CHAPTER 7

Process Comparisons

PROCESS COMPARISONS discussed in this Chapter include:

- Process availability
- Corrosion resistance
- Wear resistance
- Cost
- Distortion or size change tendencies
- Thickness attainable

In addition to the information presented below, tables and figures comparing surface-engineering process characteristics that appear in other Chapters should also be referred to. These are summarized in Table 1.

Table 1 Additional process comparison data presented in other Chapters

Source	Description
Chapter 1	
Fig. 1	Compares the thickness of various engineering coatings
Table 1	Categorizes the various surface-engineering options and lists their property benefits
Chapter 3	
Table 4	Gives friction coefficient data for different coatings applied by various processes
Chapter 4	
Table 2	Compares flame- and induction-hardening processes
Chapter 5	
Table 6	Compares the typical characteristics of carburizing, nitriding, carbonitriding, and ferritic nitrocarburizing
Chapter 6	
Fig. 14	Compares the abrasion resistance of TiN coatings applied by various thin-film processes
Fig. 15	Compares the surface hardness of hardened tool steel and a cemented carbide with that of the following surface-hardening processes: TRD, CVD, PVD, boriding, chrome plating, electroless nickel-phosphorus plating, ferritic nitrocarburizing, sulfurizing, and spark hardening
Fig. 16	Compares the wear, scuffing, and spalling resistance of sheet-metal dies coated by the following surface-hardening processes: uncoated, nitrided, borided, nitrogen ion implanted, chrome plated, sulfurized, uncoated cemented carbide, TiC + TiN by CVD, TiC by CVD, VC by TRD, and NbC by TRD
Table 1	Compares the processing characteristics for electroplating, electroless plating, CVD, PVD, thermal diffusion, ion nitriding, TRD, ion implantation, ion-beam assisted deposition, and thermal spraying

(continued)

TRD, thermoreactive deposition/diffusion process; CVD, chemical vapor deposition; PVD, physical vapor deposition

Table 1 (continued)

Source	Description
Chapter 6 (continued)	
Table 9	Compares the wear and corrosion resistance of electroplated copper, electroplated nickel, electroless nickel, electroplated chromium, and electroless nickel + chromium
Table 11	Compares the Taber abrasion resistance of electroplated nickel, electroless nickel, and electroplated hard chromium
Table 14	Compares the characteristics of various weld overlay coatings
Table 15	Compares the applications of thermal spraying, welding, and electroplating
Table 16	Compares the process requirements in thermal spraying, welding, and electroplating
Table 17	Compares the design characteristics of flame, arc wire, high-velocity oxyfuel, detonation gun, air plasma, and vacuum plasma thermal spray processes
Table 19	Compares the abrasive wear resistance of tungsten carbide coatings applied by detonation gun, plasma, and high-velocity oxyfuel thermal spray processes
Table 22	Compares the deposition temperatures for thermal and plasma CVD
Table 26	Compares the processing characteristics of PVD, CVD, and ion implantation processes
Chapter 8	
Table 1	Compares thickness ranges and hardness levels of a wide range of surface-engineering processes
Table 2	Compares surface finish characteristics of various surface-engineering processes
Table 3	Compares size and weight limitations for different surface treatments
Table 4	Summarizes design limitations for surface preparation/cleaning processes
Table 5	Summarizes design limitations for organic coating processes
Table 6	Summarizes design limitations for inorganic (metal and ceramic) coating processes

TRD, thermoreactive deposition/diffusion process; CVD, chemical vapor deposition; PVD, physical vapor deposition

Process Availability

One of the key considerations in the materials selection process is material availability and delivery time. This is especially true if a person/company has only a limited time for completing a part. Even without time constraints, materials engineers tend to use materials that are readily available. Similarly, the choice of a surface-engineering process is often based on process availability because poor logistics between the customer and surface treatment supplier can result in added shipping time and costs.

In general, the long-established surface-engineering processes are available from numerous job shops in varied locations. These would include localized surface-hardening treatments, diffusion heat treatments such as carburizing and nitriding, weld surfacing, thermal spraying, electroplating, galvanizing, and painting. However, within these surface-treatment categories there may be a wide disparity in the availability of specific processes. For example, most heat treating job shops offer flame and induction localized hardening, but few have facilities for electron beam or laser localized surface hardening. The same can be said of diffusion heat treatments. In a survey of 800 commercial heat treating shops in the United States and Canada (Ref 1), 70% offered carburizing services, of which:

- 48% offered gas atmosphere carburizing
- 19% offered pack carburizing
- 12% offered salt-bath carburizing
- 5% offered carburizing in fluid beds

- 2% offered vacuum carburizing
- 1% offered plasma (ion) carburizing

Thus, process availability might negate the selection of plasma carburizing over conventional methods, despite the reduced carburizing times and more uniform case depths associated with plasma methods. A similar situation exists for gas nitriding and plasma (ion) nitriding.

The more specialized pack-cementation diffusion processes, such as aluminizing, chromizing, siliconizing, and boronizing, are usually carried out at companies that specialize in these processes. Some of these processes are also performed by aerospace companies, for example, aluminizing of jet engine turbine components.

More recently developed coatings or surface modifications—such as chemical vapor deposition (CVD), physical vapor deposition (PVD), ion implantation, and laser melting, alloying, or cladding—are also performed by companies that specialize in these processes/coatings. For example, most cutting tool manufacturers offer CVD, PVD, or CVD + PVD processing. The availability of facilities offering various surface-engineering options can best be determined by contacting technical associations that offer information services for these surface treatments. Examples include:

- American Electroplaters and Surface Finishers Society
- American Galvanizers Association
- American Welding Society
- Association of Industrial Metallizers, Coaters, and Laminators
- Federation of Societies for Coating Technology
- National Paint and Coatings Association
- Powder Coating Institute
- Society of Vacuum Coaters
- Steel Structures Painting Council
- Thermal Spray Society or the International Thermal Spray Association
- The Society for Protective Coatings

Descriptions of these organizations including their scope, addresses, telephone and fax numbers, web site or e-mail access, and so forth can be found in the *Encyclopedia of Associations,* published by Gale Group Publishing and available at most local public libraries.

Corrosion Resistance

Corrosion-resistant protective coatings include various organic and inorganic coatings that provide barrier protection (e.g., a paint coating or multilayer electroplate) or sacrificial protection (e.g., zinc and aluminum

Table 2 Salt mist corrosion performance of various steels and coatings

Surface	Coating life(a), h
Steels	
Low-alloy steel or low-carbon steel	2
Induction-hardened carbon steel	2
Stainless steel (316)	<2000
Carburized mild steel	2
Nitrided low-alloy steel	20
Nitrocarburized/oxidized mild steel	400
Nitrided stainless steel	2
Phosphated mild steel	500–1000
Steam-tempered alloy steel	300–500
Coatings (on mild steel)	
Hard chrome plate	<10
Crack-free chrome	30–50
Electroless nickel (as-deposited)	100–1000
Hardened electroless nickel	50–500
Electroless nickel + polymer	1500
Electroless nickel-PTFE	<20
Electroless nickel-SiC	<20
Nickel electroplate	<1000
Nickel-ceramic electroplate	500
Cadmium plate	<2000
Zinc plate	1000
Zinc-9Ni plate	2000
Hot dip galvanized	1000
Hot dip aluminized	500
PVD TiN	2
Plasma sprayed ceramic	10
High-velocity oxyfuel cermet	1000
Spray and fused nickel-chromium	2000
Slurry/sinter formed ceramic	<2000
Aluimnum alloy 6082	5
Anodized	300
Anodized + polymer in-fill	1800

PTFE, polytetrafluoroethylene. (a) Time at which five or more individual corrosion spots have formed on the upper facing of the test panel. Copyright AEA Technology plc; used with permission. Source: Ref 2

coatings). As described in Chapter 2, the corrosion resistance of these coatings is often determined by accelerated laboratory tests. Table 2 lists the results of the neutral salt-spray (fog) test described in ASTM B 117 on substrate and coating materials. These data should be used with caution because the corrosion response of a given coating changes from environment to environment. Coating suppliers should be consulted for final coating material selection. The type of coating process selected is dependent on the design factors described in Chapter 8.

Wear Resistance

Hardness versus Wear Resistance. The wear processes that are *usually* mitigated by the use of hard surfaces are low-stress abrasion, wear in systems involving relative sliding of conforming solids, fretting wear, galling, and to some extent, solid-particle erosion (Ref 3). Unfortunately there are many caveats to this statement, and substrate/coating selection should be

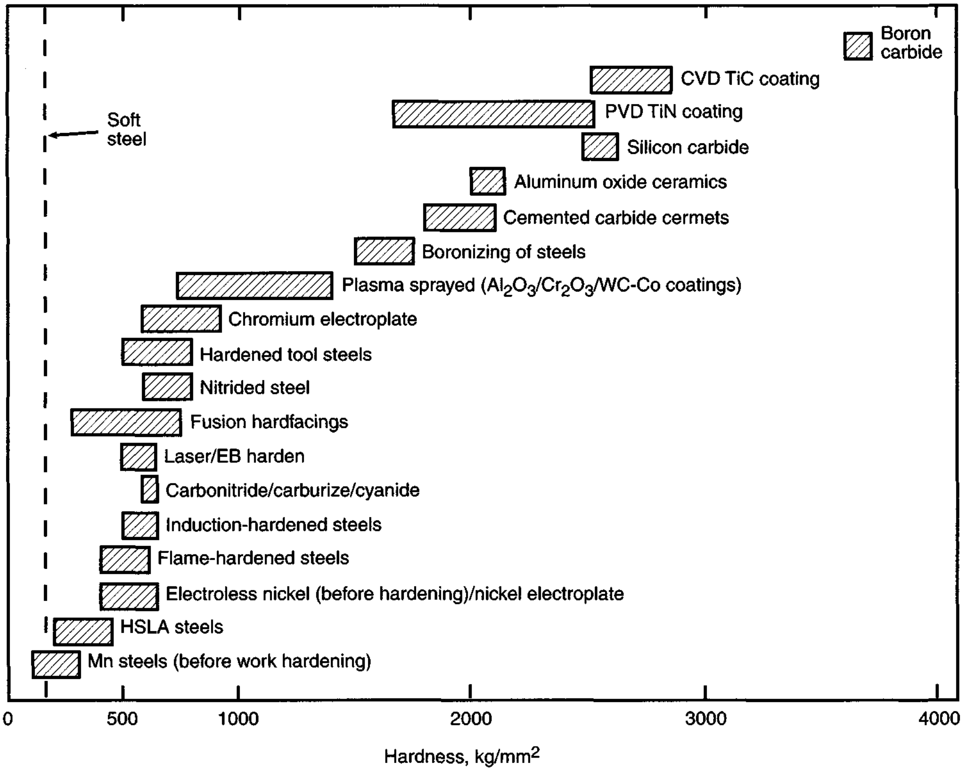

Fig. 1 Range of hardness levels for various materials and surface treatments. Source: Ref 3

carefully studied with proper tests carried out if necessary. Coating suppliers should also be consulted. Chapter 3 provides additional information on wear processes and the means to prevent specific types of wear.

Figure 1 shows typical ranges in hardness for many of the surface-engineering processes used to control wear. All of the treatments shown in this figure have hardness values greater than ordinary constructional steel or low-carbon steel. The surface-hardening processes that rely on martensitic transformations all have comparable hardness, and the diffusion treatments that produce harder surfaces are nitriding, boronizing (boriding), and chromizing. The hardest metal coating is chromium plate, although hardened electroless nickel plate can attain values just under that of chromium. The surfaces that exceed the hardness of chromium are the cermets or ceramics, or surfaces that are modified so that they are cermets or ceramics. These include nitrides, carbides, borides, and similar compounds. The popular solid ceramics used for wear applications—aluminum oxide, silicon carbide, and silicon nitride—generally have hardnesses in the range of 2000 to 3000 kg/mm^2. As shown in Fig. 1, when materials such as aluminum oxide are applied by plasma spraying or other thermal spray process, they have hardnesses that are less than the same material in solid pressed-and-sintered form. This is because the sprayed

Table 3 Comparison of thermal spray methods

As described in the text, coating porosity affects coating hardness.

	Gas flow		Flame or exit plasma temperature		Atmosphere around particles	Particle impact velocity		Maximum spray rate		Coating porosity, %
Method	m^3/h	ft^3/h	°C	°F		m/s	ft/s	kg/h	lb/h	
Combustion powder	11	400	2,200	4,000	CO, CO_2, H_2O	30	100	7	15	6–15
Combustion wire	71	2,500	2,800	5,000	N_2, CO, CO_2, H_2O	180	600	9	20	6–15
Arc wire	71	2,500	5,500	10,000	N_2, O_2	240	800	16	35	2–8
Plasma	4.2	150	5,500	10,000	N_2, Ar, H_2, O_2	240	800	5	10	<2
High-energy plasma	17–28	600–1,000	11,000	20,000	N_2, Ar, H_2, O_2	240–1,200	800–4,000	23	50	<1
Vacuum plasma	8.5	300	11,000	20,000	Ar, He	240–610	800–2,000	11	24	<0.5
D-gun	11	400	3,100	5,600	N_2, CO, CO_2, H_2O	910	3,000	1	2	<1
HVOF	28–57	1,000–2,000	3,100	5,600	N_2, CO, CO_2, H_2O	610–1,500	2,000–5,000	14	30	<0.5

D-gun, detonation gun; HVOF, high-velocity oxyfuel. Source: Ref 4

materials contain porosity and oxides that are not contained in the sintered solid form. Table 3 shows the coating porosity that can be expected from variations in the thermal spray process. The other hard surface for tools, cemented carbide, has a hardness of about 2000 kg/mm^2, about twice as hard as the hardest metal. Recently developed diamond and diamondlike carbon coatings deposited by CVD processing have hardness levels in excess of 5000 kg/mm^2.

Table 4 Low-stress abrasive wear rankings for various materials

See text for details.

	Low wear rate
100	HVOF WC-Co
200	CVD CrC (high-carbon low-alloy tool steel)
300	CVD CrN (high-chromium tool steel)
	Carbide diffusion process
400	PVD CrN, 30 μm thick
500	Hard chrome plate
	Sprayed and HIP chromium
800	Plasma sprayed alumina-titania
1,000	Electroless nickel-ceramic
	Boronized 316 stainless steel
	Plasma sprayed chromium oxide
1,500	Spray and fused nickel-chromium-chromium carbide
4,000	Carburized steel
	Induction-hardened 0.4% C steel
	Slurry/sinter formed ceramic
5,000	Nitrided 316 stainless steel
8,000	Hardened electroless nickel
10,000	As-plated electroless nickel
12,000	0.4% C steel, normalized
15,000	316 stainless steel
	PVD CrN (2 μm thick)
	Anodized aluminum alloy
50,000	Aluminum alloy
	High wear rate

CVD, chemical vapor deposition; PVD, plasma vapor deposition; HIP, hot isostatically pressed. Copyright AEA Technology plc; used with permission. Source: Ref 2

Table 5 Erosive wear rankings for various materials

Test conditions: 1000 ppm of silica sand in water with an impact velocity of 25 m/s (80 ft/s)

	Low wear rate
100	High-chromium iron weld overlay
200	Spray and fused nickel-chromium-chromium carbide Boronized 316 stainless steel
300	High-energy sprayed WC-Co
700	Hard chrome plate
800	Nitrided 316 stainless steel
1000	Electroless nickel
1500	Slurry/sinter formed ceramic
2000	PVD TiN 316 stainless steel
	High wear rate

PVD, plasma vapor deposition. Copyright AEA Technology plc; used with permission. Source: Ref 2

Test Results. Table 4 shows results of the ASTM G 65 dry-sand/rubber-wheel test on various coatings. The low-stress abrasion resistance performance is indexed to that of the best quality tungsten carbide-cobalt (WC-Co) coating, denoted a value of 100, and is related to volume loss per revolution of the wheel under a fixed load, at constant speed and abrasive throughput.

Table 5 shows the resistance of various coatings to erosive wear. The results are indexed to that of a high-chromium cast iron hardfacing alloy, again denoted by a value of 100.

Table 6 shows typical adhesive dry rubbing wear values for surface treatments and coatings. These were determined from a pin-on-plate

Table 6 Adhesive wear rates of various materials

Wear rate, $m^3/N \cdot m$	Material
10^{-17}	Lubricated through-hardened steel
10^{-16}	HVOF WC-Co Plasma sprayed chrome oxide PVD TiN (not at high loads) CVD CrN or alumina
10^{-15}	Hard chrome plate Nitrided tool steel Nitrided stainless steel (not at higher loads) Slurry/sinter formed ceramic (not higher loads)
10^{-14}	Carburized steel Nitrided low-alloy steel Unlubricated through-hardened steel Glass-filled PTFE
10^{-13}	Anodized aluminum Hardened electroless nickel
10^{-12}	Electroless nickel, as plated Normalized, unlubricated steel
10^{-11}	Austenitic stainless steel Copper plate Electrolytic nickel plate
10^{-10}	Aluminum alloy Unfilled PTFE coating
10^{-9}	Cadmium and zinc plates Unfilled PFA or FEP polymer coatings
10^{-8}	Silver plate

HVOF, high-velocity oxyfuel; PVD, plasma vapor deposition; CVD, chemical vapor deposition; PTFE, polytetrafluoroethylene; PFA, perfluoro alkoxy alkaline; FEP, fluorinated ethylene propylene. Copyright AEA Technology plc; used with permission. Source: Ref 2 sliding test using a polished hardened steel pin rubbing against the treated surface at a load of 10 N/m^2 (~100 gf/ft^2).

Cost of Surface Treatments

Cost must be weighed against the performance required for the surface-treatment system. A low-cost surface treatment that fails to perform its function is a wasted expense. Unfortunately, it is nearly impossible to give absolute comparative costs for different surface-engineering options. Often, a range of prices will be offered for a particular job from different, equally competent candidate suppliers. Probably the most important factor that relates to costs of producing a corrosion- or wear-resistant surface on a part is part quantity. Treating many parts usually allows economies in treatment and finishing.

Another consideration when assessing surface treatment costs is part size. There are some critical sizes for each surface-treatment process above which the cost of obtaining the treatment may be high. A number of surface treatments require that the part fit into the work zone of a vacuum chamber. The cost of vacuum equipment goes up exponentially with chamber volume.

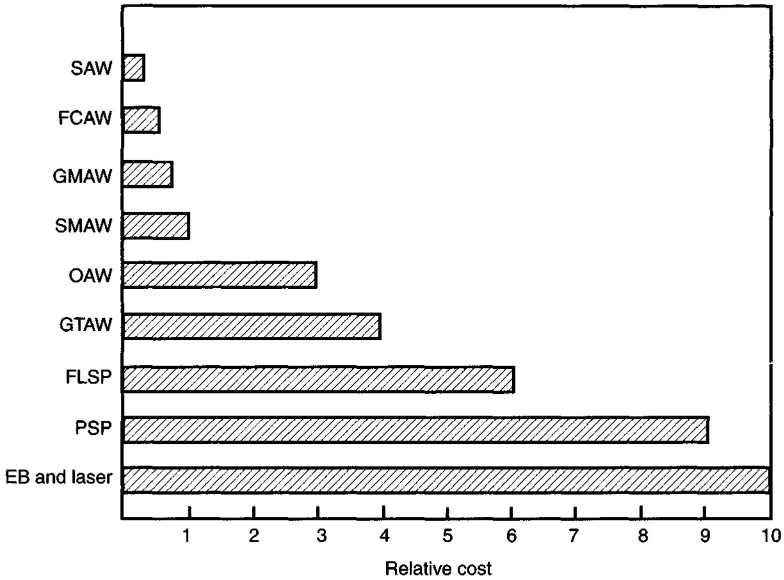

Fig. 2 Relative costs (based on pounds of alloy deposited) for various weld overlay and thermal spray processes. SAW, submerged arc welding; FCAW, flux-cored arc welding; GMAW, gas metal arc welding; SMAW, shielded metal arc welding; OAW, oxyacetylene gas welding; FLSP, flame spraying; PSP, plasma spraying; EB, electron beam. Source: Ref 3

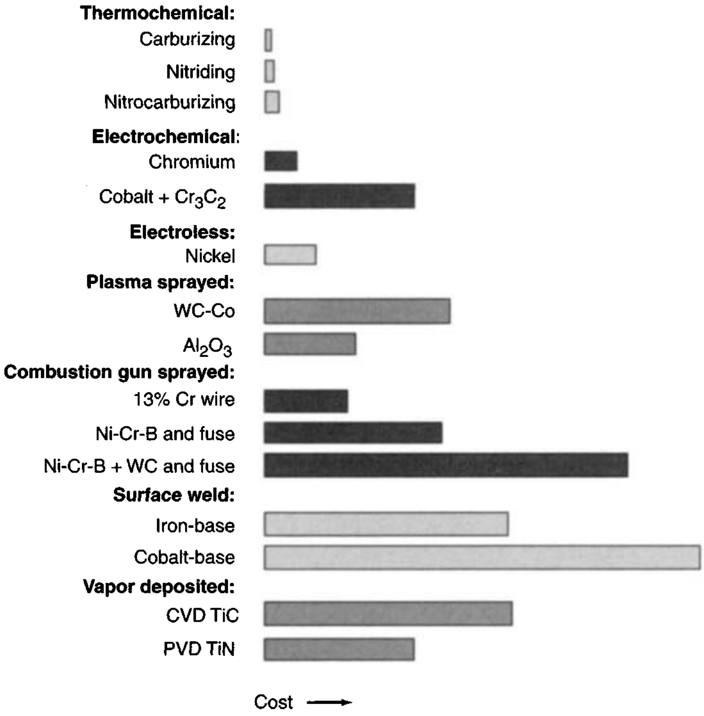

Fig. 3 Approximate relative costs of various surface treatments

Other factors to be considered are:

- The time required for a given surface treatment
- Fixturing, masking, and inspection costs
- Final finishing costs
- Material costs
- Energy costs
- Labor costs
- Environmentally related costs, for example, disposal of spent plating solutions
- Expected service life of the coating

Because of these various factors, it is difficult to compare costs with a high degree of accuracy. Figures 2 and 3 provide some general guidelines for cost comparisons.

Distortion or Size Change Tendencies

Figure 4 shows the surface temperatures that are encountered in various surface-engineering processes. As indicated in the figure, the processes are categorized into two groups: one group produces negligible part dis-

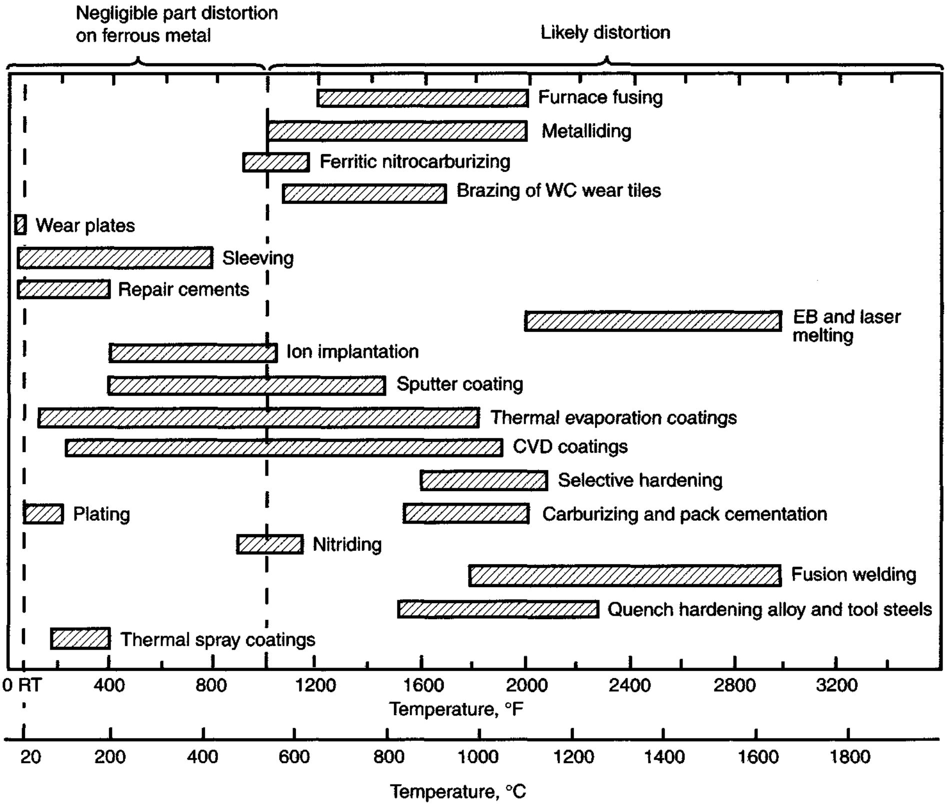

Fig. 4 Maximum surface temperatures that can be anticipated for various surface-engineering processes. The dashed vertical line at 540 °C (1000 °F) represents the temperature limit for distortion for ferrous metals. Obviously, a temperature of 540 °C (1000 °F) would melt a number of nonferrous metals, and it would cause distortion on metals such as aluminum or magnesium. However, this process temperature information can be used to compare the heating that will be required for a particular process. Source: Ref 3

tortion, and the other group contains processes that have varying potential for causing distortion. Obviously if a part could benefit from a surface treatment, but distortion cannot be tolerated, processes that require minimal heating should be considered.

Coating Thickness Attainable

Figure 5 shows the typical thickness/penetration capabilities of various coating and surface treatments. As indicated in the figure, some surface-engineering treatments penetrate into the surface and there is no intentional buildup on the surface. These are the surface-engineering processes described in Chapters 4 and 5. Other surface treatments coat or intentionally build up the surface. This is a selection factor. Can a part tolerate a buildup on the surface? If not, the selection process is narrowed to the

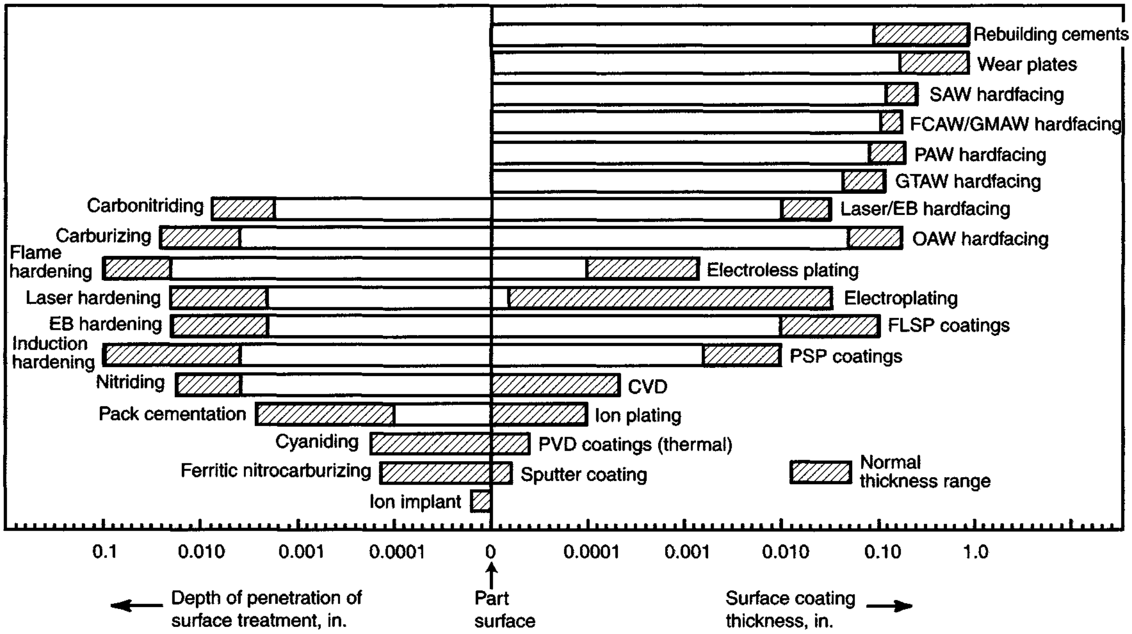

Fig. 5 Typical coating thickness/depth of penetration for various coating and surface-hardening processes. Source: Ref 3

treatments that penetrate into the surface. Other factors affecting the thickness of a given surface treatment include dimensional requirements, the service conditions, the anticipated/allowable corrosion or wear depth, and anticipated loads on the surface. Questions or concerns related to coating thickness should be discussed with the contractor. Available specifications should also be reviewed. Additional information regarding the thicknesses associated with various surface-engineering processes can be found in Chapters 4 to 6 and 8.

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