

## 1 Background to the Subject

The products of surface engineering are an integral part of our daily lives. We all take them for granted, whether we are merely simple users or consumers of these products or take a more active part in their design or the technologies used to create them, either as scientists, engineers or artists. Our homes are invariably surface engineered inside (painted, plastered, papered) and out (clad with tiles and/or cement layers containing stones and pebbles), or if timber framed, clad in timber weatherboards. Ancient dwellings, created by famous civilisations, contained many surface engineered features. These are immediately familiar to us, like tiles, which themselves have been rendered with protective and decorative glazes (Matin & Matin, 2012; Rehren, 2008), of pleasing colours and effects (**Fig. 1.1**). And there are the more impressive great pyramid structures of the Nile, which although built of bricks and stone were in their original state clad with brilliant white layers of limestone (white stucco – Graves, 1978). Today's concrete jungles of our downtown areas are dominated by steel-framed edifices skinned in layers of glass that are often held in place by networks of steel or aluminium. Although these structural arrangements are themselves surface engineering products, they now frequently contain added finesse, in that the glass itself has been specifically surface engineered to enable it to control sunlight (ultraviolet radiation) transmission or to invoke remarkable self-cleaning qualities, saving on the need for the uncomfortable business of high-rise window cleaning. Taking a closer look at our kitchens and our transportation vehicles (automobiles, rail engines, carriages, aircraft and ships), we find numerous examples of surface engineered components designed to provide pleasure as well as efficiency and durability (form and function). Similarly, the worlds of manufacturing and health care contain many products and devices that have a key reliance on surface-modified materials to enable them to provide sustained functionality. In the same way, all electronic devices – e.g. computers – contain numerous thin film components (including surface engineered metal hard disks) that have been created with the aid of specialist vapour deposition (coating) processes. More mundane, and more massive, structural examples are our roads and highways that have many specialised coverings ranging from various grades of Tarmacadam to diverse types of non-light reflecting and sound absorbing concrete.

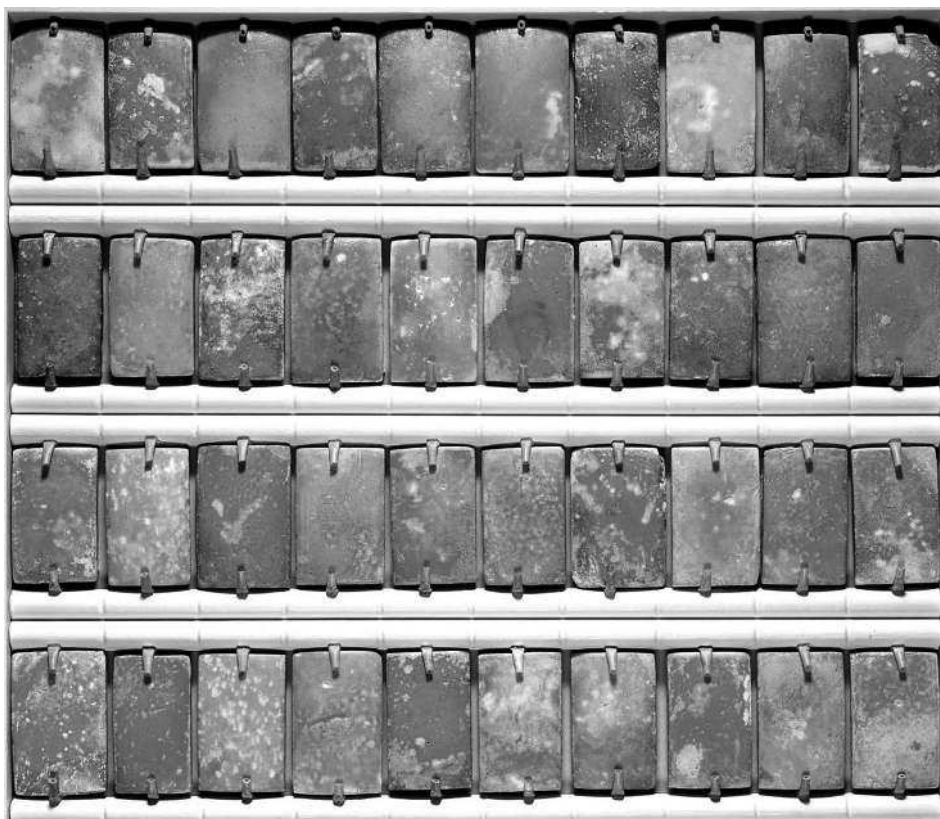


Figure 1.1 Faience tiles with a bright blue/turquoise surface glaze, Egyptian Old Kingdom, Dynasty 3 (2667–2648 BC).

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From the preceding paragraph, it is evident that surface engineering (SE) has vast character. This book largely reflects, but is not limited to, the author's personal contact with the subject over several decades. After dealing with some general features of the subject in **Chapter 2**, effort is initially given (Chapters 3 to 5) in providing detailed reviews of the surface engineering technologies and processes that are widely exploited by the Mechanical Engineer for a plethora of intermediate raw materials and end uses. In **Chapter 6**, an in-depth assessment of the surface degradation phenomena of materials is given, specifically showing how surface engineering can, to a greater or lesser extent, mitigate against these effects; this chapter centres on the responses of surface engineered materials to narrowly defined degradation effects. Real engineering operating environments are, however, more complex; commonly, many forms of degradation operate simultaneously or sequentially. Accordingly, the latter part of the book is devoted to specific application situations, which illustrate how conventional and surface engineered materials behave in complex engineering situations. Hence, detailed chapters are provided on surface engineered cutting tools (**Chapter 7**), automotive engine components

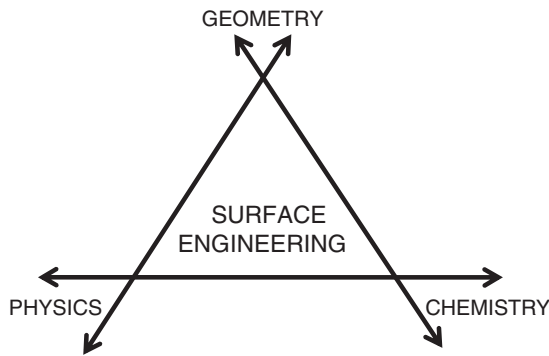


Figure 1.2 The surface engineering triangle.

(**Chapter 8**), gas turbine engine (GTE) devices (**Chapter 9**) and bio-implant surfaces (**Chapter 10**). All of these make demands on the physics, chemistry and geometrical aspects of a surface, which are inter-related as depicted schematically in **Fig. 1.2**.

## References

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- Matin, M. and Matin, M. (2012), ‘Egyptian faience glazing by the cementation method part 1: An investigation of the glazing powder composition and glazing mechanism’, *Journal of Archaeological Sciences* **39**, 763–776.
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## 2 Surface Engineering Basics

### Summary Points

- SE where and when?
- Real engineering surfaces and their preparation
- Depth-property profiles for surface engineered materials
- Contact mechanics
- Surface roughness and running-in
- Hardness testing

### 2.1 Surface Engineering: Where and When?

Surface engineering is a specialised activity that is applied at or very near the final stages of materials manufacture. Three exemplar materials processing routes – for metals (Path A), polymers/plastics (Path B) and ceramics (Path C) – are schematically depicted by the flow sheet shown in **Fig. 2.1**. As a rule of thumb, it is safe to say that surface engineering should be applied as efficiently and as rapidly as possible within the materials manufacturing pathway without impeding subsequent detailed component manufacture. Whilst traditionally such techniques were ‘farmed out’ to specialist subcontractor facilities, the trend is now changing towards more and more integration into the main production line. The manufacture of surface engineered metal sheet strip product (Path A in **Fig. 2.1**) – for example, steel or aluminium alloy (destined for car bodies or aircraft skins) – is nowadays best achieved as an addendum to the sheet metal finishing stages of cold rolling (**Fig. 2.1** – Path A – Route 3), before being cold pressed into panel components. Here astonishing rates of production are possible: for example, steel strip can be zinc galvanised via the hot dip immersion method or coated with tin electroplate (**Chapter 4**) at speeds of up to 600m/min! Similarly, aluminium alloy sheet can be anodised and subsequently sealed via hot water immersion, at the more moderate speed of 30m/min (**Chapter 5**). However, such surprising rates of manufacture are not possible when surface engineering is applied at later stages of manufacture, as is the case for most mechanically engineered components. This is the

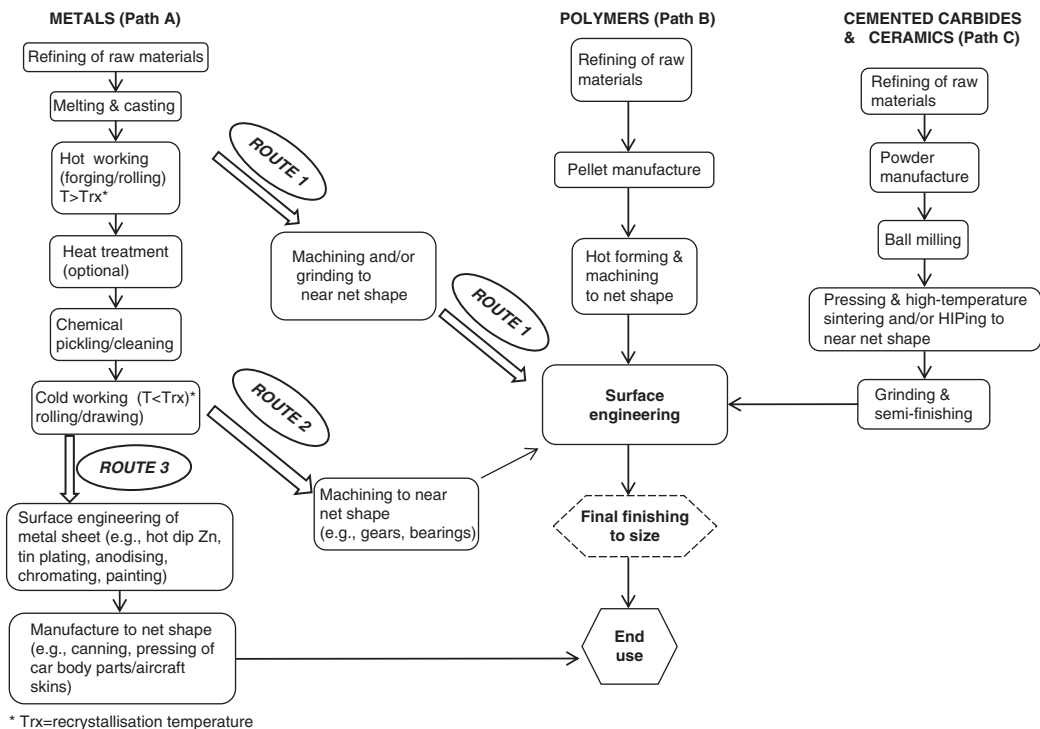


Figure 2.1 Routes to surface engineering: WHERE & WHEN?

situation for specialised cast metal products like single-crystal nickel alloy turbine blades (**Fig. 2.1** – Path A – Route 1 and/or 2) – discussed in more detail in **Chapter 9** – or for the manufacture of precision power transmission gears made from heat-treated steel bar that must be initially machined to shape and subsequently carburised or nitrided before being finally ground to their operational dimensions (**Fig. 2.1** – Path A – Route 2). Further examples include: (i) the manufacture of surface cross-linked polyethylene acetabular cups (via electron beam irradiation, refer to **Chapter 5**) via Path B in **Fig. 2.1**; (ii) thermal oxidised zirconium alloy femoral heads and condyles used in some designs of total joint replacement (**Chapter 10**) via Path A – Routes 1 or 2 in **Fig. 2.1**; and (iii) PVD or CVD multi-layer ceramic-coated cemented carbides (via Path C, **Fig. 2.1**) used as cutting tools (inserts) for the high-speed machining of steels, cast irons and other workpieces (**Chapter 7**). The latter substrates are prepared using specialised powder technology routes that require final high temperature sintering and occasional hot isostatic pressing (HIPing).

## 2.2 Real Engineering Surfaces and Their Preparation before and after Surface Engineering

### 2.2.1 Enabling Surface Engineering

The state of an engineering material surface is not pleasant to contemplate for the idealist who might think it should comprise a neatly arranged collection of atoms

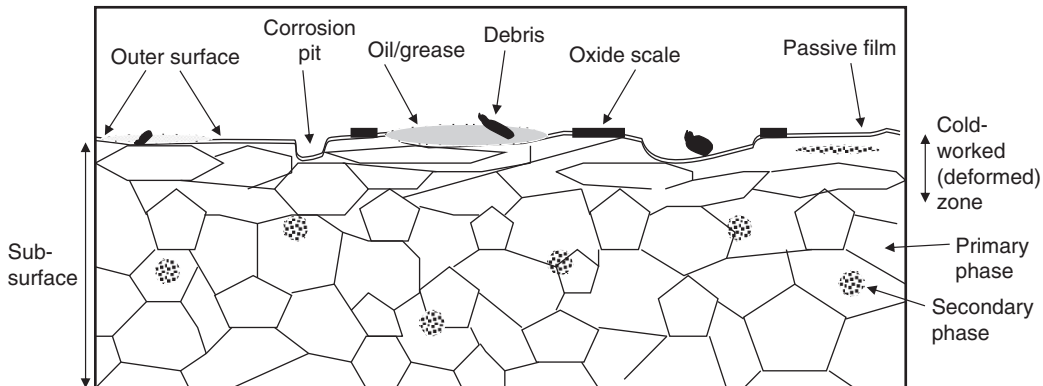


Figure 2.2 Schematic cross-section of ‘as received’ metal surface/sub-surface prior to surface engineering.

perfectly packed together to form regular grains or crystals. **Fig. 2.2** is a schematic cross-section through a metallic surface and its adjacent sub-surface as it would appear in the ‘as received’ state following the Path A processing indicated in **Fig. 2.1**. Whilst it is convenient to consider a metal surface/sub-surface (**Fig. 2.2**), the reader should be aware that polymer (plastic), ceramic, glass and cemented carbide surfaces/sub-surfaces have their own specific imperfections resulting from their individual prior methods of manufacture (e.g., Paths B and C in **Fig. 2.1**). As received metal surfaces may also be covered in various features – dust/debris, oil/grease, residual oxides/scales (from prior working operations) – and in many cases have a very thin (~10nm deep) layer of passive oxide film. This collection of surface/sub-surface features – which less kindly can be considered as ‘rubbish’ or ‘garbage’ – gets in the way of our desire to improve the various surface properties of materials, through the application of the surface engineering technologies described in **Chapters 3, 4 and 5**. Hence, as many of the undesirable artefacts as possible (indicated in **Fig. 2.2**) must be removed, by appropriate steps; otherwise, the ability to efficiently apply the various surface engineering technologies will be severely impeded.

The state of residual stress (also termed the ‘residual elastic strain’) relevant to metals is shown in **Fig. 2.3**. Here it is noted that this parameter varies as a function of depth beneath the surface. In the case of metal surfaces that have been prior machined or ground, there is often a shallow zone (~5–20µm deep) that is in a state of compression (**Fig. 2.3**) due to localised sub-surface plastic deformation (cold working; **Fig. 2.2**). Further below the surface, the residual stress state becomes positive (tensile) and finally returns to 0 at greater depth (**Fig. 2.3**). The purpose of some SE technologies, at least in part, is to develop distinctive residual stress states – as achieved by roll hardening, peening, carburising and nitriding (**Fig. 2.4**) – to inhibit or prevent surface degradation involving crack formation as in rolling contact fatigue pitting (**Chapter 6 – Section 6.5**).

Solid particles and oily film deposits (**Fig. 2.2**) can be readily removed from metal surfaces by immersion in various proprietary aqueous and organic solutions,

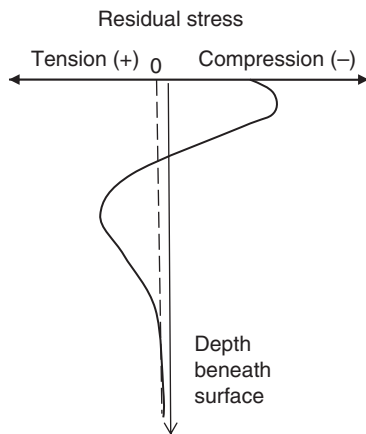


Figure 2.3 Schematic showing residual stress state distribution at and beneath a solid surface prior to or after surface engineering.

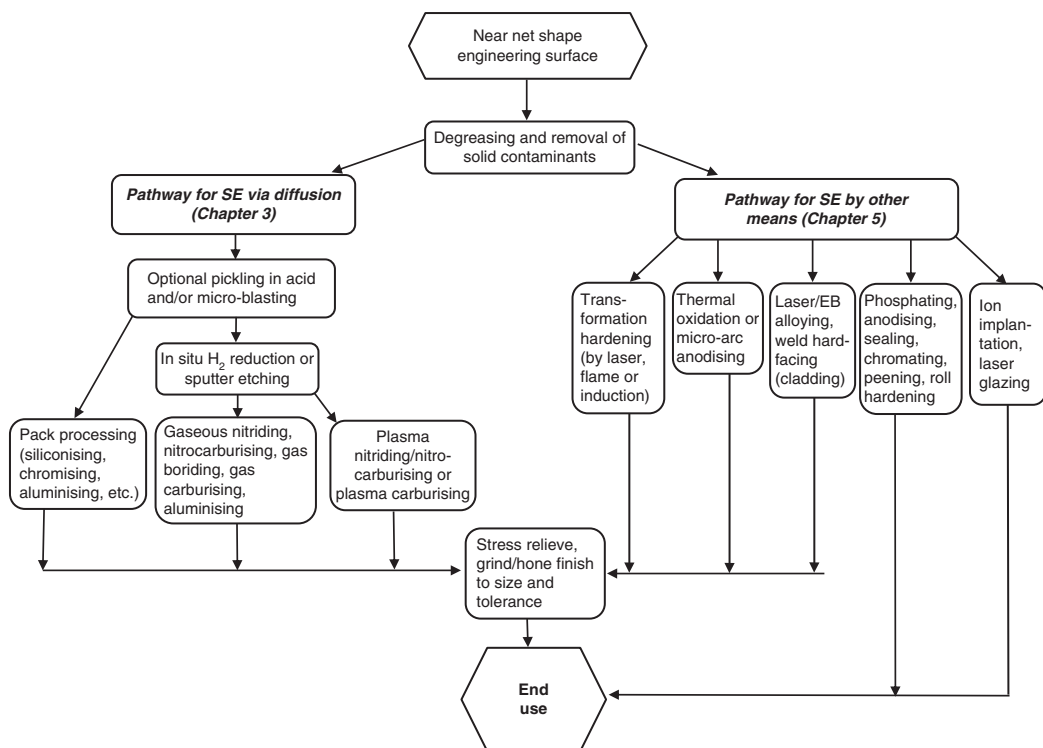


Figure 2.4 Surface preparation pathways for SE via diffusion or other technologies.

some of which contain detergents. This procedure is greatly assisted by the application of ultrasonic vibration (not always available), followed by drying in warm air. Such preparation procedures vary according to the nature of the SE process technology being adopted (Figs. 2.4 & 2.5). Relatively thick (>0.5µm) oxide scale (Fig. 2.2) may be removed via grit blasting, microblasting or pickling in acidic (HCl or H<sub>2</sub>SO<sub>4</sub>)/alkaline solutions. Removal of the passive film (depassivation; Fig. 2.2) – particularly important for stainless steels, Co-Cr and titanium alloys – is



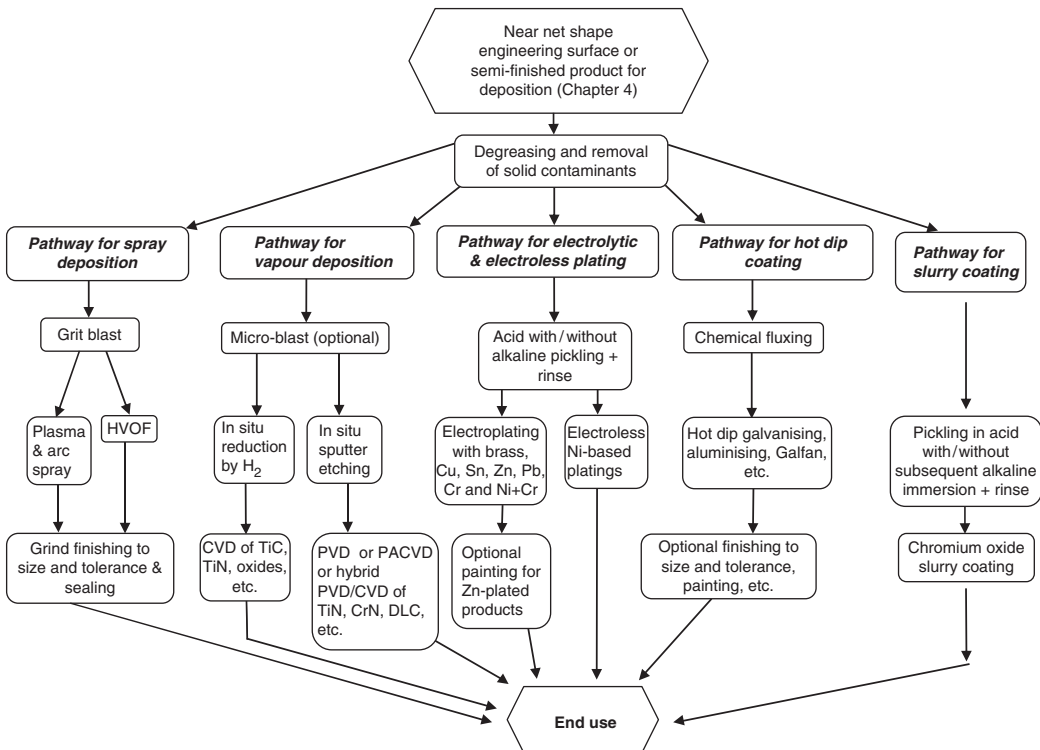


Figure 2.5 Surface preparation pathways for SE via deposition technologies.

further aided by immersion in alkaline solutions or through the use of proprietary fluxing agents. An appreciation of the complexity of such somewhat traditional procedures can be gleaned by referring to well-established standard texts (Canning, 1982; HMSO, 1986; Thelning, 1981; Dennis & Such, 1993). Alternatively, the selection of plasma-assisted SE processes like plasma nitriding (**Section 3.2.1 in Chapter 3**) or physical vapour deposition (PVD – see **Section 4.11 in Chapter 4**) assures a significant degree of passive film removal via in situ sputtering of the component surfaces (**Figs. 2.4 and 2.5**). In the case of gaseous processes – like chemical vapour deposition (CVD) or gaseous carburising – dry  $H_2$  (**Fig. 2.5**) or dedicated endothermic gas mixes respectively, are used to remove surface oxides via chemical reduction reactions. Such procedures greatly facilitate subsequent chemical bonding across a given coating/substrate interface or the coupling of diffusion solute atoms, to a virgin surface in the case of diffusional-based SE procedures. The alternative use of a grit blasting preparation pathway – prior to the application of thermal spray (plasma sprayed, HVOF sprayed and arc sprayed) coatings (**Fig. 2.5**) – although similarly aimed at assuring subsequent coating adherence, works in a different way. (A similar preparation pathway is also used prior to SE via cladding/weld hard facing and fusion coating.) Here, only *moderate* chemical bonding takes place across the coating/substrate interface. Instead, thermal sprayed



coatings are highly reliant on mechanical interlocking (keying-in) with the substrate; this is discussed in greater detail in **Chapter 4 (Section 4.14.1)**.

An often overlooked procedure by designers is the need to apply mechanical finishing steps to surface engineered materials; these range from relative gentle lapping, honing and polishing steps to more severe grinding procedures. (The amount of material removed by such procedures has to be allowed for at the engineering drawing stage of design.) The latter step (grinding) is essential after carrying out SE processes that result in significant distortion – e.g., after the carburising or transformation hardening of steels that causes an unavoidable volume change during formation of the martensite phase that accompanies the penultimate cooling (quenching) step. Grinding to final tolerance and size is also essential after applying thermal spray coatings such as plasma-sprayed (PS) or HVOF-sprayed ceramic, composite or metallic coatings, or following the micro-arc oxidation of aluminium alloys, since all these treatments produce relatively rough surfaces ( $R_a > 10\mu\text{m}$ ) that are unsatisfactory for engineering components. For example, PS-ceramic coatings used for internal combustion engine (i.c.e.) piston rings (**Fig. 8.5 in Chapter 8**) and exhaust valves require accurate ( $\pm 15\mu\text{m}$ ) grind finishing before use. Lapping and polishing stages may be essential for some components destined for sliding contacts – e.g., after the specialised nitriding, oxy-nitriding or nitrocarburising of plain carbon/low-alloy steels or low-temperature carburised/nitrided stainless steels; here, very small amounts of material should be removed since the protective layer is often only  $\sim 30\mu\text{m}$  thick or less (e.g., see **Fig. 3.35 & 3.40 in Chapter 3**). Other post-SE processes may also involve thermal stress relieving (at temperatures  $< 250^\circ\text{C}$ ), but this should only be applied to materials like carburised or transformation-hardened steels to relieve stresses built up *beneath* the surface and avoid detriment to the beneficial surface/sub-surface stress state developed by the SE treatment. In this respect, stress-relieving heat treatments should *never* be applied to prior peened or roll-hardened materials, or ion-implanted or laser-glazed surfaces (as indicated in **Fig. 2.4**), as this procedure can easily destroy the benefits of such treatments.

## 2.2.2 Preventing Localised Surface Engineering

An intermediate procedure, *not* indicated in **Figs. 2.4 and 2.5**, is that of ‘masking off’ surfaces in order to prevent surface modification in specific surface locations – for example, to allow subsequent minor finish machining operations like the thread tapping of drilled holes, or to better aid subsequent assembly of a component within a complex engineering assembly, like an automobile engine. To protect specific areas from being electroplated, a relatively high melting point wax or plastic resin (Canning, 1982; Dennis & Such, 1993) like the proprietary ‘lacomit’ can be used, whereas to prevent diffusion hardening of various component zones – e.g., via nitriding or carburising – regions may be electroplated with Cu, Sn or Ni (Thelning, 1981). For some SE procedures, like chemical vapour deposition (CVD) coating with hard ( $\sim 2000\text{kg/mm}^2$ ;  $\sim 20\text{GPa}$ ) titanium nitride (TiN) or other

hard materials, the prevention of local coating deposition can prove difficult when precision manufacturing necessitates the attainment of tolerances ( $\pm 10\mu\text{m}$ ). The use of temporary protective metal (e.g., steel) covers put in place during the SE processes may help but may not always prove completely effective. In another area, that of thermal spray coating, proprietary ‘high temperature’ duty plastic adhesive tapes are used to physically mask off zones that do not require coating (Matejka & Benko, 1989; Pawlowski, 1995). All such procedures require diligent care by semi-skilled, highly dextrous technicians.

### 2.3 Surface Engineered Depth-Property Profiles and the Role of Substrate Type

Surface engineering technologies outlined in **Chapters 3, 4 and 5** have the purpose of altering the physical, chemical and geometrical properties of engineering material surfaces (**Fig. 1.2**). Whilst it is relatively simple to determine changes in hardness as a function of depth below the surface (using established laboratory tools like microhardness testing), it is more challenging to determine similar variations for properties like internal residual elastic stress (strain), electrode potential, chemical composition, chemical bonding character, fracture toughness and Young’s modulus. It is also very demanding to establish how such property distributions change – for example, as a function of temperature, which is essential for products destined for high-temperature applications like those encountered by coated cutting tools used in machining operations where, during use, coating hardness is profoundly reduced (see **Section 7.3** in **Chapter 7**).

Despite the limitations described, it is nonetheless useful to consider the *shape* of the property profile as a function of depth beneath the surface. Consider the schematic diagram shown in **Fig. 2.6**. This shows *four* situations. In **Fig. 2.6a** we see a sudden change in composition and hardness as a function of depth beneath the surface, as happens after applying a hard coating material like titanium nitride (TiN) or chromium nitride (CrN) to a low-alloy steel surface. The resulting stark change in hardness can be termed a ‘dog leg’ profile. By contrast, the profile shown in **Fig. 2.6b** represents a gentle change in hardness and composition, which can be thought of as having a ‘reverse-S shape’. The latter is typical of a carburised low-carbon steel (for example, see **Figs. 3.22 & 3.36** in **Chapter 3**). More complex profile shapes can be formed, depending on the surface technology or combination of surface technologies used (e.g., **Fig. 2.6c**), which results after diffusion hardening low-alloy steel via nitriding in situations where an external compound layer of iron nitride (like  $\gamma\text{-Fe}_4\text{N}$  – see **Fig. 3.8** in **Chapter 3**) is formed atop the diffusion zone, resulting in a profile that is essentially a mix of the profiles shown in **Fig. 2.6a/2.6b**. Yet a further possibility is the profile depicted in **Fig. 2.6d**, which is representative of duplex surface engineered steel (**Section 4.16** – **Chapter 4**), which schematically depicts a CVD-TiC coating applied to a prior carburised steel substrate. Specific hardness-depth profile shapes applicable to the SE technologies reviewed in **Chapters 3, 4 and 5** are summarised in **Figs. 2.7, 2.8 and 2.9** respectively. A further augmentation is to create surface