Electrospun Nanofibres and Their Applications

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1 Introduction

1.1 What is Nanotechnology?

The importance of *nanotechnology* as an emerging technology has been recognised in the USA, where a National Nanotechnology Initiative (see *http://www.nano.gov*) was launched, with an investment of over $1 billion in nanotechnology research over the past few years. Nanotechnology has attracted much attention recently, and it can be applied to all aspects of science and engineering, as well as to life. But what is *nanotechnology*? There are many definitions of the term, but here we adopt El-Naschie's definition [1].

The naive and direct answer to the frequently posed question what exactly is Nanotechnology is to say that it is a technology concerning processes which are relevant to physics, chemistry and biology taking place at a length scale of one divided by 100 million of a metre.

Thus, 1 nanometre = 1 nm = 10^{-9} metre = 10^{-9} m.

> ### *Etymology*
>
> The Greek word *nanos* or *nannos* means 'little old man' or 'dwarf', from *nannas*, meaning 'uncle'. The metric prefix nano- means one billionth of a unit or 10^{-9}. A single human hair is around 80,000 nanometres in width.

An obvious phenomenon is the remarkably large surface-to-volume ratio of nanomaterials. Consider a fibre with radius of 1 mm and length of 10 mm. Its surface area is:

$$S = 2\pi rL = 2\pi \times 10^{-3} \times 10^{-2} = 2\pi \times 10^{-5}\,\mathrm{m}^2$$

Now we divide the fibre into nanofibres with radius of 10 nm. The number of nanofibres can be calculated as:

$$n = r^2 / r_0^2 = 10^{-6} / 10^{-16} = 10^{10}$$

So the total surface of the nanofibres is:

$$S_0 = 2\pi n r_0 L = 2\pi \times 10^{10} \times 10^{-8} \times 10^{-2} = 2\pi\,\mathrm{m}^2$$

The volume remains unchanged, while the surface area increases remarkably by the factor:

$$S_0 / S = 10^5$$

Maybe a little bit more enlightening although equally naive is to say, according to El Naschie [1], that nanotechnology is the art of producing little devices, machines and systems that have novel properties. These include extremely small electronic devices and circuits built from individual atoms and molecules, DNA computers, microelectromechanical systems, motors, nanosensors, nanowires, nano-satellite missions, and others, somewhat at atomic, molecular, or macromolecular scales. **Figure 1.1** gives an example of the possibilities.

Atoms are roughly angstroms (Å) in size: a hydrogen atom is about 1 Å in diameter, a carbon atom is about 2 Å in diameter, and the diameter of an oxygen atom is about 1.75 Å. One angstrom (1 Å) is one ten-billionth of a metre or one-tenth of a nanometre. Thus 1 nm = 10 Å.

On the molecular or angstrom scale, quantum-like phenomena occur. In a scientific sense, El Naschie [1] defined nanotechnology as a

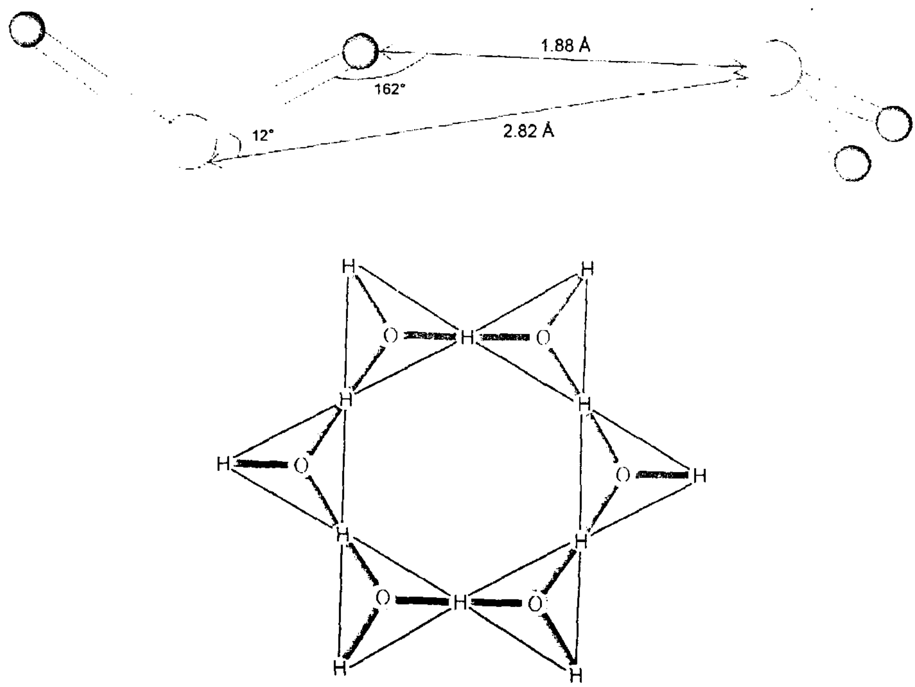

Figure 1.1 Aqua technology on the angstrom scale, shaping the world atom by atom.

technology applied in the grey area between classical mechanics and quantum mechanics. Classical mechanics is the mechanics governing the motion of all the objects we can see with our naked eye. This is mechanics that obeys deterministic laws (Newton's laws) and that we can control to a very great extent. By contrast, quantum mechanics, which is the mechanics controlling the motion of things like the electron, proton, neutron and the like, is completely probabilistic. We know nothing about the motion of the electron except that there is a probability that the electron may be here or there. Even crazier than this, if we know the exact location of an electron, it is impossible to know its speed; and if we know the exact speed of the electron, it is impossible to know its exact location. Such a relationship is called the Heisenberg uncertainty principle.

Nanotechnology links to both deterministic classical mechanics and chaotic quantum mechanics [1]. There should be a law controlling the change from a classical object like a stone to a quantum object like an electron. Somewhere between these two scales these changes happen, but this does not happen suddenly. There is a grey area between these two scales, which is neither classical nor quantum [1].

To model quantum processes, we can use the deterministic chaotic geometry, which is used in El Naschie's E-infinity theory [2-4]. Consider an extremely simple quadratic equation in iterated form [5]:

$$x_{i+1} = \lambda x_i (1 - x_i)$$

where λ is a parameter. The incredible complexity displayed by the bifurcation diagram of this equation as λ varies was one of the most amazing discoveries in this field (see **Figure 1.2**).

The main application of E-infinity theory shows miraculous scientific exactness, especially in determining theoretically the coupling constants and the mass spectrum of the standard model of elementary

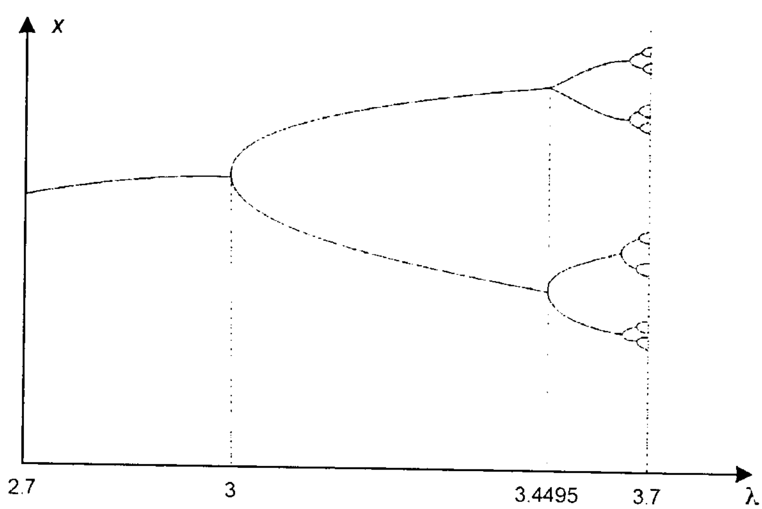

Figure 1.2 From deterministic path to chaotic path.

particles. For example, the absolute zero temperature can be derived using E-infinity theory [1–5] as:

$$T_0 = (4)(10)(1/\phi)^4 - 1 \text{ K}$$

or the mass of an expectation proton [1–5] is:

$$m_p = (20)(1/\phi)^8 \text{ MeV}$$

where $\phi = (\sqrt{5} - 1)/2$ is the golden mean.

On the nanoscale, some new properties occur, and in many instances the origins of the new properties are, at present, not fully understood. Scale is of utter importance in physics as well as nanotechnology. Different scales lead to different laws (or theories) and thus result in different dimensions, as illustrated in the following formula:

$$\text{dimensions} = 3 + 1 + \phi^3 = 4.236\ldots$$

3 dimensions	Newton: three-dimensional absolute space
3 + 1 dimensions	Einstein: four-dimensional continuous space–time
4.236 dimensions	El-Naschie: infinite-dimensional discontinuous space–time.

In view of El-Naschie's E-infinity theory, nanoscale systems may possess entirely new physical and chemical characteristics that result in properties that are well described neither by those of a single molecule of the substance nor by those of the bulk material. A similar phenomenon is observed on the quantum scale (see **Figure 1.3**). On such a scale, Einstein's space–time resembles a stormy ocean and his original Riemannian smooth manifold is only an approximation [6]. This is the very reason for Einstein's failure to unify gravity with electromagnetism.

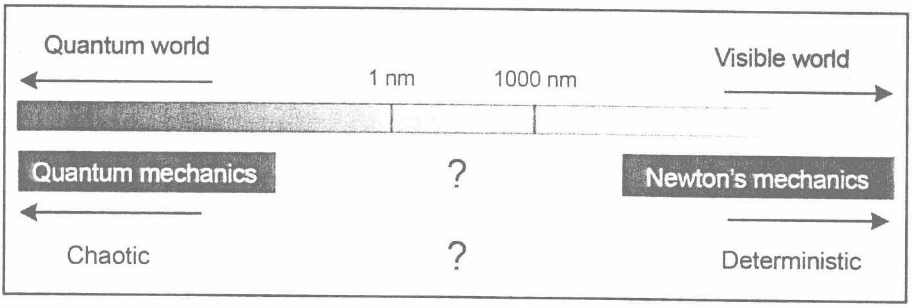

Figure 1.3 Nanomechanics – is it chaotic or deterministic?

1.2 What is Electrospinning?

There are various approaches to producing nanofibres. For example, the following can be used: drawing technology for producing micro/nanofibres using a micropipette with a diameter of a few micrometres; template synthesis of carbon nanotubes, nanofibre arrays and electronically conductive polymer nanostructures; and thermally induced phase separation method for producing nanoporous nanofibres.

Electrospinning is the cheapest and the most straightforward way to produce nanomaterials. Electrospun nanofibres are of indispensable importance for the scientific and economic revival of developing countries.

Structured polymer fibres with diameters in the range from several micrometres down to tens of nanometres are of considerable interest for various kinds of applications. It is now possible to produce a low-cost, high-value, high-strength fibre from a biodegradable and renewable waste product for easing environmental concerns. For instance, a pore structured electrospun nanofibrous membrane used as a wound dressing can promote the exudation of fluid from the wound, so as to prevent either build-up under the covering or wound desiccation. The electrospun nanofibrous membrane shows controlled liquid evaporation, excellent oxygen permeability and promoted fluid drainage capacity, while still inhibiting exogenous microorganism invasion because its ultrafine pores. Other examples include thin fibres for filtration application, bone tissue engineering, drug delivery, catalyst supports, fibre mats serving as reinforcing component in composite systems, and fibre templates for the preparation of functional nanotubes.

In 1934, a process was patented by Formhals [7] entitled *'Process and apparatus for preparing artificial threads'*, wherein an experimental set-up was outlined for the production of polymer filaments using electrostatic force (**Figure 1.4**). When used to spin fibres this way, the process is termed electrospinning.

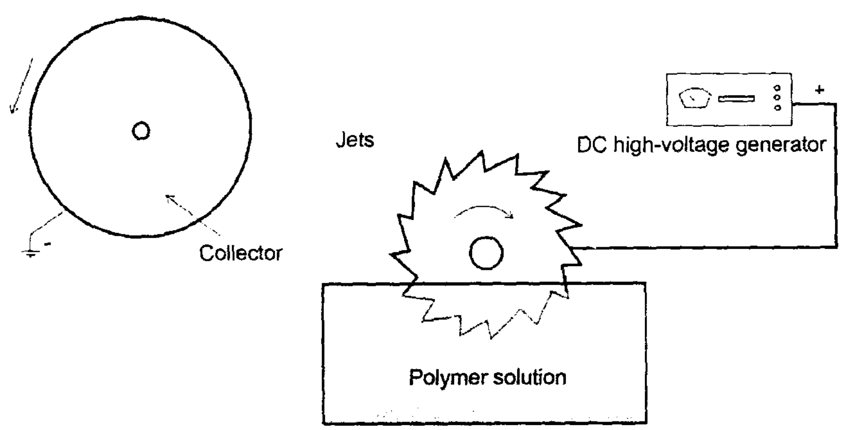

Figure 1.4 Formhals' electrospinning set-up.

Electrospinning is a novel process for producing superfine fibres by forcing a viscous polymer, composite, sol–gel solution or melt through a spinneret with an electric field to a droplet of the solution, most often at a metallic needle tip (**Figure 1.5**). The electric field draws this droplet into a structure called a Taylor cone [8]. If the viscosity and surface tension of the solution are appropriately tuned, varicose break-up is avoided (if there is varicose break-up, then electrospray occurs) and a stable jet is formed.

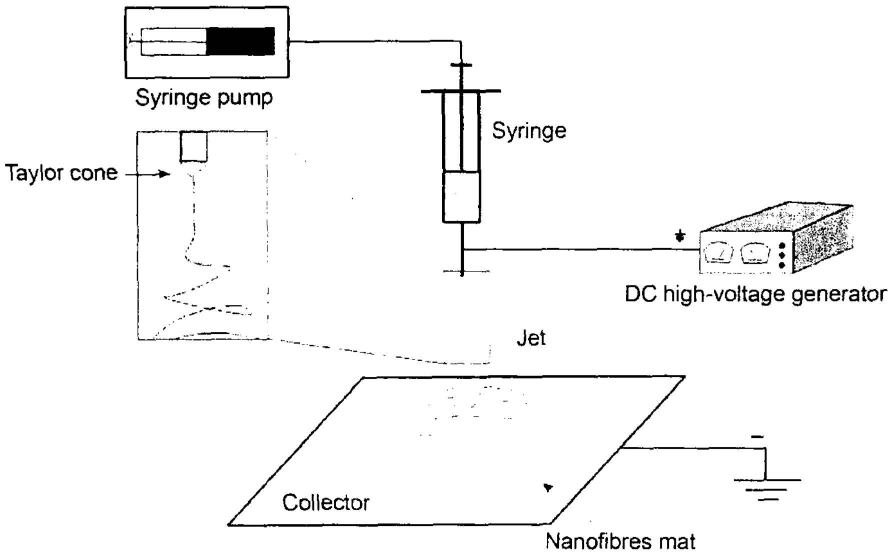

Figure 1.5 The most frequently used electrospinning set-up.

Taylor cone

A Taylor cone [8] is caused by equilibrium between the electronic force of the charged surface and the surface tension. A higher applied voltage leads to an elongated cone; when it exceeds its threshold voltage, a jet is emanated.

Electrospinning traces its roots to electrostatic spraying. Electrospinning now represents an attractive approach for polymer biomaterials processing, with the opportunity for control over morphology, porosity and composition using simple equipment. Because electrospinning is one of the few techniques to prepare long fibres of nano- to micro-metre diameter (**Figure 1.6**), great progress has been made in recent years.

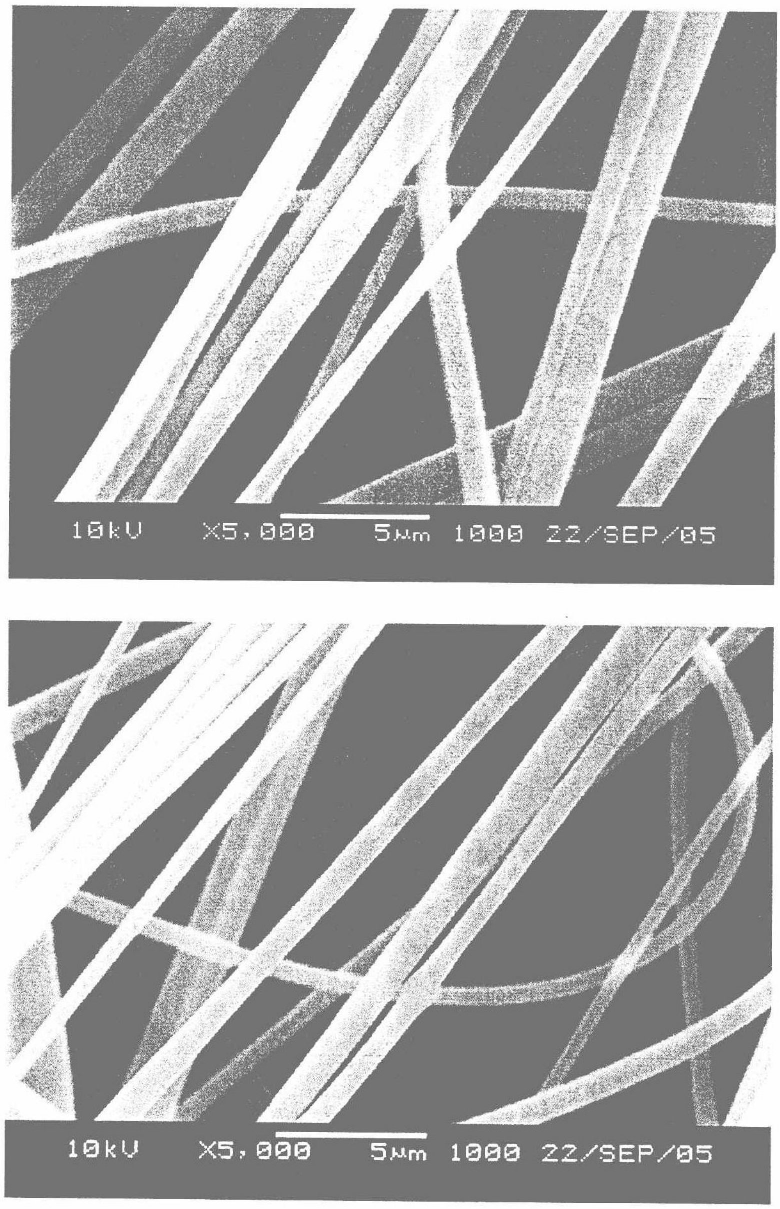

Figure 1.6 SEM photographs of electrospun fibres.

Nanofibre is defined in this book as a slender, elongated thread-like object or structure on the nanoscale, from several hundred to several thousand nanometres. Nanofibre is an emerging, interdisciplinary area of research, with important commercial applications, and will, most assuredly, be a dominant technology in new-world economies.

Materials in nanofibre form have an exceptionally high specific surface area, which enables a high proportion of atoms to be on the fibre surface. This will result in quantum efficiency, nanoscale effect of unusually high surface energy, surface reactivity, high thermal and electrical conductivity, and high strength.

Electrospun fibres can be used in the following applications: non-woven fabrics, reinforced fibres, support for enzymes, drug delivery systems, fuel cells, conducting polymers and composites, photonics, sensorics, medicine, pharmacy, wound dressings, filtration, tissue engineering, catalyst supports, fibre mats serving as reinforcing component in composite systems, and fibre templates for the preparation of functional nanotubes, to name just a few.

1.3 What Affects Electrospinning?

We have difficulty in precisely controlling the diameter, morphology and porosity of electrospun fibres, which means that we should develop a new theory linked to classical mechanics and quantum mechanics. As a first step towards the new theory, we should define the dimensions needed for theoretical analysis on a suitable scale, certainly different from our three-dimensional space or the four dimensions of space–time. Thus El-Naschie's E-infinity theory is needed.

Note that Einstein's special theory of relativity forbids discontinuous space, leading to the failure to unify gravity with electromagnetism. El Naschie set out to resolve the contradiction and the result was his famous E-infinity theory [1]. According to El Naschie, space and time are discontinuous. The main conceptual idea of E-infinity theory is in fact a sweeping generalisation of what Einstein did in