Foresight in surface engineering

Document compiled by the Surface Engineering Committee of The Institute of Materials

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Surface engineering is a critical technology underpinning the competitiveness of UK industry. As the examples in Table 1 indicate, this influence is broad and of major economic importance. This document, prepared by the Surface Engineering Committee of The Institute of Materials, highlights the contribution made by surface engineering to key industry sectors and identifies some challenges for the future. Obvious links exist with parallel Foresight activities in areas that include bioengineering, construction, corrosion, packaging, energy, and steel.

The UK market for surface engineering processes in 1995 has been estimated[1] as about £10bn, of which £4.5bn was 'engineering' coatings to improve wear or corrosion resistance (Table 2). These treatments critically affected manufactured products valued at £95.5bn (about 7% of UK GDP). On current trends, the equivalent values for 2005 were conservatively predicted[1] as £21.3bn and £143bn respectively in 1995 prices. Particularly strong growth was predicted in the aerospace, agriculture, automotive, electrical consumer goods, and electronics sectors. The report[1] concluded: 'surface engineering provides one of the most important means of engineering product differentiation in terms of quality, performance and life-cycle cost.'

Some idea of the pervasive influence of surface engineering can be gathered from a review of the topics identified by the Delphi survey conducted as part of the first Foresight exercise. Of the 80 topics listed in the materials survey,[2] at least 15, in sectors including biomaterials, power generation, offshore, and electronics, will require surface engineering solutions, while another 25–30 will involve surface engineering to a significant extent.

Estimates of the cost of wear and corrosion to the UK and other economies (Table 3) suggest that these costs are a significant fraction (up to 4%) of GDP. Despite the widespread view that the situation has improved since the classic assessments of Jost and Hoar, effective use of surface engineering, coupled with improved education of designers, has the potential to deliver sizeable economic benefits.

Bridging end-user sectors

Surface engineering may be defined as:[3]

> The design of surface and substrate together as a functionally graded system to give a cost effective performance enhancement of which neither is capable on its own.

This is by definition a highly interdisciplinary activity. The successful implementation of surface engineering requires an integrated approach at the design stage, involving collaboration between design and surface engineers, as is increasingly being realised by managers in diverse industry sectors. In addition to being able to solve problems, surface engineering technologies have the ability to supply *added value* and thus add profit. The aim in surface engineering is to manipulate appropriate technologies to achieve optimal surface property designs for specific applications in the most cost effective manner.[4] Surface engineering thus has the ability to act as a bridge, transferring technology and expertise between end-user sectors that would not normally benefit from this cross-fertilisation. The interaction between design, properties, surface engineering technologies, and industry sectors has been summarised using the 'road map' concept[4] (Fig. 1).

Key areas for development

Key cross-sectoral issues identified include:

Environment and sustainability Surface engineering offers materials savings and environmental benefits in numerous applications, e.g. through increased service life, reduced emissions and energy consumption, improved recyclability. Many modern surface engineering processes have low environmental impact. An increasingly important activity is the *reclamation* and recoating of expensive components. *Environmental legislation* will continue to be an important driver for change, particularly in sectors where small companies predominate. Restrictions and cost penalties on emissions and disposal/landfill will render some established processes and product life cycles unsustainable; development of alternatives will be a priority.

Lightweighting The drivers to reduce weight will increase, particularly for motor vehicles. Aluminium, magnesium, and titanium alloys all require surface engineering to improve corrosion and tribological properties; here and elsewhere, *duplex treatments* (combinations of surface engineering technologies) will become more important. The surface engineering of ***polymers*** for structural applications has strong potential for growth.

Smart layers and structures Applications of functionally graded structures capable of a response tailored to their environment will increase. This will involve further growth in use of sensor technology, increasingly combined with applications such as smart oxidation resistant layers for gas turbines, self-monitoring buildings, food packaging, etc., in all of which surface engineering will play a key role.

Process robustness Surface engineering processes and process–property relationships need to be better understood. This will improve process control and quality assurance, and hence productivity and customer confidence. *Modelling* will play a major role in this process. Generation of assured *design data* is a priority.

Cost effectiveness of some important surface engineering technologies could be improved by process development to increase deposition rates and/or move from batch to semi- or fully continuous processing.

Education and training Engineers must be made more aware of the potential of surface engineering and its integral role in design: mechanical engineering courses should include this topic. Similarly, surface engineers should receive training in manufacturing engineering. The mismatch between industry requirements and academic expertise identified by Bull,[5] in particular a lack of expertise in 'traditional' surface engineering technologies, is a cause for concern. The Link Surface Engineering Programme was effective in promoting university–industry collaboration and should be revisited; however, the lack of pilot scale development facilities in the UK is felt to hinder technology transfer.

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[2] http://www.foresight.gov.uk/servlet/DocViewer/doc=304/26_1.htm.

[3] *See*, for example, D. Melford: 'A study of surface engineering in the UK'; 1989, London, CEST and:

[4] T. Bell: 'Towards a universal surface engineering road map', *Surf. Eng.*, 2000, **16**, (2), 89–90.

[5] S. J. Bull: 'Surface engineering in UK academia', *Surf. Eng.*, 1997, **13**, 177–178.

Table 1 Contribution of surface engineering to key industry sectors

- The performance of aircraft* and motor vehicles* is critically dependent on surface engineered components; some 80% of both these industries is affected by coatings†.
- The UK leads the world in advanced coatings for gas turbines employed for power generation*, a sector in which UK industry has a £1bn trade surplus and which would not exist without surface engineering.
- Advanced coatings for tooling have increased productivity during machining severalfold over the past decade. In 1997, 23% of all high speed steel cutting tools and 67% of cemented carbide tools worldwide were physical or chemical vapour deposition coated‡ and in the UK physical vapour deposited (PVD) coating of tools* represents a business with an annual turnover in excess of £10m.
- Modern PVD multilayer coatings for high performance cutting tools permit dry machining*, eliminating the need to dispose of coolants, without reducing productivity.
- Duplex surface engineering of titanium alloys* has increased wear resistance by more than an order of magnitude, permitting their use for lightweight components in Formula One vehicles and in other advanced applications in the offshore, biomedical, and sports sectors.
- The production and successful functioning of packaging* depends critically on surface engineering: the 33 billion beverage cans produced annually in Europe could not be made without coated forming tools; coatings are vital to improvement in the performance of the packages themselves, e.g. as water and gas permeation barriers on crisp and ready-meal packs, and as crack prevention layers to allow thinner walled glass bottles.
- Multilayer magnetron sputtered Low-E coatings on architectural glass* reduce winter heat loss by up to 60%, equivalent to 20 L of fuel per square metre of glass per year. It is predicted that by 2005, 50% of all architectural glass will be coated.
- Plasma surface treatment of ultrahigh molecular weight polyethylene has almost eliminated sliding wear in mild regimes and has strong potential for enhancing performance in biomedical applications.
- Biomedical devices, from prosthetic joints to substrates for tissue regeneration to advanced biosensors, rely on engineered surfaces to provide both functionality and biocompatibility.
- Effectively 100% of electronic components and advanced sensors, optical coatings, etc. are fabricated using surface engineering technologies.

* Sector covered by statement in this document.

† A. Matthews, R. Artley, and P. Holiday: '2005 revisited: the UK surface engineering industry to 2010'; 1998, Farnborough, NASURF.

‡ E. Lugscheider and C. Herbst-Dedrichs: Proc. Euro PM99: 'Advances in hard materials production', 15–23; 1999, Shrewsbury, EPMA.

Table 2 Market for surface engineering processes in UK*

	Market value (1995 prices)		Value of manufactured products critically affected by these treatments (1995 prices)	
	1995	**2010**	**1995**	**2010**
Engineering coatings	£4.5bn	£7.0bn	£82.9bn	£117.3bn
Semiconductors	£3bn	£9.0bn	£3.3bn	£9.9bn
Other functional coatings	£2.5bn	£5.4bn	£9.2bn	£16.6bn
Total	**£9.6bn**	**£21.3bn**	**£95.5bn**	**£143.9bn**

* Source: A. Matthews, R. Artley, and P. Holiday: '2005 revisited: the UK surface engineering industry to 2010'; 1998, Farnborough, NASURF.

Table 3 Estimates of cost of wear and corrosion

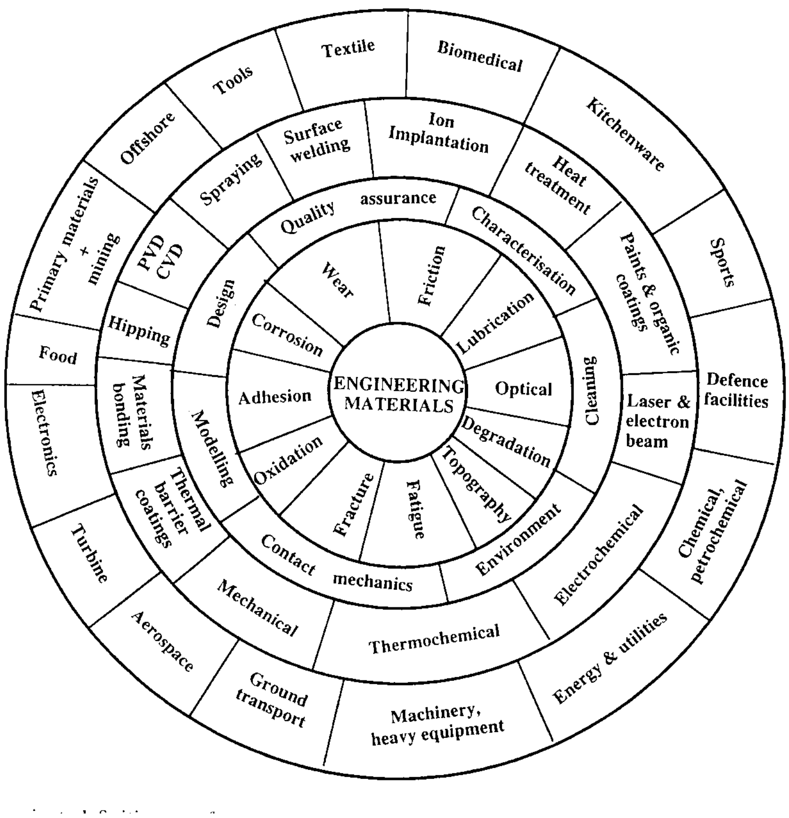
Wear	
Jost report (1966)	Annual savings of £515m available in UK within 10 years through education to improve awareness of tribological problems. Surveys in India, China and USA suggest similar fraction of GDP.
Peterson (1980)*	Cost of wear up to $100bn annually for US economy.
Corrosion	
Hoar report (1971)	Annual cost to UK economy in excess of £1300m, equivalent to 3.5% of GNP, with potential savings of £310m.
NACE (1984)†	$48–50bn annually in USA, equivalent to 4% of GNP.
McIntyre (2000)‡	UK corrosion costs, based on DTI funded industry survey: offshore oil and gas sector 1–2% of turnover (potential to reduce corrosion costs by 15%); chemical/petrochemical 0.1–9% depending on service conditions (potential to reduce corrosion costs by up to 40%).
Jotischky and Whitehouse¶	Qualitative examination of progress made by automotive industry since Hoar, driven by customer demands and globalisation, facilitated by improved technology. Perhaps some 'corrosion cost' transfer from user to manufacturer.

* M. B. Peterson: 'Wear control handbook'; 1980, New York, ASME.

†'Corrosion prevention by protective coatings'; 1984, Houston, TX, NACE.

‡ P. McIntyre: 'Corrosion problems and costs in the UK offshore and chemical industries', Proc. Eurocorr 2000, London, September 2000, EFC. This DTI funded project is also examining the automotive (*see* below), food and drink, and constructional steelwork sectors.

¶ H. Jotischky and N. R. Whitehouse: 'From Hoar to the millennium: continuity and change in the UK corrosion scene – an introduction to a current DTI funded project', Proc. Eurocorr 2000, London, September 2000, EFC.



1 The surface engineering road map: a multisectoral, interdisciplinary technology

Surface engineering in the automobile industry

There are some 27 million cars and 3.3 million commercial vehicles on Britain's roads,[1] the European car sales amount to some 12 million units per annum of which in 1997, for example, UK production contributed 1.7 million. Despite the effects of the strength of sterling exports increase, year by year: automobile manufacture has been predicted to provide 17% of the value of surface engineering to British industry by 2005, an increasing share. These figures deny a poor press and prophecies that progressive internationalism is bringing decline in Britain.[2]

Nevertheless stagnation in the Western Europe market is forecast and over-supply is apparent; although the UK customer has found himself to be the victim of commercial pricing practice, competition between manufacturers for market share continues to be a prime stimulus for technological advance. Car owners may care to reflect on rising expectance for quality, in terms of appearance, reliability and safety.

Incremental improvements become taken for granted. Older drivers may remark on current 7 to 10 year guarantees of corrosion protection and on mileages above 150,000 before engine wear becomes significant. Whatever the costs of driving, the car itself is affordable by an increasing proportion of the population and presents progressively better value for money.

Surface engineering contributes very significantly in this manufacture. It is not generally appreciated that some 6% of the costs of manufacturing engines and transmission is involved in coating technologies. Organic finishes are highly decorative and functional: the total value of paint supplied to the industry is approaching £300m. The steel shell and structural members require preparation as substrates so that, for example, an increasing number of components are galvanised and provided with appropriate conversion coatings to receive paint. Whilst metal is usually finished with an organic coating, so plastic may be metallised: here the established 'wet' processes compete with developments in PVD and CVD.

Technology is not only market driven. Environmental concerns and consequential legislation are also powerful drives. Paint contributes some 2 kg to the weight of a car; but in painting over 5 kg of volatile organic compound (VOC) is emitted to the atmosphere. This prompts the development of powder (low-loss) technology. Many proprietary conversion coatings involve the use of hexavalent chromium compounds, as does conventional chromium electroplating; alternatives are being sought. The car industry is turning from electroplated zinc to zinc alloy plating for access to an environmentally more acceptable product and process of production, as the use of $Cr^{\underline{VI}}$ can be avoided.

These are example of current developments some of which are already the subjects of European Council Directives[3]. Large companies have the resource to react rapidly to such legislation – see, e.g. reference 1. The evolving situation is more difficult for the many small firms[2] whose commercial relationship is with enormously larger trading partners. This challenge in the emergence of relationship marketing may have a dramatic effect on the conventional, dispersed metal finishing industry.[4]

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2. A. Matthews, R. Artley, and P. Holiday: '2005 revisited: the UK surface engineering industry to 2010'; 1998, Farnborough, NASURF.
3. 'On the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain activities and installations', EU Council Directive 1999/13/EC, 1999.
4. *See* e.g. C. Larson: 'Contract coaters, customers and closeness', *Trans. IMF.*, 2000, **78**, B67–B73.

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Surface engineering in the power generation industries

Power generation in this respect, includes high performance engines for the aerospace industry, marine gas turbines, utility turbines for electric power production and gas turbines as part of advanced combined cycle plant.

Materials issues in the power generation industry are well covered and reviewed by other Foresight documents, namely ‘Foresight for the gas turbine and advanced combined cycle technology sector’[1] and ‘Foresight for the cleaner coal power generation technology sector’,[2] both of which have been produced and published by the Foresight Energy Panel. In each of these surface engineering is an important enabling technology.

Industrial/utility turbines
Both of these Foresight documents focus on the need for more efficient power production, with lower emissions (reduced to acceptable levels) whilst maintaining production costs at a competitive level. Both documents allude to combined cycle technology as the way forward with the gas turbine engine an integral part of this energy efficient power production technology. The focus on gas turbine technology as part of an advanced combined cycle energy system reflects the facts that:

- the gas turbine has the lowest emissions of any fossil fuel power plant, offering significant advantages over conventional coal fired steam generating plant
- gas turbines are capable of handling a wide range of different fuels at competitive costs and efficiencies
- combined cycle plant has the highest power conversion efficiencies, approaching 60%, of any current fossil fuel plant
- combined cycle plant currently offers the lowest installed cost/kW and the lowest through life base-load costs.

Furthermore, the technology is still developing and therefore further improvements are possible through advanced design, more efficient combustion – high operating temperatures – and improved materials technologies – including the use of coatings and surface engineering.

Within the UK power engineering has a turnover of £13.3bn, employs over 160,000 employees, and has a balance of exports over imports of almost £1bn per year. The UK contributes to this sector in three ways: it manufactures small and medium size gas turbines, it provides expertise for the development of large machines – particularly in the key technologies of materials and advanced combustion, and it is a major manufacturer of combined cycle power plant.

The estimated world market for gas turbine power plant over the next 15 years is 575 GW_e, of which UK companies (Alstom and Rolls-Royce) have a 5% share. In the small to medium size plant (up to 80 MW_e) the UK has a 12% share. This values the UK share of the projected industrial gas turbine market as £1500m over the next 15 years.

Setting technological targets for the power generation sector of a 2%/year reduction in the cost of electricity generation, the attainment of ultralow emissions, and improved reliability over current acceptable levels has significant materials implications. Improved efficiencies and reduced costs require an increase in the cycle temperature and pressure, and this requires that materials within the hot gas path of the engine are under increased thermal loads (expected to run hotter, with reduced cooling). The need to reduce emissions means that many contaminants, formerly vented to the atmosphere, have to be retained in the power plant. A corollary of this is that hot gas path components will see more corrosive environments.

Thus improved efficiencies, lower emissions and reduced downtime of plant operation have a knock-on effect on reliability, availability and maintainability (RAM), with the higher temperatures and more corrosive environments increasing the environmental severity. Improved efficiency, reduced emissions and improved RAM can only be achieved through new materials development, particularly coatings technologies.

Aero gas turbines

In the aerospace sector, replacement of older aircraft and growth opportunities will lead to a doubling of the aircraft fleet over the next 20 years. The airline customer business is worth $340bn for engines and spare parts – 48 100 new engines – whilst the defence market is able to address a market opportunity of $190bn – Rolls-Royce enjoys industry leading growth. In 1987 there were 200 civil engine deliveries, in 2000 this will increase to 1100 engines, a market share in excess of 25%. Surface engineering is central to remaining competitive in this sector with increasing reliance being placed on coating or surface treatments to achieve reliability, cost and performance targets.

Aerospace needs are for high powered, efficient, lightweight plant to power the future generation of high capacity civil aircraft. Power to weight ratio and specific fuel consumption are therefore important performance indicators. Thus additional emphasis is placed on:

- the development of new materials, coatings and design concepts to achieve the future performance and environmental needs
- optimisation of current coating systems, to offer the desired performance, while managing cost and environmental impact
- future/further integration of surface engineering into the design process to capitalise on strategic performance benefits.

The future

Critical components are high temperature components associated with the combustion process and the downstream hot gas path. Component degradation depends on service duty. In the case of peaking machines, with many start/stops, thermal mechanical fatigue is the dominant failure mechanism. For base-load machines, creep, oxidation and corrosion are the more significant factors. Thus Foresight 'Energy' recognises that 'materials and lifing' is one of the core technologies for the development of future efficient power generation plant.

Coating systems are widely used in all modern gas turbines to provide hot gas path protection and improved life. They may take the form of low cost diffusion treatments – first introduced in the 1960s – through custom designed corrosion resistant alloys – the MCrAlY series of overlay coatings – to advanced thermal barrier coating systems that offer the potential of dropping 150–200ºC across a 250 µm coating, when combined with advanced cooling technologies.

The aim must be to develop new, advanced coating systems, capable of extending the materials performance range, coupled with new technologies and models capable of lifing these new and existing materials. Based on a review of the industrial requirements for protective coatings in advanced power generation[3] the following generic targets have been set for coating development over the next 5 years:

- a 50°C increase in operating temperature
- a 10 000h increase in component life
- a factor of ×2 on inspection intervals
- a wide fuel capability – natural gas, liquid fuels and 'dirty' fuels from the combustion of coal, biomass etc.

To achieve these aims new coating systems will have to be developed. Many alternatives are being researched in the UK and overseas. Of those funded in the UK by EPSRC and industry we have seen the development of 'smart' corrosion resistant overlay coatings that are capable of responding to the local corrosive environment to provide the best protective oxide – this class has been developed through a combination of plasma spray technology and CVD;[4] the development of improved platinum aluminide diffusion coatings, plus considerable work on novel thermal barrier coating (TBC) concepts, including layering and dopant additions – both of which lower the thermal conductivity.

In these areas, the UK has an international lead, but will only retain this lead with continued funding of high quality coating research.

Ultimately, one could see the design of a composite surface protection system for industrial turbines that will mirror that being developed in the aero-turbine industry. This would consist of a layered, strain tolerant TBC system, deposited onto a bond coat that offers good oxidation and corrosion resistance, but more importantly matched thermal expansion coefficients with the ceramic top coat. Within the bond coat the composition would be graded to provide the required corrosion resistance and coating mechanical properties. A diffusion barrier would be included at the interface with the substrate which would limit interdiffusion.

This concept is only a few years away with much of the fundamental research under way in the UK at present.

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Thermally sprayed coatings*

Thermal spraying is now regarded as one of the key enabling surface engineering technologies. It is an environmentally friendly process that uses the minimum of strategic materials. Since their humble origins, some 90 years ago, the use of thermally sprayed coatings has grown enormously and they are extensively used across the whole spectrum of engineering and manufacturing. From automobiles to aeroplanes, from surgical implants to golf clubs, the list is almost endless. Thermal coatings play an important part in everyday life – every time you drive your car, every time you fly, every time you switch on a fluorescent light then you are probably relying on a thermally sprayed coating.

Any material that has a well defined melting point and does not decompose when heated can be thermally sprayed. The resultant coating can be applied to most substrates to provide a functional surface exactly where its needed, enabling the designer to specify low cost, lightweight and easily workable base materials.

From a handful of materials in the early days, over 500 are now available for coating selection. Most metals, alloys, carbides, and ceramics and some polymers can be deposited to form low cost surface coatings which can be tailored to meet the exact in-service requirements.

Thermally sprayed coatings can be used to impart many surface characteristics such as:

- wear resistance
- heat resistance
- oxidation resistance

- corrosion resistance
- electrical resistance
- electrical conductance
- restoration of size.

Applications

Aero-engine manufacturers are the biggest users of thermally sprayed coatings, both at the original equipment manufacturing stage and during the subsequent repair and overhaul. Coatings are applied to combat surface degradation mechanisms such as wear, corrosion and oxidation. Thermal barrier coatings are applied to combustors and nozzle guide vanes to protect against extreme heat. Clearance control coatings, which are designed to allow the rotating blade tip to machine its own seal path, generate significant savings in fuel consumption. Coatings are also used to rebuild mismachined or service worn components. Similar applications apply to industrial gas turbines and compressors.

The automotive industry has also been a major user of thermally sprayed coatings for many years. The combustion wire and plasma spray processes are used in the high volume production of a number of products of different shapes and sizes in the automotive industry worldwide. These applications include the outside diameters of piston rings, the bearing surfaces of shifter forks, synchronisation rings and cones, fuel injector nozzles, alternator covers and exhaust oxygen sensors.

Today the automotive industry is not only driven by the requirement to make vehicles that are safe and reliable; but also by the need for low fuel consumption, low emission of pollutants, as well as low mechanical and corrosive wear.

Thermally sprayed coatings can help the designer achieve these objectives by providing specific surface properties for lightweight components. Lowering the unsprung weight of a vehicle improves fuel efficiency, reduces emissions and enables the manufacturer to add safety and luxury features whilst still maintaining maximum weight targets.

Two areas where this is happening are:

- lightweight engine blocks – cast iron liners are replaced with a thin plasma sprayed coating. Production machines utilising rotating plasma spray guns and capable of processing 800 blocks per day have been built
- lightweight brake discs – aluminium metal matrix composite discs are coated with a special ceramic to give the desired frictional characteristics.

The success of thermal spraying in the automotive industry is due to the wide range of materials available, the properties of these materials and the ease in providing a high rate/low cost deposition for the large number of parts involved. Thermal spraying is a versatile process that can easily be integrated into a production line.

Other applications include:

- surgical implants, such as replacement hips, are coated with porous titanium or with synthetic bone to promote fixation in the body
- rolls used in the paper, printing and steel industries are protected against wear and corrosion
- thread guides and other components used in the textile industry are ceramic coated to combat the abrasive nature of synthetic fibres
- chemical industry pumps sleeves and shafts and other components are coated to prevent corrosion and wear
- paper or polymeric capacitors are metallised with thermally sprayed tin/zinc to enable electrical connection to be made
- structural foam moulded VDU and other electronic cases are sprayed with zinc to shield against stray electromagnetic or radio interference.

UK market

The current UK market value for thermally sprayed coatings is estimated to be £150m. This can be broken down as follows:

Aerospace:	£70m
General industry:	£30m
Corrosion protection	£50m

UK market potential

Aerospace	£150m
Automotive	£30m
General industry	£100m
Corrosion protection	£200m

Meeting the challenges

A number of key UK universities and research institutes are addressing the need for more understanding about the science behind the requirements for increasingly demanding applications. This needs to be prioritised to ensure maximum benefit for UK industry, especially for small and medium sized companies.

The major thermal spray manufacturers and suppliers are developing more efficient processes and materials that use less energy and conserve strategic materials. They are working with major UK companies to develop solutions to enhance product performance. These activities need to be co-ordinated to ensure that British industry gains a significant advantage.

Surface engineering including thermal spraying and other processes does not enjoy the profile it deserves. This needs to be rectified as soon as possible in order that the UK can take maximum benefit from these technologies.

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Packaging

It is very clear that improvements in packaging technologies hold the key to many of the Foresight objectives, in particular reductions in adverse environmental impacts by materials or processes. Improvements in packaging are almost all related to surface treatments and coatings. Key drivers include existing and impending environmental legislation, for example to reduce landfill waste disposal from the 1995 level of 60% of waste to 10% by 2005 (EU Waste Management Target). Simultaneously a change from 18% of all waste to be recycled (1995 figure) to 54% in 2005 is sought. Such targets will require considerable changes in the manufacturing processes for many types of packaging – for example the use of aluminised plastic film (which is difficult to recycle) should ideally be replaced with a film which has the required oxygen and water vapour barrier properties but which can be recycled (or, failing that, incinerated).

Other issues in polymeric packaging include a need to develop coatings to prevent tainting of food by the polymers. The benefits of coatings do not only lie in the packages themselves, but also in the improvement of production processes. For example, coatings are extensively used on can forming dies and cutting knives for paper and plastic, and also glass moulds. Particularly in the last case, there is an urgent need to avoid the often harmful vapours produced by the ‘anti-stick’ colloided graphite suspension lubricants used in glass moulding processes. Possible solutions are thermally sprayed or PVD coatings on the moulds and tools.

Glass products can themselves be coated to prevent breakage, for example by using tin oxide films. There is a need to further develop such coatings, so that the glass weight can be further reduced by using thinner walls.

Steel and aluminium cans also represent a significant technological challenge for coatings and treatments – due to the need to produce lighter-weight containers with improved functionality. There is (for example) a trend to replace tinplate as the external corrosion barrier, and also to improve upon the internal lacquers (about which some health concerns have been voiced). Corus has pioneered the development of pre-finished steel sheet for can applications, with its Ferrolite product.

Overall, although there is often a lot of 'negative press' about packaging (especially where this is wastefully used), the fact remains that effective packaging can considerably extend the shelf-life, hygiene and safety of food. The effective use of surface coatings thus contributes to massive reductions in the wastage of food and other products. The challenge now is to improve on these attributes, and also develop 'tamper-proof', 'intelligent' or 'smart' packs which provide the consumer with further benefits. Coatings can also hold the key to these developments.

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Glass coatings

Surface engineering (SE) techniques are now widely utilised in the production of many glass products. Market sectors in which SE techniques make a significant impact include architectural glass, automotive glass, display panels, mirrors and packaging. In some cases, the aim is to aid manufacturing, or add value to an existing product; whereas in other cases the deposition of functional films has allowed the development of entirely new products.

Examples of the former case can be found in the glass container industry. Glass containers can have their mechanical, operational and decorative properties enhanced by a range of coating technologies. These technologies are employed to enable glass to remain competitive in a market that also contains plastic and metal packaging materials. A specific example is the coating of bottles as they leave the forming machine.[1] The primary aim of this coating is to prevent damage to the glass surface by sliding contact during transport, filling and use. In addition, the coating must be uniformly applied, transparent, non-toxic, and allow labels to be readily attached, whilst not increasing the torque required open the bottle. Economics require the coating to be applied at line speeds of up to 550 bottles per minute. The current solution to this demanding problem is a two-stage deposition process. Firstly a bond layer, typically monobutyltin trichloride, is applied to the bottles as they pass through a vapour hood. Following this a thin layer of polyethylene is sprayed onto the bottles. The application of this type of coating has allowed progressively thinner-walled, lighter bottles to be used, without a reduction in mechanical properties.

The deposition of functional films onto glass products has been a major area of growth in recent years. Developments in coating technology now permit complex, multi-layer structures with specific properties to be routinely deposited in high throughput, large area coating systems. Applications include low-emissivity (Low-E) and solar control coatings on architectural glass; solar control and electrically conductive coatings on automotive glass; high reflectance coatings for solar collectors and telescope mirrors; moderate reflectance coatings for headlamp reflectors and rear view mirrors; photovoltaic coatings for solar cells; anti-scratch coatings on opthalmic lenses; and conductive anti-reflective coatings for computer monitors and television screens. The functional films are typically less that 1 μm thick and are usually deposited using PVD (physical vapour deposition) and CVD (chemical vapour deposition) techniques.

Low-E coatings provide a good example of the rise in importance of this type of product. Low-E coated double-glazed surfaces reduce winter heat loss by up to 60%, compared to uncoated windows, which is the equivalent of saving 20 litres of heating fuel per square metre of glass per year.[2] Such coatings might typically consist of a multi-layer 'stack' incorporating layers of tin oxide and silver. And are now commonly deposited by the PVD technique of magnetron sputtering. Large in-line production systems have been developed in which glass sheets up to 6x3 m in size pass under a series of magnetron cathodes. There are currently about 150 large area glass coaters in use worldwide, with a total capacity of some $220x10^6$ m^2/year.[3] Recent developments in magnetron design and the introduction of the pulsed magnetron sputtering process now allow the stable, high rate deposition of high quality films. As a consequence, it is predicted that the market for Low-E glass will grow to double the 1995 market by 2005. At this point 50% of all architectural glass will be coated. However, to achieve this position, continued development of the process will be required. The key areas to address are the durability of the product, in terms of scratch-resistance and corrosion resistance, and throughput, in terms of deposition rate and downtime. The current product is vulnerable to damage during transport and is prone to corrosion arising from moisture ingress before the sheet is sealed in the glazing unit. New materials will be required to overcome these problems. New materials may also impact on the deposition rate, whilst developments in the power delivery systems and magnetron designs will also be needed to raise throughput.

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PVD toolcoating

State of the technology

Physical vapour deposition (PVD) has been carried out as a method of applying coating layers to materials for many years. The vacuum deposition of metallic coatings for electrical, corrosion protection and decorative purposes has been widely used since the war and now forms a significant sector of the coating industry. In the early 1970s advanced PVD coating systems began to be developed which could be used to deposit compound coatings with compositions unobtainable by any conventional plating process.

It was found that the nitrides of the group 4 transition metals could readily be formed using PVD systems fitted with high efficiency ionisation sources and that these compounds demonstrated very high hardness combined with low coefficient of friction. These coatings applied to high speed steel cutting tools produced dramatic reductions in tool wear and enabled plant to be run at much higher rates of production than had hitherto been possible whilst also providing an improved quality of finish on the product. Throughout the 1970s and 1980s PVD coatings of titanium nitride (TiN) onto cutting tools saw rapid growth and were at least partially responsible for the loss of several tool manufacturers whose market was shrunk by the new longevity of the tools which they made.

During the past 10 years the technology has developed rapidly with a wide range of new coating products being introduced into the market. The properties of coatings are better understood. Compositions and microstructures can be tailored to particular applications resulting in further significant tooling budget savings for manufacturers. Coatings containing TiAlN, for example, offer high temperature oxidation resistance and can be used to coat tooling used in dry, or coolant free, machining. The resultant environmental benefits are a major driving force towards this technology

Commercial status

From its beginnings in the 1970s PVD toolcoating has grown rapidly from a ‘cottage industry’ to a mature, profitable and increasingly important sector of the surface engineering industry. Initially coatings were applied only in the most expensive or difficult applications where the benefits of the technology resulted in dramatic savings in tooling costs.

The continuing development of the coating performance and sophistication of the deposition plant have greatly widened the scope of application, whilst the economies of scale resulting from the investment in large coating plant have reduced prices to the point that many ‘everyday’ tools are now routinely coated. Coating centres operate round the clock offering rapid turnaround on coated tools, full laboratory services and collection/delivery services throughout the UK.

It is estimated that over 50% of industrial cutting tools are now supplied with some kind of PVD coating and the business turns over £10m per annum in the UK. In recent years the potential for growth of the technology and its synergy with heat treatment processes has led to a consolidation of the industry with major heat treatment companies making significant investment in the sector either by purchase of plant or corporate acquisition.

Growth

The market for PVD toolcoatings is still expanding rapidly with applications for coatings developing in plastics moulding, die casting and forging. Coating structures involving the layering of deposition compositions to produce further enhancements in performance are being developed. These structures promise to enhance the hardness, toughness and oxidation resistance of the coatings providing manufacturing industry with substantial cost savings.

The use of coatings to enable dry cutting is being driven by environmental concerns relating to the use of, and disposal of, liquid cutting coolants. As already seen over the past 20 years the use of coatings technology will continue to reduce the requirement to manufacture new tools with consequent energy and materials cost savings to the engineering community.

A further growth area is expected in the field of re-coating services where tools are removed from service as soon as the coating begins to wear. The remaining coating is removed by stripping and the tool recoated before significant wear of the steel surface occurs. This area of tool wear management requires coating suppliers to offer the extremely rapid response times and 24 hour reprocessing schedules which are now available in the more mature market.

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Self-lubricating and wear resistant coatings

Surface engineering and tribology exist to understand and mitigate the problems that occur when two surfaces interact with each other in an engineering device. Solutions have been developed, often empirically, and have become ‘standard practice’ because they work (more or less well) and because engineers know, understand and trust them.

The existing solutions include, in a motor vehicle for example:

- case hardening (e.g. carburising, boronising and nitriding)
- through hardening
- local surface hardening (e.g. induction, flame)

- electro- and electroless plating
- oils
- greases.

Across the range of engineering applications there are comparable problems and equivalent established solutions.

It is also true that we have available to us, developed and commercially available, a number of alternative solutions that most engineers do not know about, do not understand or do not trust because the processes have no long term track record. Many of these are based upon thin films deposited by PVD techniques and have the potential to address and overcome the challenges presented by Foresight imperatives.

The Foresight imperatives

Sustainable development and quality of life are both Foresight drivers.

Engineers who design and specify devices with moving parts need to understand and appreciate the alternative techniques. Only then can they use them to complement or replace their existing practice and preconceptions to their advantage. Take the example of a vehicle engine. This combines lubrication by oil with a number of surface treatment techniques to deliver a reliable and well-understood system. However the very success of the motor vehicle has made it a key target of Foresight from an environmental standpoint. We have made the motor vehicle a part of everyday life and there is no prospect that it will go away. Consequently we must develop methods and mechanisms to mitigate its impact on the environment – there is a requirement to reduce fuel consumption substantially and this has translated into a drive to reduce vehicle weight.

A typical car or light van engine contains 5–10 L of oil that has to be replaced every 6,000 or 10,000 miles. The oil represents a contribution of 5–10 kg, or 1–3%, to the kerb weight of a car or light van. Huge efforts have gone into the use of different materials and methods of construction to reduce vehicle body weight by up to 30%. It is illogical to ignore the contribution that the reduction, or total elimination, of this oil could offer.

When the fact that used engine oil is now recognised as a carcinogen is also taken into account the case for alternative solutions becomes even more compelling.

Thus the reduction, or even total elimination, of engine oil would make a substantial contribution in terms of both sustainable development and quality of life. This derives from:

- reduced demand for oil
- lower fuel consumption for vehicles
- reduced exhaust emissions (CO, CO_2, NO_x)
- a diminished quantity or even the total elimination of a recognised carcinogen from the waste stream

Mechanisms for progress

Technologies already exist to provide alternatives to conventional lubrication in many applications. Additional systems will doubtless emerge as the market demand and commercial rewards become apparent. The main stumbling block is seen as lack of awareness and understanding in the design and specification community. It is probably true that the formal education of most engineers contains little if anything at all on traditional tribology and surface engineering let alone any mention of these newer techniques.

It is suggested that a programme of awareness and continuous professional development be implemented to fill the knowledge gap.

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Electroplated coinage in the UK

Present state of technology

Wrought metal coins have been standard currency since Classical times. The coins were usually made from metal strip (originally the precious metals, silver or gold), from which blanks were cut and then struck with dies to impress the design. In the course of time the precious metals were gradually replaced by base metal alternatives. Thus, nickel, cupro-nickel, aluminium or even stainless steels have replaced silver; brasses and aluminium bronzes have been used to create yellow-coloured coins instead of gold; and copper has been introduced to provide a third metallic colour.

After the Second World War, Germany attempted to reduce costs still further by making use of coated steel strip for its low-value pfennigs. Other countries followed. However, the use of coated steel strip is wasteful of material and creates large quantities of mixed-metal webbing which is difficult to recycle. Furthermore, the steel core is left exposed at the edges of these coins. Barrel electroplating has provided a means of overcoming these difficulties, bringing about still greater savings in the cost of manufacture. Electroplated coins are now in widespread use across the world, and have achieved universal public acceptance. As the world's leading coin exporter, the Royal Mint in Britain has played a major part in the introduction of this technology.

Importance of the sector

Since the early 1980s the Royal Mint has invested in five major barrel plating lines. One line is dedicated to nickel plating, one to brass and three to copper, so making it possible to produce substitute coins in all three of the metallic colours. The nickel- and brass-plating lines are entirely engaged in export coinage, no British coins yet being made by these techniques. The three large copper-plating plants are occupied in the production of 1p and 2p blanks (made of plated steel since 1992), 1, 2, and 5 cent blanks for the new Euro currency system where this material has been adopted, and a range of other overseas denominations.

The ever increasing demand for coinage across the world has meant that there has been no absolute reduction in the demand for homogeneous coinage made from cast and rolled non-ferrous alloys. However, plated coinage now represents over 50% of the Royal Mint's current production. The annual requirement for steel strip is now in the region of 25,000 t, with a total consumption of nearly 1000 t/year of anode metal. The copper thickness range is 20–30 µm and covers a coin surface area of ~3×10^6 m^2/year.

Future expansion

In principle, all coinage might be made by the electroplating route, although in practice this is very unlikely, if only because not all metals can be deposited from aqueous solutions in barrel plating plants. Coinage made from clad strip offers the possibility of widening the range of possible substrate-coating combinations. Indeed, clad coinage is still demanded for certain specialised applications, notably in the production of the new 1 and 2 Euro coins where a thin nickel layer is sandwiched between thicker layers of either brass or cupro-nickel.

However, it is the low-value denominations that are produced in the greatest numbers, and in this area the electroplated route is now dominant on a global scale. Credit cards, electronic banking and the like are unlikely to impact upon the need for small change. There is also no indication that paper money or non-metallic materials will be used instead for these denominations. Electroplated coinage thus looks destined to enjoy a permanent place in the currency of most countries in the years ahead.

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Surface engineered titanium: material of the 21st century

Titanium is the fourth most abundant metal, comprising about 0.63% of the Earth's crust, and is distributed widely throughout the world and has been detected in meteorites, on the moon and in stars. It was discovered as its oxide in 1791 and named after the giants of Greek mythology, the Titans.[1] Notwithstanding the fact that the pure metal was first extracted in the early part of the last century, titanium alloys have been commercially available only for circa 50 years. Therefore, titanium is the best known member of what are often called the 'new metals'.

The primary driving force of the rapid development of titanium and titanium alloys is their unusual combination of properties in terms of high strength/weight ratio, excellent resistance to corrosion and outstanding bio-compatibility. Titanium alloys have been the material of choice for the aerospace industry for more than three decades. In view of their unique combination of attractive properties, there is an ever-increasing demand for diversifying titanium alloys into such non-aerospace sectors as biomedical, performance sports, automotive, power generation, off-shore, general engineering and architectural in order to promote wealth creation and to increase the quality of life.

As we are stepping in the 21st century, the importance of and need for improved energy efficiency, along with reduced emission and other forms of pollution, will rapidly increase. Titanium will play a crucial role in this area because of its tremendous potential for weight saving in ground transport systems such as automobiles. For example, in the valve train system, component weight reduction may be translated directly into performance (noise, vibration) and fuel economy improvements, along with environmental benefit. Therefore, it has long been a dream for designers to substitute steel with titanium alloys in demanding situations.

Challenges

However, although titanium long ago crossed the barrier between laboratory curiosity and high-value consumer product, two factors, namely the high cost barrier and poor tribological behaviour, have restricted the large scale uptake of titanium alloys, especially under dynamically loaded conditions.

Despite of its abundance in nature, titanium has long been viewed as an exotic metal primarily due to the high raw material price and processing cost, representing about 15 times the cost of steel. Hence, its application is limited to industries and applications that can either afford the high cost or require a level of performance that is unavailable from any other cheaper material. For instance, the family automobile has been viewed as the potential 'holy grail' application area for titanium. However, for titanium to enter the high-volume, cost-conscious automobile industry, Ford, for example, has estimated that titanium mill product must be priced at $6-$9/lb for some engine applications and no more than $4/lb for most other applications.[2] One German car manufacturer has also worked out the threshold price, DM12/kg, for the economical uptake of titanium for mass production cars.

Solutions

Surface engineering

The Wolfson Institute for Surface Engineering in 1983 started to address the technical restrictions on the uptake of titanium. A series of strategic research programme were initiated with industrial support and the financial help of the European Commission.[3] More recently, involvement in a major Link project, AdSurfEngTi, has led to a series of non-aerospace applications in the autosport and off-shore industries, and hence the groundwork for wide-spread application has been established. This has led to UK plc having a competitive edge over other industrial countries, in that titanium designer surfaces with enhanced tribological, corrosion and load bearing capacity have been achieved.[4]

Low cost titanium
As indicated by Bromberger *et al.* in a thoughtful overview,[5] most applications, especially those in commercial markets, are cost sensitive. The size of these markets will be limited to an appreciable extent by how well the industry can reduce its cost further and compete with existing materials.[5] Clearly, the high cost of titanium remains an impediment to more widespread use of titanium-based materials. Consequently, the past two decades have seen great progress in breaking the high cost barrier by reducing the raw material price and minimising machining processes. One of the approaches to tackle the problem has been to develop lower cost alloys with less-restrictive chemistry and low-price alloying elements specific for non-aerospace use, but has achieved limited success.

However, it has been estimated that melting and fabrication represent up to 60% of the total cost in the production of material stock,[2] and that much of the expense comes from the wastage (50-80%) of material during conventional component manufacturing. Clearly, advanced near-net-shape materials processing technologies including precision casting, powder metallurgy (PM) and laser sintering processes would significantly reduce the manufacturing cost of titanium components via eliminating all mill consolidation and fabrication, reducing scrap, minimising machining and providing a basis for high-speed and efficient production. Furthermore, the emergence of hot isostatic pressing (hipping) technology has been shown to significantly raise the mechanical properties, especially the fatigue strength of cast or PM titanium parts.[6]

Therefore, how to produce low-cost titanium powders will be the key to the production of cost-effective titanium components and has the potential of revolutionising the titanium industry. Recently, a novel electrolytic reduction technology to produce titanium powder via direct reduction of TiO_2 has been developed by DERA, UK, which is a great breakthrough in producing low-cost titanium powder. It has been reported that the achievable price will be about £2–3/kg for alloy powder, which is well below the threshold material coats for the use of titanium in automobiles.[7] It is thus believed that, with the ever increasing maturity of advanced near-net-shape materials processing technologies, coupled with the emergence of low-cost titanium powder production techniques, there is enormous scope for reducing the cost of titanium parts, possibly, for non-aerospace grade titanium, to half the current price or less.[8]

In short, it is the advances in surface engineering technologies for titanium and its alloys, coupled with the emergence of low-cost titanium powder production methods and adoption of PM and hipping approaches,[6] that has the potential to introduce cost-effective titanium component technology into the titanium industry. Surface engineered titanium will be the material of the new century.

UK position
The UK holds a unique position in the development of cost-effective titanium component technology and the University of Birmingham looks forward to being involved in the planning of a long-term implementation strategy for the large scale uptake of titanium engineering components.

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Surface engineering and corrosion management in terotechnology (asset management)

Market drivers

Environment

With global climate-warming in the foreground, measures to reduce carbon dioxide emissions to 20% of current levels are required. (In the longer-term carbon dioxide emissions will be eliminated by, *inter alia*, replacing hydrocarbon fuels with hydrogen.) Chlorofluorocarbon gases are a root cause of the ozone-depletion problem; therefore their replacement is necessary to meet the demands of the climate-warming problem without impairing the ozone layer. Techniques to control the oxidation products of nitrogen and sulphur as well as particulates from automobiles (and power generators) will facilitate regulatory exhaust emission targets applied to all vehicles.

It is apparent that current patterns of industrial production and consumption are far from sustainable. As a result of market imperfections, prices are not an adequate reflection of the true costs of consumption and production decisions, and 'sub-optimal' decisions are made in response to imperfect price signals.

Manufacturing and processing

Important emerging markets will come through exploiting: room-temperature superconductors and stacked solar cells with at least 50% efficiency. Other noteworthy research areas will include nitrogen dioxide fixation technology required for protection of the global environment, drugs needed in cancer treatment and control of structure at the atomic and molecular level. Examples of manufacturing-related technologies addressing environmental issues will include methods to render waste products harmless.

Mining and marine resources

Examples can be found in prospecting for minerals and technology for developing water resources and improving water quality. Methods for economical discrimination and separation of valuable materials recovered from urban refuse will be developed. Water purification technology for rivers and lakes is essential. In addition, technology for treatment of sewage and waste water will be perfected for the removal of common biological oxygen-demanding and other pollutants.

Power generation

This includes primary and secondary energy production and focuses on utilisation. Technology for treatment of highly radioactive waste solids will be realised. Improved equipment RAM (reliability, availability and maintainability) and capability are required. For instance, for gas turbines – 'Develop advanced materials and processes to enable the demonstration of gas turbine engines with higher operating temperature and rotational speeds necessary to provide twice the thrust-to-weight or half the specific fuel consumption (*cf.* current systems) while reducing cost on a per-pound-of-thrust or per-shaft-horsepower basis' (Defense Technology Area Plan, January 1997, DTO MP.02.01).

Transportation
The goal of making traffic services more efficient and less impacting on the environment. For instance using new high speed train technology capable of continuous operation at >300km/h, new materials are to be employed in cars and rails, and noise and vibration near rail lines are to be greatly reduced.

Navigational precision and safety using a system of four-dimensional – time and position – control of aircraft will be developed. At the same time, a worldwide air traffic control system using satellites will be realised.

Large cargo lorries are to emit oxidation products of nitrogen and sulphur as well as particulates at the same levels as current petrol-powered vehicles.

Cities and infrastructure
Related to technology for construction, enhanced productivity of basic facilities and maintenance of safety.

With the aging of atomic power plants, technology for the safe and rational dismantling and abandonment of reactors needs to be established.

Recycling technology to cut urban waste by half will be targeted, and the purification of marine waters by construction of various types of purification and water exchange facilities will be accomplished in closed waters near major cities. Recycling of energy, wastes and other materials will be carried out in neighbourhood units. The recycling of industrial products, such as dry cells, will be legally specified as the responsibility of the manufacturer and almost all materials used will be recyclable.
Materials science/engineering response

Materials developments should achieve a good balance of *market-pull* and *science-push*. However some recent evidence points to existing materials science being unable to respond to *market-pull* due to market requirements being ever more sophisticated. Assessments suggest that materials science in its present form is approaching maturity – in order to re-balance the *market-pull* and the *science-push*, new concepts enabling more rapid progress in materials science are needed. Computational materials science is one such approach – in order to design new materials it may be necessary to understand the microstructure and properties on the atomic/molecular level or even on the quantum mechanics level. Computational materials science could help advance this understanding especially when it is experimentally impracticable. The concept of the *virtual laboratory* may further computational materials science and contribute to the development of advanced materials such as composites (CMCs, MMCs, IMCs, PMCs), superalloys, intermetallic alloys and superconductors.

Corrosion management response
Corrosion protection facilities will need to comply with environmental regulations, prevent pollution from coating facilities and operations, restore soil and groundwater contaminated by past practices, protect air quality, conserve wetlands and reduce costs of clean-up and disposal. Surmounting theses issues will permit engineers to control corrosion while complying with all local regulations and minimise environmental impact – environmental quality partnerships will be required.

Environmentally benign materials will be developed such as new corrosion-resistant materials and coatings. Processes such as corrosion control, fatigue analysis, non-destructive evaluation and condition-based maintenance will significantly extend the lifes of plant and address regulatory goals.

The reliability of materials and effective use of structural materials under severe operational conditions in aggressive environments requires reliable databases accurately evaluating their properties. Integrated life prediction systems need to be developed by combining factual databases with knowledge-bases of materials properties such as creep, fatigue, environmental strength, fracture process and environmental degradation measurements of corrosion rates. Quantitative test methods and predictive models for environment-assisted cracking of materials will need to be further developed. Measurement and prediction of localised corrosion in aqueous environments including the development of novel detection and monitoring methods are highly desirable.

Weight-saving technologies

To decrease weight, one approach might be to reduce the thickness of existing materials. This requires improvements in for instance quality, strength and corrosion resistance. For aircraft, to which aluminium alloys have been primarily employed from its early development, materials with excellent strength, stress corrosion cracking resistance and fracture mechanical properties have been developed successively as a design philosophy pursuing weight reduction. Railway vehicles and ships, which are good candidates for potential weight reduction using aluminium, although corrosion resistance is highly important for the latter, both also require the development of high-strength aluminium alloys for welded structures and large thin-wall extrusions together with effective design and assembly methods. Likewise, improvement in corrosion resistance is essential for the effective use of magnesium, whose specific gravity is about two-thirds that of aluminium, in general applications such as automobile parts. Since titanium, which provides excellent strength, heat and corrosion resistance, is expensive, cost effectiveness is being pursued, and the development of processing techniques involving material manufacturing is required to reduce costs as well as to improve performance.

Other topics

Other relevant topics are summarised in the table below.

Surface engineering response

Increasingly surfaces of bulk materials are being selectively engineered to obtain specific improvements in performance to match service requirements. Processes such as physical vapour deposition and chemical vapour deposition are being utilised to deposit ceramic coatings to improve corrosion and wear resistance of metal components. Metallic materials coated with ceramics are, however, vulnerable to spallation on temperature cycling because of the large expansion co-efficient mismatch. The adhesion and mechanical integrity of a coating depend on fracture strain, fracture toughness and modulus. However, there are few techniques to measure these properties for coatings.

Other responses to market drivers

- Environmental legislation is likely to be a major driving force for changes in SE.
- Environmental legislation to finally eliminate hexavalent chromium will necessitate the replacement of conventional electroplating by thermal spraying or PVD coatings for the production of hard chromium.
- Wider acceptance of environmentally friendly paints, including more acceptable solvent-based materials, will be the next important development in paint technology.
- Shortage and supply of trained personnel will constrain the uptake of novel SE processes.
- The biocompatibility and lifetime of prosthetic devices will be significantly improved by the deposition of tailored surface coatings.
- The steady transition from the use of HSS to carbide tools in automated CNC machine tools will be controlled by the development and cost of sophisticated coatings.
- The application of dry lubricants such as MoS_2 will provide significant reductions in wear and frictional forces to improve the dry cutting performance and wear resistance in engineering processes and components.
- Major advances in catalysts for process engineering will continue to emerge due to the ability of surface engineers to control the structure and properties of catalytic materials.

Novel surface treatments of structural glass will allow optimised environmental control within buildings and better utilisation of solar energy.

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Summary of corrosion management topics relating to terotechnology

Fixed & Portable Assets In ⇒ / Area ⇓	Aerospace	Automotive	Tooling	Power generation	Architecture	Transportation	Construction	Packaging	Health	Miscellaneous
High Temperature/'Dry'										
Clean coal technologies				✓						
Biomass technologies				✓						
Nuclear waste storage				✓						
Refuse/sludge incineration				✓						✓
Combined heat & power				✓						
High temperature semiconductors – engine managers	✓	✓		✓						
Ambient/'Wet'										
Non-toxic anti-fouling paints						✓			✓	
Bio-sciences – materials for systemic (smart) drug delivery (controlled corrosion!!), biocompatible coatings/materials, longevity of implants									✓	
Nanotechnology – materials for systemic (smart) drug delivery									✓	
Desalination							✓		✓	✓
Testing and protection of new coins										✓
Storage and pipeline monitoring							✓			✓
Document/artefact protection and preservation								✓		✓
Cross-Cutting Issues										
Knowledge-based systems – expert systems, data mining and smart/adaptive coatings/structures/ materials – coatings as sensors/actuators	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Modelling accelerated ageing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Life-time modelling	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Outreach, training and education	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓