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Molecular Manufacturing Technology Development: A Review

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Abstract

Research and development of molecular manufacturing and related, enabling technologies are proceeding at an accelerating pace. As its name implies, molecular manufacturing will be achieved when we are able to build things from the molecule up, and we will be able to rearrange matter with atomic precision. Other terms such as molecular engineering or productive molecular nanosystems are also often applied when describing this emerging technology. The general capability to synthesize macroscopic objects and devices to atomic specification brings with it some surprising and important consequences, which are outlined in this presentation. This new emerging technology is now receiving attention at the highest level of government all over the world. The aim of this present paper is to understand the basic terminology and concept of molecular building blocks, like nanofibers and nanowires in terms of size, properties, manufacturing process and their applications. The information presented in this paper can be a part asset to the engineer who wish to work in the field of nanotechnology.

Keywords: Molecular Manufacturing, Nanotechnology, Molecular Nanosystems.

1. Introduction

Manufacturing today works by cutting or deforming large chunks of matter, then fastening together the remaining pieces into products. Molecular manufacturing plans to be more efficient and make better products by assembling products directly from the smallest pieces: atoms and molecules. The basic idea is to develop a small set of chemical reactions that can be applied repeatedly to build large molecules, and then control the sequence and/or position of the reactions by the computer in order to build engineered molecular systems.

Molecular manufacturing (MM) means the ability to build devices, machines and eventually whole products with every atom in its specified place. Today the theories for using mechanical chemistry to directly fabricate Nanoscale structures. These are well-developed and awaiting progress in enabling technologies.

Molecular manufacturing is different from biology. In those biological systems, they are not engineered. The functional properties of a cell or even a protein are complex and hard to predict. However, the process of building protein molecules from small molecular fragments is quite programmable, and scientists are developing the ability to design and synthesize proteins with desired properties. This will allow protein chemistry to be used in engineering, rather than a biological, context. This would be one approach to molecular manufacturing. Other approaches using different kinds of chemistry may also work, producing better materials.

Discussion of molecular manufacturing has been distorted by several factors. From the beginning, it has been associated with "grey goo" (runaway biosphere-eating self-replicators), leading to excessive fear and attempts to counteract that fear. It has also been associated with extreme science-fictional projections-though it can be hard to tell fantasy from the sober calculation because the calculations predict some pretty amazing capabilities. In reaction to these factors, some mainstream scientists have attempted to shut down discussion entirely by declaring that molecular manufacturing is impossible or that its major proponents are not credible. The discussion has been further distorted by a variety of widespread conceptual confusions.

The position that molecular manufacturing is impossible is not supportable. Living organisms are not an example of molecular manufacturing because they are not based on engineering but rather on interlocking complex systems. However, the biochemistry of life could be adopted almost unchanged to a molecular manufacturing system.

A few prominent scientists have nonetheless claimed that molecular manufacturing is impossible, and others have echoed them. However, the study of their objections shows that the arguments are weak, based on intuition rather than calculation. Some of the arguments elevate engineering difficulties to the status of fundamental limitations. Others are built on basic misunderstandings of the proposals.

2. The Coming Era of Molecular Manufacturing

This generation will witness the greatest technological breakthrough in human history, the development of molecular manufacturing and personal nano factories. Molecular manufacturing (MM) refers to a process that builds complicated machines out of precisely designed molecules. This emerging technology will allow us to guide the molecular assembly of objects by mechanically positioning reactive molecules.

This new manufacturing process, sometimes referred to as molecular nanotechnology (MNT), should not be confused with “structural nanotechnology” which refers to the present-day and near-future incorporation of nanoscale elements in modern industrial products. Nanoscale components are already present in many products, such as fabrics, electronics, and pharmaceuticals.

But molecular manufacturing harbors far greater abilities. Promising to deliver a monumental impact on human society, molecular manufacturing will provide us the means to manufacture products from the bottom up and enable us to rearrange matter with atomic precision. Once molecular manufacturing is developed, it will provide us with a thorough and inexpensive system for controlling the structure of matter. In a relatively short time period following the development of the first nano-factory, mankind will appear to have complete dominion over the physical universe.

2.1 How Molecular Manufacturing Works

The central, but not the only, component necessary to achieve molecular manufacturing is a fabricator or assembler. A fabricator will be a nanoscale device capable of precisely positioning molecules. Using current computer technology, we could then direct fabricators to secure and position compounds at the precise locations where chemical reactions occur. Using this method, a network of fabricators working in tandem (such as a nano factory) can construct atomically perfect objects of any size by initiating multiple sequences of controlled chemical reactions. A simplified way to visualize this concept is to think of a fabricator as an atomic magnet able to attract and repel molecules.

2.2 How Molecular Manufacturing Might Be Developed

Molecular manufacturing will most likely be developed under the auspices of a massive governmental defense project for a major world power. Likely candidates are the United States, the European Union, Japan, India, Israel, or China - although most nations in the world community have developed limited nanotechnology initiatives. In all likelihood, the events of September 11th provided the necessary incentive for the United States (and other world powers) to undertake organized and concerted efforts to accelerate the development of molecular manufacturing. Given the enormous benefits, as well as the unacceptable national security consequences of losing this new arms race to an unfriendly power, it appears most capable nations have instituted such projects and are fervently racing toward the construction of the world’s first self-contained molecular manufacturing system.

2.3 Why Molecular Manufacturing Will Be Developed

National security concerns will constitute the initial driving force to develop molecular manufacturing and reach the assembler breakthrough as soon as possible. Able to replicate swiftly, assemblers can become abundant in a very short period (if the self-replication period for an assembler is 15 minutes, then a single assembler can replicate into two to the ninety-fifth power assemblers in the first 24 hour period). Those assemblers can then be used to create weapons pre-designed in anticipation of the future development of molecular manufacturing, weapons capable of enormous destructive power - weapons that most people would find difficult to imagine.

In addition to its national security implications, molecular manufacturing promises to change every aspect of human life. Molecular manufacturing will also yield the following:

- A cleaner environment
- The eradication of diseases
- The elimination of poverty
- Safer, inexpensive space travel
- Acceleration in the development of advanced artificial intelligence.

2.4 The Dangers of Molecular Manufacturing

We must remain alert and vigilant to a number of potential dangers as we develop molecular manufacturing. One of the more commonly perpetuated concerns is the danger of a massive accident that may reduce the biosphere to “gray goo”. Many within the field of nanotechnology have expressed concern that a lab may accidentally set loose a runaway replicator in the environment. Using the earth’s biomass as a ready-made source of components, such a device could uncontrollably self-replicate across the globe like a mutant form of crabgrass, turning the planet into a sphere of “gray goo”. However, engineering such a replicator (if it’s even possible) will be quite difficult, and it’s highly unlikely to be the result of an accident. Such an accident is more likely to arise from the escape of a replicator consciously built for such a purpose. Such a replicator, in a controlled state, constitutes a new class of weapons of mass destruction. And the construction of such weapons raises speculation of a more serious concern than mere accidents and that is the threat of the deliberate abuse.

2.5 Precautions for the Safe Development of Molecular Manufacturing

A number of organizations and individuals are working diligently to ensure the safe development of molecular nanotechnology. The Foresight Institute is the most prominent organization actively working toward this goal. Founded by K. Eric Drexler, author of Engines of Creation, the Foresight Institute has published an evolving set of guidelines titled Foresight Guidelines on Molecular Nanotechnology. These guidelines address specific design features as well as principles of development. However, much is left undone.

Nanotechnology advocates have yet to introduce a specific set of policy initiatives to be undertaken following the development of molecular manufacturing. Specific policies must be developed to deal with the implications of molecular manufacturing within the framework of international order and security, the world economic order, and safeguards must be put in place to protect our environment. In the end, no one will realize the benefits of molecular manufacturing if we fail to preserve human life and liberty.

The Centre for Responsible Nanotechnology is currently engaged in answering many of these policy questions. Distancing itself from many of the broader issues under the umbrella of The Foresight Institute, The Centre for Responsible Nanotechnology focuses its efforts on studying, clarifying, and researching the policy issues involved in molecular nanotechnology’s development - political, economic, humanitarian, and security issues.

3. Molecular Assembler

3.1 Concept

The basic idea is simple: where chemists mix molecules in solution, allowing them to wander and bump together at random, molecular assemblers will instead position molecules, bringing them together to the specific location at the desired time. Letting molecules bump at random leads to unwanted reactions, a problem that grows worse as products get larger. By holding and positioning molecules, assemblers will control how the molecules react, building up complex structures with atomically precise control.

To picture a molecular assembler in a manufacturing system, imagine that all the parts are measured in nanometers and that the transferred parts are just a few atoms, shifting from handle to workpiece through a chemical reaction at a specific site. An assembler works as part of a larger system that prepares tools, puts them on the conveyor, and controls the robotic positioning mechanism.

This will be a complex system that no one will build anytime soon. Indeed, no one is even trying to build molecular assemblers today, because nanotechnology is still in its infancy. We can see a path to assemblers, just as the rocketry pioneers of the 1930s and 1940s could see a path to the Moon. But like those pioneers, we aren't ready to attempt the final goal. They knew they must first launch many satellites, just as we must first build many molecular machines.

3.2 Molecular Building Blocks (MBB)

In recent years, there has been a rapidly rising interest in synthesizing large assemblies of organic molecules that might be able to serve as scaffolding structures in efforts to construct molecular objects of nanometer sized dimensions. Those molecular aggregates might find applications in molecular electronic and computing devices, or simply as novel materials with special chemical, optical, and electrical properties. These efforts have been an outgrowth of the field of supramolecular chemistry, which started with the serendipitous discovery that certain crown ethers are able to specifically complex (and so to "recognize") alkali metal. The resulting complexes were soluble in non-aqueous solvents, which seemed unusual for a compound that essentially is a salt. Analysis of the causes of this intriguing phenomenon has led to the synthesis of innumerable variations of these host-guest complexes. A very useful theoretical inquiry into the nature of self-assembly and molecular recognition of many similar complication arrangements has been presented.
This growing research field is moving towards establishing an important enabling technology for the technological direction that has been outlined, namely of eventually attaining manufacturing capabilities at the molecular level, leading to products which obtain their big utility from having all their atoms in precisely specifiable positions (as opposed to most of today's engineering materials like metals, ceramics, plastics, and wood, which have microscopically amorphous structures). It is useful to outline what molecular design issues in the field of supramolecular chemistry have to be systematically considered to help establish a focused effort to bootstrap molecular manufacturing.

The largest amount of insight into finding relevant design criteria for MBBs is gained if one would like to employ them in a demanding application, like the construction of molecular machinery. Not only do the MBBs have to be able to stack in three dimensions potentially infinitely (to obtain scaffolding of large dimensions), but one also has to be able to specify distinct 3D stacking patterns and sequences, to obtain the highly idiosyncratic patterns present in machinery as well as in computers.

For building machinery, it is necessary additionally to be able to specify the surfaces of interacting mechanical components in atomic detail, to construct required sliding interfaces and to place functional groups which can act as specific binding receptors or as catalytic sites similar to enzymes. In mechanical components, the ratio of interior volume to surface area is much smaller than in an infinitely extended regular crystal, because in these components mainly the surface gives a part its desirable characteristics. This being so, it follows that the slim interior of mechanical parts is best held together by strong interactions, preferably through the use of covalent bonds, to avoid the part from falling apart during usage. Most attempts in designing crystals and solids have so far only used ionic or even weaker interactions which would be unsuitable for achieving the declared goal of building molecular machinery. That is why covalent connections between the MBBs are assumed.

3.3 Classification

Ideally, one would like to split the design of MBBs into two independent problems, namely the analysis of link chemistry and the design of MBB-skeleton structures (which would consist largely of carbon-frameworks). The link-chemistry would provide the means by which individual MBBs are joined in a covalent fashion and would be implemented by attaching specific functional groups at convenient places on the skeletons.

This is, of course, a design abstraction; in reality, one could not just "attach" a functional group somewhere, but one will have to specify a detailed scheme by which an organic molecule could be synthesized so that the desired functional groups end up in the right places. But for a high-level systems analysis, this abstract point of view enables better insight into the complexity and modularity issues.

Hopefully, the analysis of these two independent problems would result in two worked out "toolsets", which could then be combined flexibly in any desired fashion to give the actual incarnations of fully functionalized MBBs.

4. Molecular Manufacturing

Molecular manufacturing is a method conceived for the massively parallel processing of individual molecules to fabricate large atomically-exact products. It would rely on the use of many trillions of molecular robotic subsystems working in parallel to process simple chemicals into new materials and devices. Built to atomic specification, the manufactured products would exhibit significantly higher performance than that of today’s products. Equally as important, the high level of automation of the manufacturing process would significantly lower the cost compared to today’s techniques. A distinguishing feature of molecular manufacturing would be that the trajectory and orientation of every molecule in the system are precisely controlled during the manufacturing operation, differentiating it from processes based on solution chemistry where molecules bump into each other in random orientations until reactions occur.
A few of the key concepts from the principal reference, Nanosystems, are summarized in Figures 1-3. Fig.1 shows a cylindrical bearing, a differential gear, and a schematic of a molecular sorting and conveyor transport system. The design and performance of the first two mechanical parts have been studied in detail and show that high efficiencies are possible when complementary atomic surfaces are properly matched. Fig.2 shows a schematic of a stiff robotic arm composed of about four million atoms. Simple hydrocarbon molecules are fed to its tip through an internal conveyor system; atoms are transferred from those molecules to the workpiece at processing speeds approaching 500,000 atoms/seconds about the speed of a fast enzyme. Fig.3 shows a conceptual diagram of a desktop molecular manufacturing system. Simple hydrocarbon molecules are sorted, attached to conveyors, positioned, and then reacted to build up atomically exact structures. It is particularly appropriate to be discussing this technology with the textile community. Of all the manufactured products that come to mind, there is no better analogy to molecular manufacturing than the production of textiles, which assembles tonnage quantities of material from small fibers using up to tens of thousands of machines operating in parallel. It is also relevant to note how clean molecular manufacturing is expected to be while these systems would manufacture products to atomic specification; they would also prepare waste products to atomic specification. Water vapor and carbon dioxide would be typical waste stream constituents.

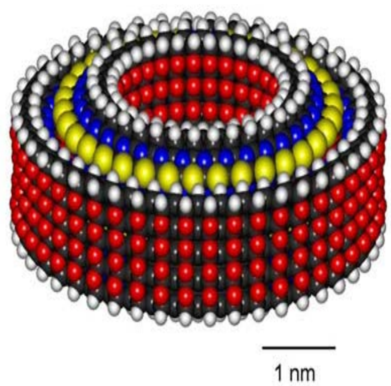

Fig.1 Molecular Structure of Cylindrical Bearing

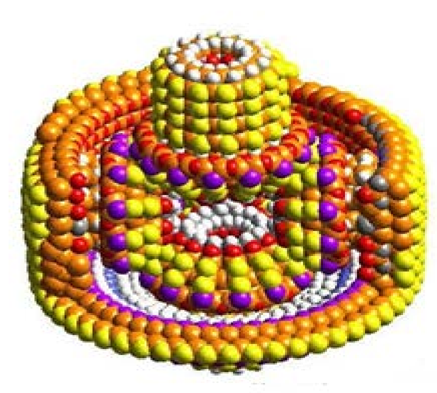

Fig.2 Molecular Structure of Siff Robotic Arm

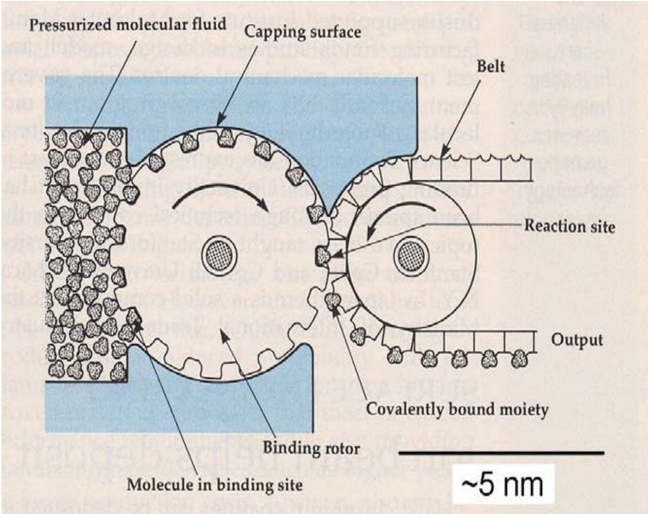

Fig.3 Desktop Molecular Manufacturing System

4.1 Implications for Textiles

There are clear advantages to having materials that are 100 times stronger than we have now. Objects made from these materials could be up to 100 times lighter, using 100 times less material. As a result, ultra-light cars, trucks, trains, and planes would use far less energy, especially with atomically smooth surfaces on moving parts and aerodynamic surfaces to reduce internal friction and air resistance losses. Textiles will have similar gains in performance. Today, basic units of fabrics are molecules of natural and synthetic materials such as cotton (cellulose), wool (α-keratins), rayon (cellulose), and polyester. Bundles of these molecules are twisted to form fibers, which can be spun into threads and yarns. An obvious way to strengthen these conventional materials would be to reinforce them with carbon nanotubes—the current darling of nanotechnology materials. In fact, there are already intensive efforts by groups around the world to create fibers from carbon nanotubes, which individually have a tensile strength of about 100 Gpa. This is more than 50 times stronger than a typical steel and 1/3 the density. By comparison, commercial rayon has a tensile strength of 0.45 Gpa and nylon, 0.08 Gpa.

One of the difficulties in using carbon nanotubes in textiles is that it is difficult to grow nanotube molecules into centimeter lengths without loss of strength (due to processing-induced defects in long molecules). It's also difficult to twist shorter nanotubes into a fiber while maintaining the high strength of the individual nanotube. With molecular manufacturing, arbitrarily long nanotubes would be possible, and textiles could be fabricated to nearly their theoretical strengths. Carbon nanotubes also have a high thermal conductivity along the axis (about three times that of diamond, and 15 times that of copper). Like a diamond, carbon nanotubes are very stable in air to 1000°C. With these properties, a carbon-nanotube-based textile would make an excellent heat resistant fabric. The high axial thermal conductivity would act as a natural heat pipe to help to dissipate energy from hot spots on the material. Thermal conductivity could be quite low in the transverse plane with an open array of molecules with long, widely spaced cross-links. Today's textile materials made with molecular manufacturing would be considerably stronger. The theoretical strength of cellulose is 12-19 Gpa, so the strength of cotton and rayon could be improved more than ten-fold with molecular manufacturing. There would be virtually 100% efficiency in converting yarns to fabric tensile strength due to the high level of uniformity in both strength and elongation from one yarn to another. Fiber separation could be eliminated as a failure mode by connecting individual fibers end to end and making them continuous, but still bundled and twisted in the same amorphous way. It seems possible to do this while maintaining the look and feel of current fabrics if desired.

4.2 Smart Materials and Nanotechnology

While synthesis of defect-free materials will lead to substantial improvements in performance, molecular nanotechnology will make more radical changes possible by integrating computers, sensors, and micro- and Nanomachines with materials. Here are some ideas:

- Micropumps and flexible microtubes could transport coolant or a heated medium to needed parts of clothing.
- The kinds of sorting rotors shown in Figure 1 could be arrayed as "pores" in a semi-permeable membrane to allow only particular kinds of molecules through.
- Water might be a useful molecule to select for, to keep one side of a fabric dry or another side wet. On the wet side, the water

could be transported away to an evaporator, or stored.

Active programmable materials, a rich integration of sensors, computers, and actuators within structural materials will blur the distinction between materials and machines, allowing the design and construction of objects that can be programmable reconfigured to sub-micron precision. These materials could monitor and report on their own state of "health." Fig.4 and fig.5 illustrate this concept with a latticework of machines linked by telescoping, interlocking arms. Both information and power would be transmitted through the arms to the individually addressable nodes. By selecting which screws would tighten and which would loosen, the shape of an item could change to conform to the needs of the user. A solid, rigid object could be made to behave like a fabric by effecting rapid changes in its shape, or with temporary disconnections between some cells. A flexible fabric could turn rigid by having loosely bound cells to connect into a stiff framework. Thus, distinctions between fabrics and other types of rigid materials could blur.

The programmable material concept is not limited to fabrics but has many potential applications there. One example would be a space suit that would allow nearly as much freedom of movement as one's own skin. Embedded computers connected to strain gauges could sense the wearer's intended movement and adjust the material accordingly. The reflectance of the outer layer could be variable to absorb needed amounts of heat from the sun-facing side and transport it to cold spots—although the material's insulative properties would allow very little of the wearer's heat to escape. Excess heat could be transported to radiators on the cold side.

Fig.4 An Individual Node

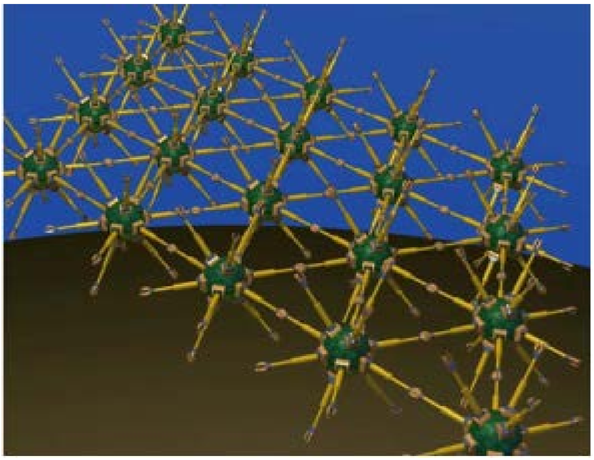

Fig.5 Two Dimensional Array of Interlocked Nodes

Materials made from these devices could be instructed to change their shape in rapid fashion.

- Fabrics could be self-cleaning: robotic devices similar to mites could periodically scour the fabric surfaces and integral conveyors could transport the dirt to a collection site, or the previously mentioned molecule-selective membrane could transport water to one side or the other for a cleaning rinse.
- Fabrics could be self-repairing: sensors would detect discontinuities in the material via loss of signal or a reported strain overload and send robotic "crews" to repair the damage. Self-shaping fabrics would be able to return to their original shape around a tear until repairs are effected.
- Large sections of fabrics could be made without visible seams by joining panels of

fabric with microscopic mechanical couplings along their edges. Similarly, surfaces could contain mechanical couplings that, when pressed together would bond with nearly the strength of the bulk material. This 'smart velcro' could latch and unlatch at the user's request.

5. Conclusions

Today molecular manufacturing and nanotechnology are still in a formative phase. Yet these fields are maturing rapidly. Investment in nanotech research and development by governments around the world is in term of millions. By 2020, products incorporating nanotech will contribute approximately $1 trillion to the global economy. About two million workers will be employed in nanotech industries and three times that many will have supporting jobs.

Here in this paper, we explained about the manufacturing of molecules. Apart from these, there are so many other processes to create nanofibers and wires like electrospinning. Application of nanotechnology is developing rapidly in medicals when to compare to other fields. Nowadays so many diseases like cancers, heart problems are curable, where before it was difficult.

Over the next couple of decades, nanotechnology will involve all stages of industrial prototyping and early commercialization. Nanotechnology should benefit every industrial sector and health care field. It should also help the environment through the most efficient use of resources and better methods of pollution control.

Nanotechnology does, however, pose new challenges to risk governance as well. Internationally, more needs to be done to collect the scientific information needed to resolve the ambiguities and to install the proper regulatory oversight. Helping the public to perceive nanotechnology soberly in a big picture that retains human values and quality of life will also be essential for this powerful new discipline to live up to its astonishing potential.

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