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APPLICATION OF NANOTECHNOLOGY FOR INDUSTRY

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Abstract

Nanotechnology can best be considered as a 'catch-all' description of activities at an almost vanishingly small scale that have applications in the real world. A nanometre is a billionth of a metre, that is, about 1/80,000 of the diameter of a human hair, or 10 times the diameter of a hydrogen atom. An early promoter of the industrial applications of nanotechnology in the UK, Professor Albert Franks, defined it as 'that area of science and technology where dimensions and tolerances in the range of 0.1nm to 100 nm play a critical role'. This definition neatly allows for both the 'bottom up' and 'top down' approaches to nanotechnology. It encompasses precision engineering as well as electronics, electromechanical systems (such as the development of 'lab-on-a-chip' devices) and mainstream biomedical research and development in areas as diverse as gene therapy, drug delivery and novel drug discovery techniques. 'Top-down' refers to the fabrication of nanoscale structures by machining and etching techniques, whereas 'bottom-up', often referred to as molecular nanotechnology, applies to the creation of organic and inorganic structures, atom- by-atom, or molecule-by-molecule. 'Top-down' or 'bottom-up' can be a measure of the level of advancement of nanotechnology, and nanotechnology, as applied today, is still in the main at the 'top-down' stage.

The role of nanotechnology as a major driver of technological change and its consequent importance in the shaping of world economies in the next millennium is undisputed, as evidenced by the commitment to nanoscale research by the US and Japan. It is crucial that the UK also identifies those technologies that may offer the most economic benefits. A recent survey (Nexus, 1998) has demonstrated that the market for microengineered products is greatest in electronics and biomedicine. These conclusions can in very general terms be extrapolated to nanotechnology. The UK is not an owner of electronics or semiconductor technology in the main, but tremendous opportunities exist in integrating these technologies into systems or components in high added value niche market products for biomedical and relatedapplications. These applications include medical and environmental sensors, diagnostic and analytical devices, and range of equipment for minimally invasive surgery. There may be also being some potential for low cost, high volume applications in these areas.

Keywords: Nanotechnology,Nano composites, Manufacturing Industries

1. Introduction

Nanotechnology has not quite reached the full extent of the vision of Dr Wu, though we are already experiencing its effects, particularly in applications resulting from nanoelectronics and semiconductor technologies. The present trend towards miniaturisation - the competitive quest for ever smaller machines and components that use fewer resources (e.g. energy, materials) - while offering the potential for thecheap mass-production of increasingly complex goods is rapidly pushing industry into the nanometre realms. The coming era of nanotechnology is being made possible by the remarkable convergence of many technological advances in this decade that include • hugely powerful computers that allow the design of new materials and the simulation of their properties • a new generation of microscopes that can provide images at the nanometre scale, as well as measure and manipulate atoms and molecules the advent of virtual reality that enables us to visit and experience the wonders of this new and hitherto unimaginable nanoworld As the work of scientists tends increasingly towards the size domains of molecules and atoms, the very nature of matter is increasingly close to being controlled and manipulated. The possibilities this opens up are endless: from the production of new, lighter and stronger materials which have applications in areas as diverse as space travel to bone implants, to the creation of therapeutic drugs with individual- specific properties. The aim of this publication is to highlight the potential applications of nanotechnology to industry, and discuss how the challenges of this new industrial revolution can be successfully met.

2. Manufacturing Infrastructure Requirements

A wide range of production capabilities, training and facilities are required as part of the creation of an infrastructure that will nurture nanotechnology and provide the basis for industrial development. For example, mathematics, computer modelling and simulation skills will be essential as well as an understanding of tools and standards. Frontier research requires advanced instrumentation to be available across the board; from the level of individual laboratories to national facilities. There is also a need for research on state-of-the-art instruments and their deployment Key issues are:

1. The production of, or access to specialist materials
2. The adoption of advanced manufacturing processes
3. Access to specialist tools needed for manufacturing, test, assembly and inspection
4. The installation of ultra-clean manufacturing facilities
5. The provision of adequate training facilities for the development of skilled manpower.

It is worth noting that business opportunities will exist at all stages of development of the new technology, including the provision of the basic requirements. Materials for the Nanoindustrial Revolution Materials science and technology are fundamental to the majority of the applications of nanotechnology. 'Raw' materials such as semiconductors, oxides and specialist organic and inorganic chemicals, will need to meet new specifications and parameters. For example. Nanoparticles: Controlled production of particles in the 1 - 100 nm size range is crucial, and handling of these fine particles will be a key issue. Quantum structures: Material purity is of the highest importance here, and research into production methodology is required. Multilayer thin films: These require clean deposition equipment and environment (impurities and defects will ruin the properties of the films) with fast turn-around and high throughput.. Also, very high purity materials will be needed for sputtering and evaporation sources. Nanomechanical devices: The physical integrity of the material used to produce the devices will be of key importance, given the strains and stresses to which it will be subject. Nanoprobe materials: These are the materials required for the manufacture of tips for scanning probe microscopes, the basic tools of nanotechnology. These need to be chemically inert, physically stable materials capable of being fashioned reproducibly into atomic sharp tips. Biosensors and transducers: The capability of synthesizing ultra high purity specialist organic chemicals having a range of terminating groups for these applications is required, as well as ways of bonding these molecules reproducibly to the surfaces of semiconductors and oxide materials Advanced Manufacturing Processes:

Manufacturing processes at the nanoscale can involve accretion or removal of material, or changes to the shape or form of material already present. Each of these processes provides new challenges and opportunities, as follows Accretion of powders: New generations of processing equipment will be needed to deal with nanopowders in the manufacture of nanocrystalline materials. Quantum structures and devices: The problem of producing devices with critical dimensions below 100nm, using 'top-down' techniques, is one that the electronics industry is currently wrestling with. Currently, commercial lithography is based on optical methods, but the wavelengths of visible and near ultraviolet light are too long to be usable on the nanometre scale. A range of alternatives is available, but parallel rather than serial writing techniques are needed for scale-up to commercial manufacturing levels, though this may not be a realistic goal for European companies. Deposition: Recent breakthroughs in the UK are making deposition on selected areas possible, in high transmission mode. Until now, this has been achieved only through focused ion beam sources operated in droplet mode - an approach which is restrictive in terms of the range of materials that can be handled. Cutting, milling: Only focused ion beam (FIB) techniques provide a means for selective cutting or removal of material with sub-100nm accuracy. Although these techniques were largely pioneered in Europe - and the UK in particular - the present suppliers of such equipment are almost exclusively American or Japanese companies.

Machine Tools and Instrumentation for Manufacture, Assembly, Test and Inspection

As structures become ever smaller, the necessity for on-line quality assurance test systems for certification duties, becomes more important and demanding. In the future, the nanometre scale will be the precision standard for material analysis, control purposes and also for material treatment. Already nano-analytical methods are used routinely for testing in the manufacture of:

- Magnetic storage disks
- Electronic multilayer systems
- Industrial polishing processes

New magnetoresistive multilayer systems offer drastically better positioning and controlling properties of sensors for application in the automotive industry and as measuring systems for velocity, strain or work piece positioning Key areas of instrumentation and characterization include

1. Scanning probe techniques: observation + operation
2. Some aspects of electron microscopy
3. Some aspects of surface analysis
4. Field emission + field ion microscopy + atomic probe analysis
5. Nanomanipulators • using principles of mechanical / optical / electric / magnetic / piezo techniques
6. Test, calibration and measurement: Standards, benchmarks, procedures
7. Nanotools, nanomotors, nanomachines
8. Nanoprobes: production, characterisation, multiprobes
9. Equipment to characterise magnetic / optical / electrical / mechanical properties of nanostructures with high spatial resolution
10. Microfluidics
11. Focussed ion beam technology
12. Computer software for data analysis and representation, simulation, modelling

An essential stage in the development of a large scale nanotechnology industry is the creation of machine tools for the production of nanodevices, and test, measurement and inspection techniques to aid manufacturers and provide quality control of nano products. It is also an area where knowledge has been, and continues to be transferred from research institutions to industry. It is the first nano area to become economically active, including the creation on numerous small and medium-sized companies. Machine tools for nanotechnology are already being developed in Japan, the USA and (to a limited extent) in the UK. Not only is it already an economically viable aspect of nanotechnology, but its strategic significance is very high. These machines will have to underpin all future production of nanodevices, and it is very important that the UK should play a key role in their development. Ultra-clean manufacturing facilities Some aspects of nanoscale manufacturing may require clean room technology - either full scale facilities or 'table top' scale; but this will depend on the particular process or industry. Refer to S2C2 - the Scottish Society for Contamination Control - as the repository of all knowledge on the subject in an international context.

3. Coatings

Coating technology is now being strongly influenced by nanotechnology. Nano-scale materials, characterised by grain sizes of less than 100nm are being investigated, and significant advances are being made in the synthesis of high quality nanocrystalline powders, and several methods such as vapour condensation and solution precipitation have been scaled up for industrial use. Metallic stainless steel coatings sprayed using nano-crystalline powders have been shown to possess increased hardness when compared with conventional coatings, although the porosity is increased. Also, the reaction kinetics involving small scale particles during spraying are notably different. Novel tungsten carbide - cobalt coatings produced from nanostructured powders have also shown promising results in terms of bond strength, but to date little work has been conducted to assess their durability. Nano-composite coatings comprising a ceramic/polymer mix have also been applied by High Velocity Oxy-Fuel (HVOF) spraying. These nanoparticle reinforced polymer composites have advantages in applications where the polymer strength is less important than the ductility of the coating. The HVOF process has also been shown to cause little polymer degradation. More studies are still required in this new area to improve the understanding of the interfacial properties at the polymer/ceramic junction, and how this affects the coating properties. In addition to being able to apply coatings made from nano-phase powders, techniques themselves are being developed in which the processing parameters involved in the spraying actually produce the nano-crystalline structure. This has been experimentally achieved using a hypersonic plasma particle deposition (HPPD)process to apply SiC coatings. Coatings were successfully applied and the properties showed great promise.

4. New materials

It is also possible to make new types of nanocomposites or organic/inorganic hybrid structures by depositing or attaching organic molecules to ultra-small particles orultra-thin man made layered structures (superlattices). There are many applications for these new materials in different products and processes, some of which are described below:

Application	Improvements using new attached molecules
Colloids	New structural, optical and thermodynamic properties.
Pigments	Better thermal stability without loss of absorption characteristics.
Dispersions	Nanoparticle size, and molecular structures can be tailored
Emulsions.	Engineering of viscosity and particle size
Anti-corrosion Coatings	Improved surface mechanical properties and stability in air.
Ferro fluids	Creation of 'fluid magnets', which can be externally manipulated using a magnetic field. As a consequence, the magnetic fluid can also be made to exhibit different rheological properties and structure.
Magnetic particles	Below a critical size, magnetic particles are superparamagnetic and the collective magnetic response is fluid. Superparamagnets adjust to weak external magnetic forces.
Ceramicprocessing technology	'Customized' ceramics for one-off applications; particularly using stabilized zirconia
Nano- emulsion .	Nanoparticle size and composition selected to produce required viscosity and absorption characteristics
Lubricants	Tailored viscosity and thermal expansion properties
Drug delivery systems:	Nanoparticles can determine the chemical reactivity rate, the location and the timing of drug delivery.
Bio-receptors fo energy transfer	Nanocomposites can be designed to exhibit well defined singlet or triplet excitonic absorption spectra. These localised bundles of light energy can be transferred over long distances to a 'receptor' and used for example for photochemistry or charge generation (the photoelectric cell).
Cosmetics .	The addition of nanoparticles can influence the flow characteristics and mechanical properties of cosmetics, as well as the absorption of harmful radiation
UV protection gels.	Sol-gel technology
Same as above.	In the design of different types of materials

The addition of nanoparticles can influence the flow characteristics and mechanical properties of cosmetics, as well as the absorption of harmful radiation.

5. Nanometrology

Fundamental to commercial nanotechnology is repeatability, and fundamental to repeatability is measurement. Many of the processes and production procedures envisaged in nanotechnology take place at the atomic level. In order to achieve adequate control of the movement of systems that might be used in such processes, for example for atomic manipulation, dimensions need to be known at the atomic level and beyond. Moreover, a knowledge of the perfection of the texture at the nanometre and sub- nanometre level is an essential requirement if highly specialised applications of nanotechnology are to operate correctly, for example x-ray optical components and mirrors used in laser gyroscopes. Thus dimensional metrology plays a key role in the success and efficient implementation of many developments in nanotechnology. Ultimately all the measurements of length must be referred back to the national standards of length which are held at the National Physical Laboratory in Teddington. How can the accuracy of position, size and displacement be achieved at the atomic level? There are basically two methods: First, by using a laser interferometer as an ultra-sensitive displacement transducer and sub-dividing the fringes to an extremely fine level. In this way displacements of the order of fractions of a nanometre can be measured which can be traced to the national standard of length. However, one problem with laser interferometer-based systems is that the components of the interferometer are not completely perfect and do introduce small uncertainties in the way the optical fringes are sub-divided. Nevertheless, such interferometers can be used for measuring over an extremely wide range (from nanometres to several metres) and are therefore extremely valuable measuring tools.

The problem in the uncertainties of sub-division of optical fringes can be overcome by using an interferometer using x-rays. Using the diffractive properties of x-rays in the silicon crystal an interferometer can be constructed that has a fringe spacing of about 0.3 nm. Because much work has been undertaken to determine the lattice spacing in silicon with exceptional accuracy, this method provides a very powerful method for measuring ultra-small displacements. But such interferometers can only perform measurements very slowly. At NPL the two types of interferometer are combined to take advantage of the extreme resolution of the x-ray system which is coupled to the range of an optical interferometer. For measurements up to 10 micrometres the measurement uncertainty of the instrument is less than 40 picometres

In order to meet the requirements of visualising surfaces at the atomic level a wide range of probes (scanning tunnelling microscopes and atomic force microscopes being the best known examples) are capable of revealing the positions of atoms. Whilst, such probes can generate very impressive pictures of atoms on a surface, however, it is only relatively recently that such probing systems have been able to be used for measurement. By fitting laser interferometers to the microscope the tip of the microscope can be tracked accurately in space. NPL has a system which can measure components, mostly surface texture reference standards, to an accuracy in the order of nanometres.

6. Nanoelectronics

Since the transistor was invented some 50 years ago, the trend in electronics has been to create smaller and smaller products using fewer chips of greater complexity and smaller 'feature' sizes. The development of integrated circuits and storage devices have continued to progress at an exponential rate; at present it takes two or three years for each successive halving of component size. However, the technologies used for data processing and storage have fundamental limits below which the devices no longer function in a predictable manner. For instance, oxide layers used in Complementary Metal Oxide Semiconductors (CMOS) devices are becoming so thin that leakage currents are conducted quantum mechanically by electron tunneling. According to recent estimates, microelectronics and magnetic storage technologies only have another 10 to 12 more years to go before reaching their ultimate limits. Using present microelectronic technology, it is predicted that by the year 2005 a chip will contain 190 million transistors and have feature sizes of 100nm with a clock speed of up to 3.5 GHz.

The lithographically defined dimensions of commercial semiconductor devices are already close to the 100 nm range, with minimum layer thicknesses in the 10nmrange, and a replacement technology to advance miniaturisation even further down, eventually to the dimensions of single atoms and molecules, is keenly sought. We have now reached a stage where totally new approaches to nanoelectronics are in evidence, such as DNA computing (proposed in 1994 and now becoming a reality), and quantum computing where a universal computer could operate using quantum mechanical effects. Both of these novel concepts also rely on being able to control of the properties of individual atoms or molecules.

In the US between 1988 and 1994, $45 billion alone was spent by the semiconductor industry on microelectronics research. Nanoelectronics, based on quantum effects, is foreseen as the successor to microelectronics, and is already involving even larger sums. It is expected that the first applications will probably be in the military sector, with the transition from microelectronics to nanoelectronics ultimately being determined purely by economic factors. A major barrier to the introduction of nanoelectronics, is that there are no established mass production techniques for creating devices on a commercial basis. Whereas the transistor is a basic building block for microelectronic devices, it is not clear what the basic (three-terminal) element of a nanoelectronic device will be. Likewise, a well-defined architecture required to process data has yet to be established.

The evolution of electronics is interesting in that it has been characterized by a series of fundamental paradigm changes 'disruptive technologies'. For instance, the mechanical relay was replaced by the vacuum tube, which in turn was replaced by the transistor. The large mainframes of the past that used power greedy bipolar devices have been now been replaced by the CMOS devices used in home PC's. Nanoelectronicsare currently not only looking for the successor to CMOS processing but to a replacement for the transistor device itself. The two possible routes to the future fabrication of nanoelectronic devices loosely termed 'top down' or 'bottom up' techniques referred to earlier. The 'top down' approach is basically an extension of the established method of engineering and microelectronics processing, using controlled damage by photons, ions and even grinding techniques. This process is often described in terms of the deposition, patterning and etching of layers of material, with typically a planarization step using chemical-mechanical polishing to create layers of wiring. There is a whole range of potential obstacles for this approach because, as the technologies are pushed to smaller sizes, the cost shoots up, the tolerances are more difficult to maintain. To be saleable to the atomic and molecular scale, softer methods with atomic tolerances will be eventually be essential.

7. Materials

The world market for materials is estimated at $10 billion p.a. and growing. Since the 1920's scientists have known that the properties of materials such as strength and the ability to conduct electricity were governed by the structure of their atoms and molecules. This insight led to the identification of semiconducting materials that laid the foundations of today's electronics industry. More recently, with the advent of the tools of nanotechnology, materials science has been transformed to a point that the relationship between the structure of a material and its properties may be controlled. Scientists and engineers are becoming increasingly able to understand, intervene and rearrange the atomic and molecular structure of matter, and control its form in order to achieve specific aims. Materials are closer to being designed to fit the needs of a specific end use, and simulate the properties of specific materials even before they are made. This ability is not the result of a continuous evolution of knowledge, but a step-change resulting from increased computer power (itself a result of progress in materials science) and advanced instrumentation, which allows complex mathematical modelling of materials from the micro-structural to the quantum mechanics level. This modelling relates the properties of a material to its internal structure, and even its behaviour when processed. The properties and performance of a material can now be tailor-made, and even information on the behaviour of a material that has been modified by advanced surface treatment, coating, joining and adhesive technologies can be designed into the manufacturing process itself. Computer modelling and simulation at the atomic level is already being used to improve the performance of currently available materials. As discussed in Chapter 9, industry will eventually be able to design entirely new materials, and build them atom-by-atom and molecule by molecule. The arrival of such nanophase materials at the commercial scale will be accompanied by new processing and fabrication technologies. From this, nano net shape devices such as sensors, robots, electronics systems, computers, engines and surgical devices can be produced with applications in medicine, pharmacology, agriculture, mining, genetic engineering, energy and the environment. These developments will also dramatically cut the R&D and fabrication cycle times.

The consequences of these revolutionary developments in science and engineering need to be addressed from a long-term perspective both by firms and nationally. There are cumulative gains to be had from the capability to design, produce and use new materials in advanced nanotechnology-based products. Time is short - it may soon be impossible for new companies not already involved to enter into the field of advanced materials.

8. Applications

As described previously, materials often behave very differently when nanostructured. Finer grain sizes can produce denser materials with greatly improved mechanical properties. The aerospace and defence industries will also benefit from new lightweight, high strength nano-composite materials, as will biomedicine, for example in stronger hip prostheses with extended life expectancy. The smaller the particle, the larger active surfaces per unit mass and greater chemical activity, for example, greater solubility in water. Nanoparticle technology will provide more durable and uniform surfaces on porcelain, and better inks forinkjet printing. The recently identified buckminsterfullerene, in the form of carbon C60 'buckyballs' has many potential applications, such as a very effective nanoparticle dry lubricant for engineering applications. The nanotube version can be used as a mould for making nanowires in metals such as gold for electronic connectors, and may even act as a conductor itself. Nanotubes can also be fabricated to form molecular sieves for faster and more selective filtration. (See below). Unprecedented opportunities are arising for re-engineering existing products and engineering new ones at the nanometre scale for a wide range of commercial applications. For example, clusters of atoms (quantum dots, nanodots, inorganic macromolecules), grains less than 100 nanometers in size (nanocrystalline, nanophase, nanostructured materials), fibres less than 100 nanometers in diameter (nanorods, nanotubes, nanofibrils, quantum wires), films less than 100 nanometers in thickness, and composites that are a combination of any or all of these. The more important materials with nanoscale applications include carbides, nitrides, oxides, borides, selenides, tellurides, sulphides, halides, alloys, intermetallics, metals, organic polymers, and composites.

9. Conclussion

Nanotechnology both offers almost limitless potential to industry particularly in the creation of new high added value niche products or in the export of know-how. There will be many social benefits also, such as the reduction of environmental pollution, better healthcare, improvement of quality of life for the aged, better transport and easier production of renewable energy. Developments in nanotechnology need to go hand-in-hand with ethical considerations. Dangers exist that must be carefully assessed, for example in the area of genetic manipulation, whether in the quest for better crops, or to reduce congenital defects or in the production of transgenic animals for food or medicine or even in the screening of unwanted characteristics in human offspring. The speed of advancement of scientific knowledge is related to the ultimate rate determining factors. In the first instance the rate controlling factors for nanotechnology are likely to be: • Identifying desirable applications that win commercial and public acceptance • Creating process routes to the products that meet the needs of these applications

Nano-grained WC/Co composites have the potential to become the new materials for tools and dies, and wear parts. Benefits of nano-grained WC/Co approach include shorter sintering time, high purity, and precise control of composition. These materials have superior properties and more homogeneous microstructure than those of conventional WC/Co composites do. Nano-grained WC/Co also allow optimization of specific properties without comprising others. Higher toughness and ductility can be achieved without reducing hardness and wear resistance. However, there are technical challenges to be overcome before such materials reach a commercial scale. The most important task is consolidation of nano WC/Co powders with limited grain growth utilizing a minimum amount of grain growth inhibitors. The costs of producing nano WC/Co powders will have to be demonstrated to be cost-effective.

Reference

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