THE DESIGN ENGINEER is faced with a wide range of options when selecting a surface treatment for a given problem or application. Some of the important factors described in this Chapter that must be considered before selecting a surface treatment include (Ref 1):

- The function of the component. Is it rolling, sliding, in static contact, and so forth?
- The base material. Is it a low-carbon steel, medium-carbon steel, low-alloy steel, a nonferrous alloy, and so forth?
- The fabrication method. Is it cast, welded, machined, and so forth?
- Temperature restrictions, that is, the temperature that must not be exceeded when carrying out a surface-engineering treatment. Will distortion of the component result?
- The interactions to which the component will be subjected, for example, sliding, rolling contact, static corrosion, including special requirements for strength or fatigue resistance
- The operating environment. Is it corrosive or abrasive in nature? Is it saline, oxidizing, caustic, and so forth?
- The temperature of the environment. What is the maximum temperature the component will likely see in service?
- The material from which any component or product in rubbing contact with the part is made, that is the counterface material and its hardness. Does the counterface material contain a hard abrasive filler?
- The predominant mode of degradation. Is it corrosion, wear, fatigue, and so forth?
- The essential requirements for successful performance, for example, low-stress abrasion, high-stress abrasion, nonsticking, and so forth
- The contact load (maximum value) and likely contact area. Is it over a large area or concentrated?
- The contact conditions, for example, impact, cyclic loading, static loading, or sliding
- The required surface hardness of the component
- The requirements for surface roughness (or smoothness)
- Constraints on any final or finishing operations. Are there any critical dimensions or tolerances that must be met after processing?
- The required surface coverage and thickness of any treatment
- The geometry of the component. Are holes, sharp edges, enclosures, reentrants, and so forth, present?
- The overall size and weight of the component
- Are there special requirements that must be met, for example, Department of Defense (DOD), Food and Drug Administration (FDA)?
- Appearance, for example, color or texture

Surface-Engineering Solutions for Specific Problems (Ref 1)

This section provides surface-engineering solutions for seven operating conditions:

- Structural parts, for example, pipes, pump and valve bodies, casings, housings, supports, rigs, tanks, and so forth, subjected to corrosive conditions in various environments
- A part in static contact with another engineering component with small relative motions or vibrations
- A part in static contact with a product that is being cast, molded, cured, and so forth
- A part in rolling contact with another part, for example, shafts, journals, pistons, rings, gears, seals, and tools for metal pressing, forming, drawing, and cutting
- A part under light mechanical load but which handles, rubs, or slides against an abrasive product, for example, paper, filled plastics, textile yarns, leather, friction materials for clutches and brakes, pharmaceuticals, and some foodstuffs like wheat and soy
- A part under high mechanical load, with or without impact, that handles or slides against abrasive or erosive materials, for example, coal chutes and conveyors, crushers, digging equipment, and so forth
- A part in rolling or sliding contact with another part in the presence of corrosive or abrasive materials, for example, pumps, valves, mechanical seals, and slurry handling
Emphasis is placed on the base material, operating conditions, and applicable surface treatments. As can be seen, alternative coating processes/materials may be recommended for a given material/operating condition combination. Final selection may be based on some of the application and performance requirements listed above and further examined in subsequent sections of this Chapter.

**Structural Parts in Corrosive Environments (Ref 1)**

If the part is structural with no sliding or rubbing contacts, then the main concern will be corrosion. Also, if there is cyclic loading—that is, fatigue—corrosion can considerably accelerate mechanical failures. Environmentally assisted cracking due to corrosion fatigue, stress-corrosion cracking (SCC), or hydrogen damage is discussed in Chapter 2.

**Base Material**

Base materials for structural parts are commonly an engineering steel, cast iron, stainless steel (most probably a ferritic or martensitic type), or an aluminum alloy.

**Neutral Environments**

If there is no concern about corrosion, but there is a requirement for improved strength or fatigue resistance, the following surface treatments should be considered:

- Shot peening
- Improving the surface quality and finish by grinding, lapping, or polishing

**Specific Corrosive Environments**

If there is concern about corrosion, then both the corrosive medium and the temperature are important. Also, if the part is in contact with another metallic component of a dissimilar material, then galvanically assisted corrosion, which accelerates failure, is very possible.

For outdoor, normal atmospheric corrosion, consider:

- Hot dip galvanizing, which can provide prolonged protection even in polluted environments
- Thermally sprayed zinc or aluminum
- Electrolytic zinc
- Painting or powder coatings with appropriate surface preparation and priming
- Heavy electrolytic nickel provided there are no defects in the coating
- Electroless nickel-phosphorus coating
- Aluminum ion plating
- Phosphating for moderate protection
- Anodizing, preferably sealed, for aluminum alloys

For more hostile environments, including marine and aerospace where galvanic corrosion will be a major concern, consider:

- Hot dip galvanizing, which will provide moderate protection
- Thermally sprayed zinc or aluminum for moderate protection
- Electrolytic zinc or zinc-nickel alloy (10–14% Ni) coating followed by chromate passivation and an organic topcoat
- Painting, with appropriate preparation and priming, perhaps zinc or aluminum loaded
- Cadmium plate, preferably chromate passivated for maximum protection

High-Temperature Oxidation and Corrosion. The substrates for high-temperature corrosion applications are often superalloys, stainless steels, or titanium alloys. Protective coatings to be considered include:

- Diffusion chromizing for oxidation resistance up to 750 to 800 °C (1380–1470 °F)
- Diffusion aluminizing for protection against oxidation, carburizing, and sulfur and vanadium corrosion in chemical plants and gas turbines; can be effective above 800 °C (1470 °F)
- Slurry/sinter formed ceramics (chromium oxide based) at temperatures up to 600 °C (1110 °F)
- Thermally sprayed coatings, for example, MCrAlY corrosion protection layers and ceramic-based thermal barriers

For caustic environments, consider:

- Slurry/sinter-formed ceramics (chromium oxide based)
- Thermally sprayed ceramics, for example, chromium oxide, alumina, preferably sealed
- Cadmium plate, preferably chromate passivated for moderate protection
- Electroless nickel
- Heavy electrolytic nickel plating

For acidic environments, consider:

- Slurry/sinter-formed ceramics (chromium oxide based)
- Thermally sprayed ceramics, for example, chromium oxide, alumina, preferably sealed
For stress-assisted corrosive conditions, consider shot peening followed by corrosion protection appropriate to environmental conditions, but only those processes applied at near-ambient temperature.

**Parts in Static Contact with Vibration (Fretting) (Ref 1)**

If the part is in contact with another engineering component, but with no relative movement, then the main concern will be with corrosion. If the mating part is a dissimilar metal, then galvanic corrosion will be a significant risk (see Chapter 2).

If the contact also involves vibration or impact motion then fretting, fretting corrosion, or even fretting fatigue must be considered.

This is the case with splines and couplings where motion is transmitted from one part to another via a loaded contact and in parts fastened or fitted together where there is a source of external vibration, for example, heat exchangers and bearing housings. Fretting-type failures are also found on chains, pulleys, and wire ropes.

**Base Material**

Fretting corrosion is most prevalent with steel parts where the oxidation process produces an obvious, distinctive, red oxide abrasive dust. Stainless steels are not immune, particularly ferritic types. Fretting of aluminum alloys produces a white oxide debris that is also very abrasive.

**Contact Conditions**

**Fretting and Fretting Corrosion.** With light loads or low-cycle fatigue, the effects of fatigue will usually be small, and the preferred solution is to reduce the tendency to oxidation by applying an inert coating. Consider the following treatments:

- Hot dip galvanizing
- Heavy electrolytic nickel or copper plating, which will provide a low-corrosion surface but one with a tendency to gall and to wear quickly
- Electroless nickel, which will provide good oxidation protection, with extra wear resistance if hardened. Additional improvements can be obtained by adding a further solid-lubricant coating of molybdenum disulfide (MoS₂), ideally in an epoxy binder
- Hard chrome plate for maximum wear protection
- Silver or indium plating, which provides a soft, ductile interface with good oxidation resistance
- Anodizing for protection of aluminum alloys, preferably sealed with a self-lubricating polymer such as polytetrafluoroethylene (PTFE)
**Fretting Fatigue**

With high loads or prolonged operation, fretting may lead to crack initiation followed by fretting fatigue. Since electroplating can impair fatigue resistance of the substrate, the best solutions are usually the intrinsically hard and tough thermally sprayed coatings. These include:

- Nickel-chromium for corrosion resistance and toughness in impact fretting
- Tungsten carbide-cobalt (WC-Co) for maximum wear resistance
- Nickel-chromium-chromium carbide for higher-temperature fretting

**Oxidative Wear**

If there is a small, slow-speed relative sliding between the parts, this may also lead to a fretting-type wear condition, with the oxidized wear debris trapped in the contact. It is common on chain links and wire ropes and sometimes occurs on pulleys.

The only viable solution for wire ropes is regular oil or grease soaking. For parts under high loading, and that are traditionally made of high-strength engineering steels, there is usually no easy way to reduce the corrosive contribution to the wear process. The best approach is to increase the surface hardness so that it can resist the abrasion by the oxide debris.

For example, consider:

- Local surface hardening, for example, flame, induction, or laser for medium-carbon steels
- Case hardening, for example, carburizing, carbonitriding for low-carbon steels
- Nitriding or nitrocarburizing if the loads are not too high and the steel has some alloying elements such as chromium or molybdenum

**Parts in Static Contact with a Product (Ref 1)**

This operating condition applies to molding, casting, and activities such as baking and curing when a product is held against the component surface for an extended time. The issue is not usually one of wear; rather the principal requirement is that the product and component will separate without adhesion or damage to either surface. However, in many cases, the product must first flow into the mold and, if pressure is applied during processing, the product may also creep across the surface as it cures or sets. All of these can cause wear.

**Base Material**

In many food applications the substrate will be stainless steel or an aluminum alloy. Dies and molds for plastic molding are most likely to be
made of alloy steel, aluminum, brass, or copper. Die casting of aluminum or zinc products will generally use hot-work (H-series) tool steels; glass molding uses tool steels, cast irons, and beryllium-copper alloys.

**Specific Applications**

**For food baking and molding**, consider:

- Fluorinated polymer coatings. Fluorinated ethylene propylene (FEP) provides the best release. Perfluoro alkoxy alkane (PFA) gives release and wear resistance. PTFE provides best low friction. Ensure that the grade chosen is approved for food use.
- Electroless nickel plus PTFE, which will provide both low friction and good release properties, but not high wear resistance
- Anodizing plus PTFE seal for nonsticking aluminum alloy parts

**For plastic injection molding tools**, consider:

- Nitriding of alloy steel parts when the plastic is filled and abrasive
- Hard chrome plate for steel, brass, or copper parts when abrasion is expected
- Ion implantation for improved wear resistance of alloy tool steels and chrome-plated parts
- Anodizing plus PTFE seal for nonstick and wear resistance with aluminum alloy parts

**For die casting**, consider:

- Nitriding for H-series tool steels
- Physical vapor deposition (PVD) coatings, for example, TiN, TiAlN

**For glass molding**, consider:

- Diffusion chromizing on cast iron molds for hot erosion-corrosion resistance
- Slurry/sinter formed ceramics (chromium oxide based) coatings
- Hard chrome plate (crack-free form is best)

**Parts in Sliding or Rolling Contact with Another Surface (Ref 1)**

If the part is in sliding or rolling contact with another engineering component then, even if it is lubricated, there is the likelihood of adhesive wear.

Adhesive wear can occur in many engineering situations, for example, shafts, journals, pistons and rings, cams, bearings, pads gears, seals, slide-
ways, and so forth, in metal cutting, drawing, and forming. In general, if both mating parts are metallic, it will be the softer part that suffers the greater wear and should be surface engineered. However, in cases where replacement of a particular part is difficult, then it is that part that should be protected, even at the expense of extra wear on the mating surface.

If the mating part is nonmetallic, wear could still occur on the counter-facing component. If the counterface is plastic, determine whether it has any fillers that could cause abrasive wear. This would also be the case if the counterface was a ceramic.

**Base Material**

Common base metals include cast iron, low-carbon steel, medium-carbon steel, alloy steel (including tool and bearing steels), stainless steel (austenitic, martensitic, or ferritic), aluminum alloys, titanium alloys or other nonferrous metals, for example, bronzes, copper, and brasses.

**General Contact Conditions**

**Is the Part Lubricated?** If it is, or could be, then wear, even without surface engineering, might be reduced by a factor of 1000 compared to running unlubricated. In lubricated systems under high load and at high speed (e.g., cams and tappets, piston bores and rings) there is still the possibility of scuffing.

**Is the Part Unlubricated yet There is a Need to Reduce Friction?** For dry sliding it is important to specify the exact requirements. A low friction coefficient (see Chapter 3) can be defined as 0.1 or less and is generally achieved with polymers such as PTFE, but these have high wear rates. If, without surface engineering, the friction would be unacceptably high, for example, galling between two soft steel parts, then most surface treatments will reduce friction as well as reduce the wear.

**Is the Specific Loading High?** Loads above 100 MPa (14.5 ksi) are considered high, in which case the hardness and thickness, or case depth, of the surface treatment is the critical factor. Both the substrate and the coating must be able to withstand that load. It is important to remember that rolling parts are often under high specific loading.

**What are the Requirements for Reducing Wear?** In general, the higher the hardness of the surface layer, the lower will be the wear. It is vital to understand the consequences of the wear; for example, it may be that an increase in clearance between two parts must be avoided in service. If the wear is concentrated in a small area, then even a low wear rate will lead to a rapid increase in the clearance, and a high surface hardness is needed in that area. If the wear is spread out over a wider area the corresponding increase in clearance will be smaller, and a simpler, less expensive solution may be adopted.

**Is There an Element of Corrosion?** For instance, if moisture or salt water is present there is a major risk of combined wear and corrosion that
can rapidly increase surface material loss. Select coatings with good corrosion resistance rather than high hardness. Corrosion is generally the more damaging feature.

**Surface-Engineering Options**

**For mild steel or cast iron parts,** consider:

* Case hardening, that is, carburizing or carbonitriding for high hardness and load-carrying capacity. With case-hardening processes, however, distortion problems must be considered.
* Nitriding or nitrocarburizing. This gives a thin compounded layer.
* Electroless nickel and associated composites for corrosive wear. Heat treating at 400 °C (750 °F) will provide additional hardness and wear resistance. Ceramic-filled electroless nickel gives greater wear resistance. PTFE-filled electroless nickel will give low friction, but high wear if the load is high.
* Hard chrome plate for excellent wear protection, for example, on auto body dies. Select the thickness according to the load. Good for corrosive wear if protected with an underlayer of electrolytic nickel.
* Thermally sprayed metals or alloys. Use for wear and corrosion.
* Thermally sprayed ceramics or cermets, for example, WC-Co, alumina, chromium oxide, and so forth, for maximum wear resistance. If corrosion is likely, a corrosion barrier is required under the hard coating.
* Hot dip galvanizing on steel parts. Use if corrosive wear is likely.

**For medium-carbon steel parts,** consider the surface treatments listed above for mild steels, plus local surface hardening, for example, flame, induction, or laser for maximum loading, and for large rolling components (e.g., large cylindrical roller bearings and tracks).

**For low-alloy steel parts** (steels containing chromium, vanadium, and/or molybdenum), consider the surface treatments listed above for both mild and medium-carbon steels, plus nitriding or nitrocarburizing to give a diffused case. Follow with oxidation and oiling treatment for corrosive conditions.

**High-Alloy and Tool Steel Parts.** Tool steels or high-speed steels (including AISI 440C, and the A, D, and M series steels) can be heat treated to high hardnnesses and are wear resistant in their own right. For additional wear resistance and to reduce pickup, particularly in metalworking operations, consider:

* Nitriding or nitrocarburizing. Follow with oxidation and oiling treatment for reduced pickup. Used on warm forming tools.
* Hard chrome plate for excellent wear prevention, but postprocessing heat treatment may be necessary to prevent hydrogen embrittlement. Good for deep-drawing tools
PVD coatings, for example, TiN, CrN, and diamondlike carbon will give low friction and low wear under moderate loads. Used on cutting and cold-forming tools.

Chemical vapor deposition (CVD) coatings, for example, TiN, TiC/TiN, Al₂O₃, and TiC for higher loads than with PVD. Used on carbide inserts and other cutting tools, cold- and hot-forming tools.

Carbide diffusion, also called Toyota diffusion process (see Chapter 6), for high-carbon and precarburized steels. Uses a salt bath to produce a vanadium carbide (VC) layer.

**For austenitic (300 series) stainless steel parts**, consider:

- Electroless nickel and composites used as-deposited or heat treated to provide some wear resistance. Ceramic-filled electroless nickel will give greater wear resistance. PTFE-filled electroless nickel will give low friction but high wear if the load is high.
- Hard chrome plate for excellent wear resistance. Choose the thickness according to the load.
- Thermally sprayed metals or alloys for wear and corrosion.
- Thermally sprayed ceramics or cermet, for example, WC-Co, chromium oxide, alumina, and so forth, for maximum wear resistance.
- Nitriding or nitrocarburizing can produce a very high surface hardness. However, all corrosion resistance will be lost.

**For aluminum or titanium alloy parts**, consider:

- Electroless nickel and composites for corrosive wear. Hardening at 400 °C (750 °F) will provide additional wear resistance. Ceramic-filled electroless nickel will give greater wear resistance. PTFE-filled electroless nickel will give low friction, but high wear if the load is high.
- Hard chrome plate for excellent wear resistance. Choose the thickness on the basis of the load.
- Thermally sprayed metals or alloys for wear and corrosion.
- Thermally sprayed ceramics or cermet, for example, WC-Co, alumina, chromium oxide, and so forth, for maximum wear resistance.
- Anodizing for wear protection of aluminum alloys; can be sealed with PTFE for reduced friction. Anodizing of titanium produces only a very thin decorative layer.
- Nitriding or nitrocarburizing for wear protection of titanium alloys (requires high-temperature processing).

**Bronze, Brass, and Copper Parts.** Some copper and copper-base alloy substrates have relatively low load-carrying capacity. The principal options to reduce wear are:
Electroless nickel and composites for corrosive wear conditions. Heat treating at 400 °C (750 °F) will provide additional wear resistance. Ceramic-filled electroless nickel will give additional wear resistance. PTFE-filled electroless nickel will give low friction, but high wear if the load is high.

- Hard chrome plate for excellent wear resistance. Choose the thickness according to the load.
- Thermally sprayed metals or alloys for wear and corrosion
- Thermally sprayed ceramics or cermets, for example, WC-Co, chromium oxide, alumina, and so forth, coatings for maximum wear resistance

Specific Contact Conditions

Rolling and Rolling/Sliding Contact. In rolling-element bearings and similar rolling components, the base material is usually a temper-sensitive steel. Concern about the effect of surface engineering on tolerances and possible distortion leave few options. In some circumstances, the following surface-engineering options may be considered:

- PVD coatings, for example, TiN, CrN, MoS₂, and so forth, but must be processed at below the tempering temperature of the steel
- Oxide treatments, for example, caustic treatment of needle rollers
- Hard chrome plate, using the thin, dense variety (restricted to approximately 5 μm thick)

For gears, where the motion is combined rolling and sliding, the main options are:

- Case hardening, that is, carburizing or carbonitriding, of low-carbon steels to give high hardness and wear resistance
- Local surface hardening of medium-carbon steels to give maximum load capacity
- Nitriding of alloy steels for lower loads

Scuffing Conditions. Cams and tappets, cylinders and pistons, even when lubricated, can be prone to scuffing. Options include:

- Hard chrome plate for moderate-speed cylinder bores
- Electrolytic nickel/ceramic composite for cylinder bores in high-revving engines
- Nitrocarburizing for tappets and cams made from nitriding steels
- Diamondlike carbon for high-revving cams and tappets on a polished hard substrate

Reducing Friction in Dry Sliding. For any base material, certain polymer systems can be considered:
• PTFE in a binder, wet sprayed and cured
• PFA wet sprayed and melt flowed at 400 °C (750 °F)
• MoS₂ wet sprayed in a phenolic binder
• Electroless nickel plus PTFE heat treated to give improved wear performance
• Diamondlike carbon, but only on a hard, polished substrate

**Sliding against Nonmetallic, Abrasive Counterfaces.** This operating condition might be the case for some plain or journal bearings or for mechanical seals. If the counterface is a polymer, it will probably contain an abrasive filler. If the counterface is a ceramic or cermet, then its surface roughness will greatly influence its abrasiveness.

For all of these conditions, high hardness must be the basis on which a surface-engineering treatment is chosen. Examples include:

• Hard chrome plate, which is the best of the electroplates. Electroless nickel, even hardened is not recommended.
• Sprayed ceramic or cermet, for example, chromium oxide. A ceramic versus ceramic combination is possible.

**Parts in Low-Load Sliding Contact with an Abrasive Product (Ref 1)**

Many products are abrasive, either as a result of their basic structure and composition or through the action of added fillers or pigments. In low-load situations (as defined by the product areas discussed later in this section), the choice of surface treatment can be made primarily on the basis of surface hardness, since even very thin coatings are able to support the contact loads.

The industrial areas covered in this section include textiles, printing, plastics, packaging, food, pharmaceuticals, leather goods, paints, inks, ceramic powders, and wood processing. It is assumed that the part in question is in direct contact with the product (e.g., a textile guide, a print roller, a wood-cutting tool, a food chute, etc.) and not with another engineering component.

The applications also cover seals, where a nonmetallic, for example, a filled polymer or elastomer, part is in sliding contact with a shaft or a thrust pad.

**Base Material**

The substrate will usually be mild steel, low-alloy steel, austenitic stainless steel, or an aluminum alloy. Tool steels will be used for knives or other cutting or trimming tools.
Specific Applications

Chipboard, Wood, or Composite Products and Ceramic Powder Handling. The content of wood products is always uncertain, with metal and mineral contaminants being common. The only safe solutions are thermally sprayed or welded ceramics or cerments, for example, WC-Co, alumina, chromium oxide, and so forth, for maximum wear and damage resistance.

Synthetic Textiles (Nylon, Polyester), Glossy Newsprint, Glass-Filled Plastics (Including Seals), and Pigmented Plastics Other than Black (i.e., Specifically White, Green, and Red). These are all abrasive as they contain inorganic pigments or fillers. A surface hardness of at least 1000 HV is needed to ensure acceptable part lives. Applicable coatings include:

- Thermally sprayed or welded ceramics or cerments, for example, WC-Co, alumina, chromium oxide, and so forth, for maximum wear resistance
- Nitriding may be used on austenitic stainless steel substrates to achieve maximum hardness, but it destroys corrosion resistance.
- Hard chrome plate will provide good wear resistance in applications where the contact is not concentrated on one area of the part. It can be used on textile feed rollers but not on eye-guides.
- PVD coatings, for example, ceramics such as TiN or CrN
- Slurry/sinter-formed ceramics, that is, chromium-oxide-based composites loaded with ceramic particles

Black and White Newsprint, Natural Textiles (Cotton, Wool), Cardboard and Packaging, Carbon-Fiber-Reinforced Plastics, Black-Pigmented Plastics, Paints and Inks, Food Products, Leather, and Pharmaceutical Products. These are mildly abrasive and require a surface hardness more than 600 HV for effective protection. Effective coatings include:

- Thermally sprayed or welded ceramics or cerments, for example, WC-Co, alumina, chromium oxide, for example, for maximum wear resistance
- Nitriding or nitrocarburizing on any alloy steel substrate
- Hard chrome plate will provide good wear resistance in all applications
- PVD coatings, for example, TiN or CrN
- Slurry/sinter-formed ceramics, that is, chromium-oxide-based composites loaded with ceramic particles
- Case hardening, that is, carburizing, carbonitriding for low-carbon steels to give high hardness and wear resistance
- Local hardening, that is, induction, laser, and so forth, for medium-carbon steels
• Anodizing of aluminum alloys (provides only limited protection and is best for dry food products under the lightest loads)

Parts in High-Load Sliding or Erosion with an Abrasive Product (Ref 1)

When abrasion takes place under high loads, and where impact occurs and erosion is prevalent, then hardness alone is not a reliable parameter on which to select the appropriate surface treatment. Applications include coal chutes, mining conveyors, diggers, crushers, millers, extruders, cutters, and compactors. Erosive conditions also exist in turbines, impellers, and pipework.

The surface must not only be hard, it must also be tough and resilient and able to withstand high specific loading without deforming into the substrate.

Base Material

The substrate is most likely to be constructional steel or low-alloy tool steels in plate form.

Surface-Engineering Options

Suitable surface treatments for high-stress abrasive conditions include:

• Welded or spray and fused coatings, including nickel or cobalt-base materials with high carbide content, deposited at least 2 mm (0.08 in.) thick
• Thermally sprayed and hot isostatically pressed (HIP) coatings, including nickel and iron-base materials, with a high content of the carbides of tungsten, chromium, and titanium, deposited 5 mm (0.2 in.) or more thick
• High-velocity oxyfuel (HVOF) thermally sprayed coatings including nickel or cobalt-base cermets with low porosity and high bond integrity, at least 1 mm (0.04 in.) thick
• Elastomer-based coatings for high-angle erosive situations where there is no abrasive, cutting element

Parts in Contact with Another Engineering Component in the Presence of an Abrasive and Corrosion Product or Environment (Ref 1)

When a component has surfaces that roll or slide against others with abrasive and/or corrosive product trapped between them, it creates the very extreme condition of three-body high-stress abrasive wear (see
Fig. 5 and 6 in Chapter 3). It is particularly common in pumps, valves, and mechanical seals that are working in abrasive slurries such as sand, water, and hydrocarbons found in oil and gas extraction. The condition is typified by a crushing and grinding action between the surfaces, perhaps the two sliding surfaces of a journal bearing, which breaks down the abrasive particles and continuously creates new cutting edges. When combined with corrosion this creates a very extreme wear situation.

**Base Material**

The substrate is most likely to be austenitic or ferritic stainless steel, high-alloy steels, nickel-base alloys (e.g., Inconels), or cast grades of Stellite (Co-Cr-W-C) materials.

**Surface-Engineering Options**

Surface treatments for three-body high-stress abrasive wear and corrosion applications are limited to those which provide a combination of hardness, toughness, load-carrying capacity, and corrosion resistance. They include:

- Welded or spray and fused coatings, including nickel or cobalt-base materials with high tungsten, chromium, or titanium carbide content
- Thermally sprayed and HIP coatings, including nickel and iron-base materials with high tungsten, chromium, or titanium carbide content
- HVOF coatings, including nickel or cobalt-base cermets with low porosity and high bond integrity
- Diffusion chromizing for combined corrosion and wear resistance, but only on substrates with a sufficient carbon content to produce a surface layer of chromium carbide
- Boronizing for high wear resistance of carbon and alloy steels, but without appreciable corrosion resistance. Stellites, sintered cemented carbides, and some sprayed coatings can be boronized to reduce wear of their binder phases.
- Hard chrome plate, provided the substrate is corrosion resistant and the situation is not too aggressive; crevice corrosion can undermine the plating

**Preprocessing and Postprocessing Heat Treatment (Ref 1)**

Heat treatments performed before or after surface processing are carried out to:

- Relieve residual stresses
- Restore mechanical properties of the metal core
- Reduce the risk of hydrogen embrittlement
Restoring Core Strength. If the surface hardening or coating process involves high temperature, the core strength or hardness of a steel component can be compromised. In the case of carburizing, particularly if carried out in a sealed quench furnace, the part will be quenched and tempered as part of the process, and the core properties (where the carbon content will be lower than the case) will generally be restored. For high-temperature processes like boronizing or chromizing, there will need to be a subsequent heat treatment step to reharden the core for most applications. After a CVD or carbide diffusion process on high-alloy tool steel, there will usually need to be a vacuum heat treatment step to restore core properties. These coatings are thin and depend on adequate support from the substrate to perform properly.

Heat Treatment to Avoid Hydrogen Embrittlement. With most of the electroplating processes, and in particular cadmium and hard chromium plating, and some of the chemical processes including electroless nickel, there is a risk of hydrogen embrittlement of high-strength steel components. It is essential to carry out a postprocessing heat treatment immediately after plating. The recommended treatments for steels of varying strength levels are:

### Stress Relieving

<table>
<thead>
<tr>
<th>Tensile strength</th>
<th>Stress-relief treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>ksi</td>
</tr>
<tr>
<td>Up to 1100</td>
<td>Up to 160</td>
</tr>
<tr>
<td>1100–1650</td>
<td>160–240</td>
</tr>
<tr>
<td>1650–1800</td>
<td>240–260</td>
</tr>
<tr>
<td>Over 1800</td>
<td>Over 260</td>
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<tr>
<th>Tensile strength</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>ksi</td>
</tr>
<tr>
<td>Up to 1100</td>
<td>Up to 160</td>
</tr>
<tr>
<td>1100–1650</td>
<td>160–240</td>
</tr>
<tr>
<td>1650–1800</td>
<td>240–260</td>
</tr>
<tr>
<td>Over 1800</td>
<td>Over 260</td>
</tr>
</tbody>
</table>

Coating Thickness, Case Depth, and Component Distortion Considerations (Ref 1)

The thickness of a surface coating or case depth is governed by both the process characteristics and the cost. For example, in theory it would
be possible to build up a PVD coating thickness of 100 \( \mu \text{m} \), but it would take so long as to be both impractical and too expensive. From the user’s point of view, it is important to know the thickness of the surface layer so that its load-carrying capacity and potential service life can be assessed and any likely changes in dimensions of the component predicted. Assuming that the final dimensions of the part are critical, below are some guidelines to help the designer predict coating thickness and potential distortion problems. In addition, Table 1 lists the thickness ranges and hardness values for a wide range of coating/surface-hardening processes.

**Weld overlays** will produce significant distortion of the part and a surface growth at least equal to the layer thickness. They will need to be surface-ground.

**High-temperature diffusion processes** such as carburizing can produce component distortion. The only option is to allow for postgrinding.

### Table 1  Thickness ranges and hardness levels associated with various surface-engineering processes

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Substrate</th>
<th>Thickness or case depth</th>
<th>Hardness, HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local surface hardened</td>
<td>Medium-carbon steel</td>
<td>1–10 ( \mu \text{m} )</td>
<td>700–900</td>
</tr>
<tr>
<td>Carburized (case hardened)</td>
<td>Low-carbon steel</td>
<td>1–3 ( \mu \text{m} )</td>
<td>700–900</td>
</tr>
<tr>
<td>Nitrided or nitrocarburized</td>
<td>Low-carbon steel</td>
<td>5–10 ( \mu \text{m} )</td>
<td>400–600</td>
</tr>
<tr>
<td></td>
<td>Tool steel</td>
<td>50–200 ( \mu \text{m} )</td>
<td>800–1000</td>
</tr>
<tr>
<td></td>
<td>Stainless steel</td>
<td>20–50 ( \mu \text{m} )</td>
<td>1000–1200</td>
</tr>
<tr>
<td>Boronized</td>
<td>Mild steel</td>
<td>10–20 ( \mu \text{m} )</td>
<td>~200</td>
</tr>
<tr>
<td></td>
<td>Low-alloy steel</td>
<td>20–30 ( \mu \text{m} )</td>
<td>800–1000</td>
</tr>
<tr>
<td></td>
<td>Stainless steel (316)</td>
<td>30–40 ( \mu \text{m} )</td>
<td>1000–1200</td>
</tr>
<tr>
<td>Chromized</td>
<td>Stainless steel (316)</td>
<td>20–50 ( \mu \text{m} )</td>
<td>300–400</td>
</tr>
<tr>
<td>Aluminized (diffusion)</td>
<td>Stainless steel (316)</td>
<td>20–50 ( \mu \text{m} )</td>
<td>400–500</td>
</tr>
<tr>
<td>Phosphated</td>
<td>Low-carbon steel</td>
<td>4–7 ( \mu \text{m} )</td>
<td>~200</td>
</tr>
<tr>
<td>Chromated</td>
<td>Various</td>
<td>1 or 2 ( \mu \text{m} )</td>
<td>Not accurately known</td>
</tr>
<tr>
<td>Oxidized</td>
<td>Steel</td>
<td>3–5 ( \mu \text{m} )</td>
<td>250–350</td>
</tr>
<tr>
<td>Ion implanted</td>
<td>Steel</td>
<td>0.1–1 ( \mu \text{m} )</td>
<td>Not accurately known</td>
</tr>
<tr>
<td>PVD TiN</td>
<td>Various</td>
<td>1–5 ( \mu \text{m} )</td>
<td>2000–3000</td>
</tr>
<tr>
<td>PVD CrN</td>
<td>Various</td>
<td>2–20 ( \mu \text{m} )</td>
<td>1800–2500</td>
</tr>
<tr>
<td>Diamondlike carbon</td>
<td>Various</td>
<td>1 or 2 ( \mu \text{m} )</td>
<td>1500–2000</td>
</tr>
<tr>
<td>CVD chromium nitride</td>
<td>Stainless steel (316)</td>
<td>10–15 ( \mu \text{m} )</td>
<td>1100–1300</td>
</tr>
<tr>
<td>CVD chromium carbide</td>
<td>High-carbon steel</td>
<td>10–15 ( \mu \text{m} )</td>
<td>1500–2000</td>
</tr>
<tr>
<td>CVD alumina</td>
<td>Steel</td>
<td>5–10 ( \mu \text{m} )</td>
<td>1500–2000</td>
</tr>
<tr>
<td>Chromium plate</td>
<td>Various</td>
<td>5–250 ( \mu \text{m} )</td>
<td>800–1000</td>
</tr>
<tr>
<td>Nickel plate</td>
<td>Various</td>
<td>10 ( \mu \text{m} ) to 1 ( mm )</td>
<td>250–650</td>
</tr>
<tr>
<td>Copper plate</td>
<td>Various</td>
<td>10–250 ( \mu \text{m} )</td>
<td>70–90</td>
</tr>
<tr>
<td>Cadmium plate</td>
<td>Various</td>
<td>5–10 ( \mu \text{m} )</td>
<td>~50</td>
</tr>
<tr>
<td>Zinc plate</td>
<td>Various</td>
<td>5–10 ( \mu \text{m} )</td>
<td>~50</td>
</tr>
<tr>
<td>Electroless nickel</td>
<td>Various</td>
<td>5–50 ( \mu \text{m} )</td>
<td>500–1000</td>
</tr>
<tr>
<td>Electroless nickel/ceramic</td>
<td>Various</td>
<td>5–50 ( \mu \text{m} )</td>
<td>&lt;1300</td>
</tr>
<tr>
<td>Hot dip galvanizing</td>
<td>Steel</td>
<td>20–250 ( \mu \text{m} )</td>
<td>70–250</td>
</tr>
<tr>
<td>Electrogalvanized steel strip</td>
<td>Low-carbon steel</td>
<td>5–10 ( \mu \text{m} )</td>
<td>~70</td>
</tr>
<tr>
<td>Hot dip aluminized steel strip</td>
<td>Low-carbon steel</td>
<td>5–10 ( \mu \text{m} )</td>
<td>~70</td>
</tr>
<tr>
<td>Thermally sprayed chromium oxide</td>
<td>Various</td>
<td>20–100 ( \mu \text{m} )</td>
<td>1200–1600</td>
</tr>
<tr>
<td>Thermally sprayed alumina</td>
<td>Various</td>
<td>20–100 ( \mu \text{m} )</td>
<td>1500–1800</td>
</tr>
<tr>
<td>Thermally sprayed tungsten</td>
<td>Various</td>
<td>20–100 ( \mu \text{m} )</td>
<td>1100–1600</td>
</tr>
<tr>
<td>carbide/cobalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermally sprayed and spray</td>
<td>Various</td>
<td>Up to 1 ( mm )</td>
<td>1000–1100</td>
</tr>
<tr>
<td>and fused chromium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>carbide/nickel-chromium</td>
<td>Steel</td>
<td>20–100 ( \mu \text{m} )</td>
<td>1000–1200</td>
</tr>
</tbody>
</table>

PVD, physical vapor deposition; CVD, chemical vapor deposition. Source: Ref 1
to size. Case depths in the range 200 to 2000 \( \mu \text{m} \) allow for such finishing. The same principles apply to local surface hardening such as induction or flame hardening, provided the depth of hardening is sufficient.

**CVD and carbide diffusion processes** will produce some distortion and growth of 50 to 100% of the coating thickness. There is insufficient coating thickness (up to 20 \( \mu \text{m} \), usually less) to allow for postcuring grinding. Normally such processes are applied to tooling where trials and experience prove that dimensional accuracy can be consistently maintained at acceptable levels.

**Nitriding and nitrocarburizing** produce only minimal distortion, with a small surface growth (a few microns). Such processes often produce a thin "compound" layer (10 \( \mu \text{m} \)) on the surface of the main case (200–500 \( \mu \text{m} \)), and this is usually removed by a finish-grinding operation.

**Thermal spray processes** impart little general heat to the part and, therefore little distortion. The surface growth will equal the coating thickness and, if the finish is important, they will need grinding. Spray and fused deposits, or coatings that are HIP after spraying, will grow and distort from the effects of high temperature. They will require grinding to improve surface finish.

**Slurry-based ceramic coatings** are sintered at high temperature and experience surface growth equal to the coating thickness (typically 10–100 \( \mu \text{m} \)) that may cause some distortion. These coatings are normally left unfinished.

**Coatings for corrosion protection**, for example, zinc or cadmium plating, phosphating, and chromating will produce surface growth in the range of 2 to 20 \( \mu \text{m} \). They cannot be finished after processing. Electroless nickel will produce growth equal to the coating thickness (typically 10–100 \( \mu \text{m} \)) with no distortion unless the substrate is sensitive to the heat treatment temperature of 400 °C (750 °F).

**Hot dipped galvanized coating** thickness ranges from 10 to 250 \( \mu \text{m} \) and is controlled by the steel chemistry, section thickness, and immersion time.

**Electrolytic Coatings.** Hard chrome and heavy nickel and copper plating can vary in thickness from just a few microns to 250 \( \mu \text{m} \). Surface growth will equal the coating thickness and, except for the thinnest layers, they will need finish grinding.

**PVD coatings** are usually less than 10 \( \mu \text{m} \) thick and will produce minimal distortion. They are not finished after processing.

**Paints and polymer coatings** are usually around 10 to 30 \( \mu \text{m} \) thick. They are left as-coated.

**Anodizing** produces no distortion. The surface growth is half that of the coating thickness, the coating growing 50% in and 50% out of the original aluminum alloy surface.
Table 2  Surface finish characteristics of various surface-engineering processes

<table>
<thead>
<tr>
<th>Process</th>
<th>As-treated surface finish</th>
<th>Normal finishing operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlays</td>
<td>Very rough</td>
<td>Grind</td>
</tr>
<tr>
<td>Thermal spray</td>
<td>Very rough</td>
<td>Grind</td>
</tr>
<tr>
<td>Local hardening</td>
<td>May be rough and distorted</td>
<td>Grind</td>
</tr>
<tr>
<td>Case hardening</td>
<td>May be rough and distorted</td>
<td>Grind</td>
</tr>
<tr>
<td>Nitriding and nitrocarburizing</td>
<td>Slightly roughened</td>
<td>May be ground, but often used as-treated</td>
</tr>
<tr>
<td>Galvanizing</td>
<td>Slight roughening</td>
<td>Not finished</td>
</tr>
<tr>
<td>Phosphating</td>
<td>Slight roughening</td>
<td>Not finished</td>
</tr>
<tr>
<td>Oxidizing</td>
<td>Slight roughening</td>
<td>Not finished</td>
</tr>
<tr>
<td>Electroplating</td>
<td>May roughen</td>
<td>Chromium and copper usually ground, cadmium and zinc used as-plated</td>
</tr>
<tr>
<td>Electroless nickel</td>
<td>Replicates surface finish</td>
<td>Not finished</td>
</tr>
<tr>
<td>PVD</td>
<td>Replicates surface finish</td>
<td>Not finished</td>
</tr>
<tr>
<td>CVD</td>
<td>Some roughening</td>
<td>Not usually finished</td>
</tr>
<tr>
<td>Ion implantation</td>
<td>Replicates surface finish</td>
<td>Never finished</td>
</tr>
<tr>
<td>Shot peening</td>
<td>Deliberate alteration</td>
<td>Not finished</td>
</tr>
<tr>
<td>Paints and polymers</td>
<td>Some roughening possible</td>
<td>Not finished</td>
</tr>
</tbody>
</table>

PVD, physical vapor deposition; CVD, chemical vapor deposition. Source: Ref 1

Surface Roughness and Finishing (Ref 1)

The surface finish of the surface-engineered component will depend on the process itself and, in some instances, on the finish before it was processed. As described in the previous section, some parts will have to be ground after treatment because of distortion or growth, or to develop an acceptable finish. Others will be left untreated, regardless of their surface roughness. In some cases, the primary objective will be to preserve original surface texture without the need for postfinishing operations. Table 2 gives some general surface-finish guidelines relevant to the various surface-engineering treatments.

General Design Principles Related to Surface Engineering (Ref 2)

There are a number of general design principles that apply to a variety of surface-engineering processes, while others are specific to individual treatments/techniques. These general principles are discussed in this section, and the following three sections discuss design aspects relating to: (1) surface preparation techniques, including cleaning, (2) organic coating processes, and (3) inorganic (metal and ceramic) coating processes. Fabrication Processes. Some methods of fabrication such as the forging, extrusion, molding, and casting of metals and ceramics can lead to surface defects that must be removed by subsequent surface-finishing techniques, such as grinding, lapping, and polishing or electropolishing, or hidden by techniques such as applying a leveling copper deposit before a decorative plated finish. Defects include laps, tears, cracks, pores, shrinkage cavities,
gating and venting residues, ejection marks, and, parting lines. Careful design of the casting or molding operation—including the dies, gates, vents, and overflows—will minimize finishing problems by ensuring such defects are avoided, occur on nonsignificant surfaces, or are hidden by specially incorporated design features, such as steps or ridges at parting lines.

Whatever the type of material being cast or molded, dimensional and warpage allowances must be made in the design of the tooling (i.e., dies) to accommodate shrinkage and distortion during solidification and cooling. Otherwise, parts may be undersized or require excessive machining to obtain the specified dimensional tolerances.

Control of fastening or joining processes also can influence surface finishing. For example, two flat surfaces riveted together produce cavities that can entrap processing solutions, impair coating, and lead to corrosion (Ref 3). Spot or tack welding is no better in this regard. However, a continuous weld—with a smooth bead and no weld spatter—will prevent this problem and make surface finishing easier. Also, the elimination of sharp edges and comers will prolong the life of grinding, polishing, and buffing belts and wheels.

**Component Size and Weight and Handling Problems.** The size, dimensions, and weight of a part to be surface engineered have a direct influence on part handling and fixturing and the size and type of equipment that is used (Fig. 1). Put simply, there are two main issues in relation to size and weight of components:

- Are they too big for the process to accommodate, either in respect to the pretreatment surface preparation/cleaning facilities or plating tanks, vacuum chambers, and the like?

---

**Fig. 1** Interrelation between the component, fixturing, and equipment limitations. Source: Ref 2
Are they so small, or too numerous, to make the holding, manipulating, or cleaning for the chosen process impractical or too expensive?

Objects weighing in excess of 20 kg (about 50 lb) will probably need hoists or overhead moving cranes to manipulate them through the cleaning lines and treatment chambers. Some heavy objects that are to be treated in front-loading furnaces can often be handled by a fork lift. Table 3 provides some likely limits on size and weight for various surface-engineering processes.

Aesthetics and Function. Another general consideration is that not all surfaces may require the same high standard of surface finish. While surfaces exposed to view must be aesthetically pleasing, and surfaces subjected to more aggressive conditions of exposure or use require durable coatings, hidden (internal) surfaces or less-exposed surfaces may not need such a high-quality finish. Specifications for surface finishes for a part depend not only on the design and end-use application, but also must take into account that the requirements may differ for different areas or surfaces on that part. A design should take this into consideration, as well as the fact that different types of equipment or equipment operation settings may be necessary for those areas and surfaces.

Functional requirements of a part also influence the selection of surface-preparation processes. For example, grinding processes can introduce stresses that could have a negative impact on fatigue properties. Choosing an alternative process, such as chemical milling, or mitigating the stresses by shot peening can alleviate the problem.

Design Features. Shape and features such as recesses, holes, threads, keyways, slots, fins, and louvers can present problems to the finisher, and the severity of the problem can depend on the finishing technique. For example, when holes are included in thin sections that require a finishing

<table>
<thead>
<tr>
<th>Process</th>
<th>Largest dimension restraint</th>
<th>Weight restraint</th>
<th>Small parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlays</td>
<td>None, assuming access</td>
<td>None, particularly if on-site work is possible</td>
<td>Not less than about 100 mm</td>
</tr>
<tr>
<td>Thermal spray</td>
<td>Around 2 m</td>
<td>Several tonnes</td>
<td>Down to 10 mm</td>
</tr>
<tr>
<td>Local hardening</td>
<td>None, assuming access</td>
<td>None, particularly if done on-site</td>
<td>Not less than about 100 mm</td>
</tr>
<tr>
<td>Shot peening</td>
<td>None, assuming access</td>
<td>Often done on-site</td>
<td>Not less than about 100 mm</td>
</tr>
<tr>
<td>Case hardening</td>
<td>Around 3 m</td>
<td>About 1 tonne</td>
<td>Not less than about 5 mm</td>
</tr>
<tr>
<td>Nitriding and nitrocarburizing</td>
<td>Around 3 m</td>
<td>About 1 tonne</td>
<td>Down to 1 mm</td>
</tr>
<tr>
<td>Galvanizing</td>
<td>Around 30 m</td>
<td>10-15 tonnes</td>
<td>20 mm or M8 fastener</td>
</tr>
<tr>
<td>Phosphating</td>
<td>Around 5 m</td>
<td>Several tonnes</td>
<td>Not less than about 1 m</td>
</tr>
<tr>
<td>Oxidizing</td>
<td>Around 1 m</td>
<td>About 1 tonne</td>
<td>Down to 1 mm</td>
</tr>
<tr>
<td>Electroplating</td>
<td>Around 3 m</td>
<td>About 5 tonne</td>
<td>Down to 10 mm</td>
</tr>
<tr>
<td>Electroless nickel</td>
<td>Around 1 m</td>
<td>About 0.5 tonne</td>
<td>Down to 5 mm</td>
</tr>
<tr>
<td>PVD, CVD</td>
<td>Around 1–3 m, usually smaller</td>
<td>Lighter</td>
<td>Down to 10 mm</td>
</tr>
<tr>
<td>Ion implantation</td>
<td>Around 1 m</td>
<td>About 0.5 tonne</td>
<td>Down to 10 mm</td>
</tr>
<tr>
<td>Paints and polymers</td>
<td>None, assuming access</td>
<td>None assuming access</td>
<td>Down to about 10 mm</td>
</tr>
</tbody>
</table>

PVD, physical vapor deposition; CVD, chemical vapor deposition. Source: Ref 1
operation such as grinding, if too much pressure is applied edges and corners might be chipped. If only a light pressure is used to avoid this possibility, then the desired finish might not be obtained. Another example is when paint is applied by conventional solvent spraying or when a part is electroplated, bowl-shaped recesses, blind holes, and similar features can trap the paint or plating solution, leading to areas that sag or do not cure properly (in the case of paint), or carry over trapped chemicals to subsequent processing steps (in electroplating). The latter can cause problems such as rinse-water contamination and increased waste-treatment costs. Also, solutions that are trapped can lead to blistering or delamination of the plated coating, especially if there is a posttreatment step that requires the part to be heated (such as for electroless nickel, cadmium, and hard chromium deposition).

For parts that will be sprayed, especially with paint, another problem with deep recesses, closely spaced, large fins or partitions, and the like is the entrapment of air. The back pressure of entrapped air causes incomplete coverage at the bottom of the recesses. One way to avoid this problem, if a change of design is not possible, is to use an “airless” spraying technique (Ref 4). During electrostatic powder coating there is the problem associated with “Faraday cage” effect, in which the charged components of the powder-coating system are attracted by the high fields at the edges and corners of parts, causing excessive coverage there and incomplete coverage in other areas (Ref 5), as shown in Fig. 2. Rounding corners and edges, tapering the sides and decreasing the depth of recesses, minimizing the use of louvers or fins, or changing their dimensions are ways to avoid the Faraday cage effect. In electroplating, a similar phenomenon exists whereby the depositing metal or alloy ions are attracted to the high-current-density areas at edges and corners, and thicker coatings are obtained in those locations. Rounding such edges, changing dimensions to allow for the excessive buildup, or using shields and current “robbers” or “thieves” will help the finisher to obtain the desired coating thickness distribution. Reference 6 provides some examples of the use of such devices.

Fig. 2 Faraday cage effect in powder coating. Adapted from Ref 5
In conventional paint spraying and many vacuum-deposition techniques, such as ion plating, ion implantation, PVD, and sputtering, attention has to be paid to the limitations imposed by the "line-of-sight" deposition process. Certain features, such as ridges, flanges, and fins, can shadow or mask areas behind them leading to incomplete or nonuniform coverage, as shown in Fig. 3 and 4. Similarly, if the aspect ratio of holes and recesses is too high (i.e., the depth is much greater than the diameter of the opening), it is not possible with line-of-sight limited techniques to penetrate to the bottom surfaces and coat them (Fig. 4). Decreasing the
aspect ratio, providing rounded edges, and tapering the sides of ridges and fins or holes will help to facilitate finishing, as will lowering the height of features such as fins. Of course, rotating or translating a part in the spray plume also will help to obtain complete and more uniform coverage, but this approach usually requires longer times and more sophisticated finishing equipment and fixturing; hence, it often leads to higher costs. The same can be said for using multiple line-of-sight sources to obtain better coverage.

Finally, as a general rule of thumb, parts of the same size, weight, design, and material should always be finished at the same time so that the finishing process(es) can be optimized for those parts. Batches of mixed parts should be avoided unless they share some common features, such as shape and substrate material.

Design Guidelines for Surface Preparation Processes

Surface preparation, including cleaning, is the essential first step in all successful surface-engineering practice. To facilitate surface preparation prior to subsequent coating operations, there are a number of design features that must be considered. Abrupt changes in surface contours should be avoided, and features such as fine grooves, recesses, surface patterning, blind holes, and reentrant areas should be avoided because they will be inaccessible to polishing media or would trap polishing media, making subsequent cleaning more difficult. Such features also would entrap cleaning chemicals, making rinsing more difficult, or could possibly entrap air, preventing cleaning of these areas.

Sharp corners and edges or protrusions can cause excessive wear of polishing wheels and belts and lead to uneven polishing because the high areas are polished at the expense of the surrounding lower areas. As mentioned earlier, rounding edges and corners is a good design precept, while minimizing the height of protuberances is beneficial, as is decreasing the aspect ratio of holes, grooves, and recesses.

Large expanses of flat surfaces may be a problem if these are significant surfaces, especially if these surfaces must be polished to a reflective, mirrorlike finish. Imperfections are exaggerated. Minimizing the area of such surfaces and providing a slightly rounded contour will help to attain the desired finish and help with visual appearance.

Simpler designs lend themselves to automatic finishing processes, while more complex designs may require manual surface-preparation techniques. If parts are to be mass finished (e.g., by tumbling or vibratory finishing) significant flat areas should be avoided. Otherwise, parts may stick together, and these occluded surfaces will not be finished. Designs that prevent access by the deburring or polishing media (such as small recesses
and holes) or that entrap the media (such as narrowly spaced ribs) should be avoided as mentioned above.

When it is impractical or impossible to use mechanical polishing, chemical etching, chemical milling, or electropolishing can be used. The design principles for the latter are similar to those for electroplating, which is discussed later. In electropolishing, the workpiece is the anode, which is the opposite of electroplating. Current-density distribution is extremely important, as is the original surface of the pan being electropolished. In high-current-density areas on susceptible materials, the surface layers may be removed and etching of the substrate can occur. Polishing occurs on a microscopic scale, so macro features such as large grooves or scratch marks will not be removed, but will receive a luster and become more noticeable. Similarly, parting lines can be smoothed, but not removed; therefore, parting fines must be minimized by good die design and careful molding operations.

Solvent cleaning is a fairly forgiving surface-finishing process, but part design can influence its efficacy, as already alluded to. If agitation or other cleaning aids are used, such as ultrasonic energy, care must be taken to prevent soft materials or thin and fragile features or cross sections from being damaged. The energy released during cavitation, for example, in ultrasonic cleaning is very large. If techniques such as plastic media blasting are used, the blasting parameters should be tailored to the part material and design, and the part should be designed to allow easy access by the media and easy removal of the media once the desired finish (cleanliness) is obtained.

If a power spray washing technique is used, the part design should allow for proper drainage to conserve chemicals and minimize carryover to the next process step. Providing drainage holes may be necessary. These should be either a natural feature of the design or located on nonsignificant surfaces. As the design of a part becomes more complex, rinsing requirements become more stringent, and several rinsing stages may be necessary. If an air knife is used afterward to remove excess water, the part must be capable of withstanding the pressure or must be fixtured such that the air pressure does not distort any delicate design features while holding the part steady.

Table 4 provides a summary of the design limitations of some surface-preparation and cleaning processes and indicates which design features to avoid.

Design Guidelines for Organic Coating Processes (Ref 2)

Organic coatings are applied by a variety of techniques, such as dipping, brushing, spraying, airless spraying, or electrostatic spraying. In addition, some primers are deposited using electrophoretic techniques, while electropolymerization is being looked at for certain types of organic coatings.
<table>
<thead>
<tr>
<th>Process</th>
<th>Design limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blasting/deburring</td>
<td>Avoid recesses, holes, channels, and similar features (such as closely spaced ribs) that could trap blasting media Avoid thin cross sections (such as fins, louvers, walls) that could be distorted by the blasting media Avoid intricate designs and surface features</td>
</tr>
<tr>
<td>Broaching/honing</td>
<td>Typically used for inside diameters of tubes and other cylindrical parts, or for grooves, large holes, and other cavities Surfaces must be accessible to tools and withstand the local pressure and heat buildup Avoid very thin cross sections/wall thickness</td>
</tr>
<tr>
<td>Brushing/burnishing</td>
<td>Surfaces must be accessible to tools and withstand the local pressure and heat buildup Avoid very thin cross sections/wall thickness that could deflect Avoid sharp corners and edges Avoid intricate designs and surface features</td>
</tr>
<tr>
<td>Chemical milling</td>
<td>Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air or evolved gases and prevent chemical action from occurring or cause uneven attack Mask areas not to be attacked</td>
</tr>
<tr>
<td>Conversion coating</td>
<td>Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air and prevent surface chemical reactions from occurring or cause staining Mask areas not to be attacked</td>
</tr>
<tr>
<td>Electrocleaning</td>
<td>Allow for electrical contact to be made on nonsignificant surfaces Avoid features that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air or evolved gases and prevent cleaning from occurring or cause staining Mask areas not to be attacked</td>
</tr>
<tr>
<td>Electropolishing</td>
<td>Allow for electrical contact to be made on nonsignificant surfaces Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air or evolved gases and prevent polishing action from occurring or cause staining Mask areas not to be attacked</td>
</tr>
<tr>
<td>Etching</td>
<td>Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air or evolved gases and prevent etching action from occurring Avoid sharp corners and edges Avoid shallow intricate designs and surface features Mask areas not to be attacked</td>
</tr>
<tr>
<td>Grinding</td>
<td>Surfaces must be accessible to tools and withstand the local pressure and heat buildup Avoid very thin cross sections/wall thickness Avoid sharp corners, edges, and protuberances Avoid intricate designs and surface features</td>
</tr>
<tr>
<td>Lapping/buffing</td>
<td>Surfaces must be accessible to tools (preferably flat or simple, curved contours) Avoid very thin cross sections/wall thickness that cannot withstand the local pressure and heat buildup Avoid sharp corners and edges Avoid intricate designs and surface features that would trap the lapping/buffing compounds</td>
</tr>
<tr>
<td>Pickling</td>
<td>Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air and prevent pickling action Mask areas not to be attacked</td>
</tr>
<tr>
<td>Polishing</td>
<td>Surfaces must be accessible to tools and withstand the local pressure and heat buildup Avoid very thin cross sections/wall thickness Avoid sharp corners, edges, and protuberances Avoid intricate designs and surface features that could trap the polishing compound</td>
</tr>
<tr>
<td>Solvent cleaning, immersion</td>
<td>Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air and prevent cleaning from occurring Avoid flat or curved surfaces on small parts that could stick together during immersion and prevent cleaning of those surfaces</td>
</tr>
<tr>
<td>Solvent cleaning, ultrasonic</td>
<td>Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover Avoid features that could trap air and prevent cleaning from occurring</td>
</tr>
</tbody>
</table>

Source: Ref 2
Table 4 (continued)

<table>
<thead>
<tr>
<th>Process</th>
<th>Design limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent cleaning,</td>
<td>Avoid thin cross sections that could be damaged by the energy released during cavitation</td>
</tr>
<tr>
<td>ultrasonic (continued)</td>
<td></td>
</tr>
<tr>
<td>Stripping, chemical</td>
<td>Avoid features (e.g., small recesses, blind holes, cavities) that would trap smut and process chemicals or prevent satisfactory rinsing. Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover. Avoid features that could trap air and prevent coating removal from occurring.</td>
</tr>
<tr>
<td>Stripping, mechanical</td>
<td>Avoid recesses, holes, channels, and similar features that could trap blasting media. Avoid thin cross sections or intricate designs that could be damaged by the stripping media. Mask areas not to be attacked.</td>
</tr>
<tr>
<td>Stripping, thermal</td>
<td>Avoid thin cross sections or intricate designs that could be distorted by the thermal cycling. Try to provide uniform cross-sectional mass throughout the part to help provide a uniform temperature distribution during heating.</td>
</tr>
</tbody>
</table>

Source: Ref 2

Table 5 summarizes these techniques and the design limitations associated with each.

Most of the techniques are line-of-sight limited, and the guidelines provided in the previous section, “Design Guidelines for Surface-Preparation Techniques,” will apply. Allowance for drainage is important for processes that involve dripping or spraying. Avoiding sags and runs on large, flat, vertical surfaces can be accomplished by applying good coating practices and by minimizing such surfaces in the design of the part.

Table 5 Summary of design limitations for selected organic coating processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Design limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrocoating</td>
<td>Allow for electrical contact to be made on nonsignificant surfaces. Allow features that could trap air and prevent wetting by process solutions. Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover. Avoid thin cross sections or intricate designs that could become distorted during drying/curing cycle.</td>
</tr>
<tr>
<td>Electropolymerization</td>
<td>Allow for electrical contact to be made on nonsignificant surfaces. Allow features that could trap air and prevent wetting by process solutions. Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover. Avoid thin cross sections or intricate designs that could become distorted during drying/curing cycle.</td>
</tr>
<tr>
<td>Painting, brushing or dipping</td>
<td>Surfaces must be accessible to application tools (preferably flat or simple, curved contours). Avoid features that would trap excess paint. Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover. Avoid features that could trap air and prevent coating from occurring. Avoid thin cross sections or intricate designs that could become distorted during drying/curing cycle.</td>
</tr>
<tr>
<td>Painting, solvent spraying</td>
<td>Surfaces must be accessible to application tools (preferably flat or simple, curved contours). Allow for fixturing/racking on nonsignificant surfaces. Avoid features that would trap excess paint. Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover. Avoid features that could trap air and prevent coating from occurring. Avoid thin cross sections or intricate designs that could become distorted during drying/curing cycle.</td>
</tr>
<tr>
<td>Powder coating</td>
<td>Allow for fixturing/racking on nonsignificant surfaces. Allow for electrical contact to be made on nonsignificant surfaces. Avoid deep recesses and blind holes that cause the “Faraday cage” effect. Avoid thin cross sections or intricate designs that could become distorted during drying/curing cycle.</td>
</tr>
<tr>
<td>Sol-gel coating</td>
<td>Allow for fixturing/racking on nonsignificant surfaces. Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals. Avoid thin cross sections or intricate designs that could be distorted by the thermal cycling. Try to provide uniform cross-sectional mass throughout the part to help provide a uniform temperature distribution during heating cycle.</td>
</tr>
<tr>
<td>Solution coating</td>
<td>Allow for fixturing/racking on nonsignificant surfaces. Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals. Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover. Avoid features that could trap air and prevent coating from occurring. Avoid thin cross sections or intricate designs that could become distorted during drying/curing cycle.</td>
</tr>
</tbody>
</table>

Source: Ref 2
A few organic coating techniques use electric or electrostatic fields. Designing the fixtures and electrical grounding, such that points of contact are on nonsignificant surfaces, will improve the appearance of the coated part and give the impression of a better quality product. With spraying techniques, proper fixturing and racking of parts can improve the use of coating material because less empty space exists during a run. However, the parts should not be racked so closely together that they shield some surfaces and prevent some areas from being coated.

Avoiding thin cross sections and good fixturing will help prevent distortion during the curing and baking steps used after paint or powder is applied.

Optimizing a design for surface finishing, such as painting, becomes very important as coating thickness is reduced to 30 μm or less. Access to all surfaces must be possible, and any features that would prevent this should be avoided. This is because the dimensions of the solid components in the coating formulation (e.g., powder particle) are similar to the dimensions of the desired dry film thickness (Ref 7). For example, during the first part of curing, when the particles liquefy, the surface tension of the film formed will tend to pull it away from sharp corners or edges, resulting in poor coverage. If a design modification is not possible, the powder formulation should be changed to include higher-viscosity resins, and no, or only small amounts, of surfactants (Ref 7). Thin-film coatings are best applied to parts with simple geometries, with flat or curved surfaces, and few sharp edges.

Earlier, the problem with the Faraday cage effect was mentioned. This phenomenon is further complicated by back-ionization with traditional corona-charging systems (Ref 5). Not only does the design of a recess, hole, or channel control the distribution of coating thickness, but the buildup of back-ionization at the areas of high field intensity lowers the effective charge of the powder particles, further reducing their ability to reach the bottom surfaces. Some possible design modifications were mentioned earlier, but if these are not possible, changing to a turbocharging system will help. Back-ionization is greatly reduced, and the absence of free ions between the gun and the part promotes better coverage of all surfaces (Ref 5).

Design Guidelines for Inorganic Coating Processes (Ref 2)

Inorganic finishes—including metal- and ceramic-based coatings—are applied by a variety of techniques, such as electroplating, electroless plating, thermal spraying, hot dipping, and various vapor-deposition techniques. Other techniques, such as ion implantation and laser melting/alloying, modify surface properties. Table 6 summarizes design limitations for these and other types of inorganic coating processes.

Electroplating is widely used in industry to apply inorganic coatings, especially metals and alloys. Like some organic finishing processes, satisfactory coatings are only obtained when a uniform current density can be
<table>
<thead>
<tr>
<th>Process</th>
<th>Design limitations</th>
</tr>
</thead>
</table>
| Anodizing                   | Allow for electrical contact to be made on nonsignificant surfaces  
Avoid, if possible, sharp edges and corners, ridges, blind holes, etc. that would prevent uniform density distribution  
Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals  
Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover  
Avoid features that could trap air and prevent electrochemical reactions from occurring  
Avoid features that could trap evolved gases and cause staining  
Mask areas not to be anodized |
| Cementation/diffusion       | Surfaces must be thoroughly deburred and cleaned before cladding, so design principles for these processes also apply  
Avoid thin cross sections or intricate designs that could become distorted during thermal cycling  
Mask areas not to be coated |
| Cladding                    | Only for relatively simple shapes, especially with flat surfaces  
Surfaces must be thoroughly cleaned before cladding, so design principles for cleaning also apply |
| Electroless plating         | Allow for fixturing/racking on nonsignificant surfaces  
Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing  
Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover  
Avoid features that could trap air and prevent chemical reactions from occurring or cause staining  
Mask areas not to be coated |
| Electrophoretic plating     | Allow for electrical contact to be made on nonsignificant surfaces  
Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing  
Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover  
Avoid features that could trap air and prevent surface chemical reactions from occurring or cause staining  
Mask areas not to be coated |
| Electroplating (plating, electrodeposition) | Allow for electrical contact to be made on nonsignificant surfaces  
Avoid, if possible, sharp edges and corners, ridges, blind holes, etc., that would prevent uniform current density distribution; or use current robbers and/or shields  
Avoid features (e.g., small recesses, blind holes, cavities) that would trap process chemicals or prevent satisfactory rinsing  
Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover  
Avoid features that could trap air and prevent deposition from occurring  
Avoid features that could trap evolved gases and cause staining  
Avoid thin cross sections (such as fins, louvers, walls) that could be distorted by internal stress in the coating  
Mask areas not to be coated |
| Hot dipping, galvanizing     | Allow for fixturing/racking on nonsignificant surfaces for discrete, small parts  
Best for relatively simple shapes (e.g., tubing) and flat surfaces  
Allow for excess coating material to drain quickly  
Allow for doctor blades or air knives to be used to obtain uniform coating thickness  
Avoid thin cross sections that could become distorted during thermal cycling  
Surfaces must be accessible (preferably flat or simple, curved contours)  
Allow for fixturing/racking on nonsignificant surfaces  
Avoid features that would trap excess paint  
Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover  
Avoid features that could trap air and prevent coating from occurring  
Avoid thin cross sections or intricate designs that could become distorted during drying/fusing cycle  
Mask areas not to be coated |
| Inorganic painting, slurry coating | Allow for electrical contact to be made on nonsignificant surfaces or use a conductive screen  
Avoid features that would shield the surface from the beam (line-of-sight limited) unless multiple beams are used or part is rotated/translated in beam  
Avoid high aspect ratio holes and recesses, grooves, etc., that would not allow the beam to reach the bottom surfaces  
Mask areas not to be coated |
| Ion implantation            | Allow for electrical contact to be made on nonsignificant surfaces or use a conductive screen  
Avoid features that would shield the surface from the beam (line-of-sight limited) unless multiple beams are used or part is rotated/translated in beam |
| Ion plating                 | Allow for electrical contact to be made on nonsignificant surfaces or use a conductive screen  
Avoid features that would shield the surface from the beam (line-of-sight limited) unless multiple beams are used or part is rotated/translated in beam |

CVD, chemical vapor deposition; PVD, physical vapor deposition. Source: Ref 2
Table 6 (continued)

<table>
<thead>
<tr>
<th>Process</th>
<th>Design limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion plating (continued)</td>
<td>Avoid high aspect ratio holes and recesses, grooves, etc., that would not allow the beam to reach the bottom surfaces</td>
</tr>
<tr>
<td></td>
<td>Avoid recesses, holes, cavities, etc., that would trapp the laser beam</td>
</tr>
<tr>
<td>Laser melting/alloying</td>
<td>Mask areas not to be coated</td>
</tr>
<tr>
<td></td>
<td>Allow for fixturing/racking on nonsignificant surfaces</td>
</tr>
<tr>
<td></td>
<td>Avoid features that would shield the surface from the laser beam (line-of-sight limited) unless multiple beams are used or part is rotated/translated in beam</td>
</tr>
<tr>
<td>Mechanical (peen) plating</td>
<td>Avoid thin cross sections or intricate designs that could be damaged by local heating during glazing</td>
</tr>
<tr>
<td></td>
<td>Mask areas not to be treated</td>
</tr>
<tr>
<td></td>
<td>Allow for fixturing/racking on nonsignificant surfaces on large parts</td>
</tr>
<tr>
<td>Passivation</td>
<td>Avoid thin cross sections (such as fins, louvers, walls) that could be distorted by the peening action</td>
</tr>
<tr>
<td>Thermal spraying</td>
<td>Avoid sharp edges and corners that could be damaged by the peening media</td>
</tr>
<tr>
<td></td>
<td>Avoid intricate designs and small surface features that cannot be reached by the peening media</td>
</tr>
<tr>
<td></td>
<td>Provide good natural drainage or use drainage holes on nonsignificant surfaces to minimize carryover</td>
</tr>
<tr>
<td>Vapor deposition (CVD, PVD)</td>
<td>Mask areas not to be coated</td>
</tr>
<tr>
<td></td>
<td>Allow for fixturing/racking on nonsignificant surfaces</td>
</tr>
<tr>
<td></td>
<td>Avoid thin cross sections (such as fins, louvers, walls) that could be distorted by the local heating and kinetic energy</td>
</tr>
<tr>
<td>CVD, chemical vapor deposition; PVD, physical vapor deposition. Source: Ref 2</td>
<td></td>
</tr>
</tbody>
</table>
Table 7 Influence of substrate design features on electroplateability

<table>
<thead>
<tr>
<th>Feature</th>
<th>Poor design</th>
<th>Influence on electroplateability</th>
<th>Better design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convex surfaces</td>
<td>Ideal shape. Easy to plate uniformly, especially where edges are rounded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat surfaces</td>
<td>Use a 0.4 mm (0.015 in.) crown to minimize undulations caused by uneven buffing.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sharply angled edges</td>
<td>Undesirable. Reduced coating thickness at center areas requires increased plating time to obtain a minimum thickness of durable electroplate. All edges should be rounded. Edges that will contact painted surfaces should have a minimum radius of 0.8 mm (0.03 in.).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flanges</td>
<td>Large flanges with sharp inside angles should be avoided to minimize plating costs. Use a generous radius on inside angles and taper the abutment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slots</td>
<td>Narrow, closely spaced slots and holes reduce electroplateability and cannot be properly plated unless corners are rounded.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blind holes</td>
<td>Must usually be exempted from minimum thickness requirements. Where necessary, limit depth to 50% of width. Avoid diameters of less than 6 mm (0.24 in.).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sharply angled indentations</td>
<td>Increase plating time and costs for a specified minimum thickness, and reduce the durability of the plated part.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat-bottom grooves</td>
<td>Inside and outside angles should be rounded generously.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V-shaped grooves</td>
<td>Deep V-shaped grooves cannot be satisfactorily plated and should be avoided. Shallow, rounded grooves are better.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fins</td>
<td>Increase plating time and costs for a specified minimum thickness and reduce the durability of the plated part.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ribs</td>
<td>Narrow ribs with sharp angles usually reduce electroplateability; wide ribs with rounded edges pose no problem. Taper each rib from its center to both sides and round off edges. Increase spacing if possible.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concave recesses</td>
<td>Electroplateability depends on dimensions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep scoops</td>
<td>Increase plating time and costs for a specified minimum thickness.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spearlike juts</td>
<td>Buildup on jut will rob corners from their share of electroplate. Crown the base and round off all corners.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rings</td>
<td>Electroplateability depends on dimensions. Round off corners and crown from center line, sloping towards both sides.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Distribution of electroplate on design shapes is intentionally exaggerated by solid black outline. Cross-hatched areas indicate part before plating.
Similarly, plating inside holes can be difficult. The general rule of thumb is that if the hole diameter is \( x \), the plating will occur to a depth of \( 2x \). However, for blind holes, plating will only occur to a depth of \( x \). Agitation, solution flow, maximizing the throwing power of the plating bath, and other aids can improve the situation somewhat, but the best approach is to eliminate or minimize holes with high aspect ratios during the product-design stage.

In plasma-coating processes, the part design will have considerable influence over the operating parameters of the coating-deposition equipment. Complex shapes, blind holes, fins, slots, and similar features will dictate that a high vacuum pressure, low part temperature, and light plasma density be used (Ref 9). The converse will be true for simple geometries. In plasma processing, consideration also must be given to heating of the part by the plasma itself. Some design features with thin cross sections and low mass, such as fins, louvers, and bosses will heat up faster than the bulk material in the part. For parts that have been heat treated, or otherwise finished to provide desirable mechanical properties, overheating could destroy those properties or at least change the values detrimentally. Reference 9 provides some examples of process and equipment modifications to avoid such problems during plasma nitriding. Reference 10 discusses the effect of part geometry on the growth of the nitride layer during ion nitriding and how coating uniformity can be improved for grooved surfaces. As in electroplating, decreasing the aspect ratio (depth of groove to width of groove) has a positive effect.

Other Important Considerations for the Design Engineer

**Drawing up a Specification (Ref 1).** The greatest source of dispute or rejection after surface engineering is lack of communication and understanding, not a failure of the process itself. It is critically important that the contractor is provided with all the needed information to ensure that the component can, and will be, treated exactly as the customer expects. By establishing the right partnership and communication channels with all members of the purchase/supply chain, satisfactory results can be anticipated.
When a customer is seeking a quotation or evaluating a possible surface-engineering process, it is vital that the contractor has the information listed below. This information should be viewed as the basis of a specification, to be agreed upon by both parties, with no margin for error or misunderstandings. Important information to be conveyed includes:

- A current issue engineering drawing of the part
- Any applicable standards, for example, ASTM, ANSI, internal company standards, or international standards
- Indication of part weight particularly if it is a large item
- Indication of part number and quantity to be treated, in total and in each batch
- Packaging and handling requirements. Indication if parts must be returned in original packing
- The base material, including composition or formal material specification. If there is more than one material in the part, make this point very clearly. If it is a high-strength material being used in a highly stressed situation (e.g., fatigue), then clearly state this.
- Its heat treatment history during fabrication
- What coating or treatment is required
- Which areas on the part are to be treated. Mark them on the drawing. Clearly show any areas that must not be treated and agree on masking principles
- Required thickness or case depth. Indication of a tolerance band allowance
- If the part must be coated or plated to a final dimension, provide an overall tolerance band. Remember that there will be two tolerances on the part dimensions, the manufacturing tolerances and those of the coating process. These will combine to a wider tolerance on the final dimensions. Manufacturing sizes may have to be altered to accommodate the coating thickness.
- Where, on its surface, can the part be supported or jigged (the area on which it is supported will be obscured and not treated); anywhere where it must not be jigged
- Specify any precoating and postcoating heat treatment (e.g., stress relieving or deembrittlement) that will be the responsibility of the contractor. Inform the contractor of any heat treatment done elsewhere prior to their receiving the work. Remember the more people in the chain the greater the opportunities for them to deny responsibility for problems.
- Required surface finish if it is controllable. Agree on any postfinishing procedures (e.g., a subcontracted grinding operation) if it is to be part of the treatment service.
- The inspection required, with a clear statement and understanding of what is acceptable and what must result in rejection of the finished part
• Agree and establish responsibility for rework, if allowed, and scrapped work.
• Any approvals required, for example, DoD or FDA
• Date dispatched, date received by contractor, date required, and method of delivery and dispatch

**Environmental Regulation of Surface Engineering.** Environmental protection regulations are often related directly or indirectly to surface-engineering processes. This is particularly applicable for solvent cleaning procedures, cadmium and chromium electroplating, chromate conversion coatings, and organic coatings containing high amounts of volatile organic compounds (solvents). The chemicals used for such processes may pose serious health and environmental hazards. For information about specific regulatory requirements, permitting conditions, and enforcement issues, the design engineer is advised to seek assistance from federal, state, and local regulatory agencies; consulting engineering firms; and law offices. Another valuable source of information can be found in the Section “Environmental Protection Issues” in *Surface Engineering*, Volume 5 of the *ASM Handbook*. Articles contained in this Section describe various environmental statutes affecting selection of surface-engineering processes and review specific processes that can be used to replace cadmium coatings, chromium coatings, and chromate conversion coatings, as well as alternatives to vapor degreasing and wipe solvent cleaners.

### Acknowledgment

This chapter was compiled and adapted from two primary sources:


### References