen	760–870	1400–1600	2.5–125 µm (0.1–5 mils)	50–65(a)	Low-carbon steels	Good for thin cases on noncritical parts; batch process; salt disposal problems
Ferritic nitrocarburizing	Diffused carbon and nitrogen	565–675	1050–1250	2.5–25 µm (0.1–1 mil)	40–60(a)	Low-carbon steels	Low-distortion process for thin case on low-carbon steel; most processes are proprietary
<b>Other</b>							
Aluminizing (pack)	Diffused aluminum	870–980	1600–1800	25 µm–1 mm (1–40 mils)	< 20	Low-carbon steels	Diffused coating used for oxidation resistance at elevated temperatures
Siliconizing by chemical vapor deposition	Diffused silicon	925–1040	1700–1900	25 µm–1 mm (1–40 mils)	30–50	Low-carbon steels	For corrosion and wear resistance, atmosphere control is critical
Chromizing by chemical vapor deposition	Diffused chromium	980–1090	1800–2000	25–50 µm (1–2 mils)	Low-carbon steel, < 30; high-carbon steel, 50–60	High- and low-carbon steels	Chromized low-carbon steels yield a low-cost stainless steel; high-carbon steels develop a hard corrosion-resistant case
Titanium carbide	Diffused carbon and titanium, TiC compound	900–1010	1650–1850	2.5–12.5 µm (0.1–0.5 mil)	> 70(a)	Alloy steels, tool steels	Produces a thin carbide (TiC) case for resistance to wear; high temperature may cause distortion
Boriding	Diffused boron, boron compound	400–1150	750–2100	12.5–50 µm (0.5–2 mils)	40–> 70	Alloy steels, tool steels, cobalt and nickel alloys	Produces a hard compound layer; mostly applied over hardened tool steels; high process temperature can cause distortion

(a) Requires quench from austenitizing temperature. Source: Ref 1