CRITICAL NATIONAL NEED IDEA

National Nanomanufacturing Testbed Program

Integrated Hierarchical Nanomanufacturing

Submitting Organization: **Center for Hierarchical Manufacturing**
University of Massachusetts Amherst

Contributing Organization: **National Nanomanufacturing Network**

Point of Contact: Prof. James Watkins
Department of Polymer Science and Engineering
University of Massachusetts Amherst
A616 Conte research Center
120 Governors Drive
Amherst, MA 01003
Phone: (413)545-2569
Email: Watkins@polysci.umass.edu

Dr. Jeffrey D. Morse, Managing Director
National Nanomanufacturing Network
710 N. Pleasant Street, 322 LGRT
Amherst, MA 01003
Phone: (413)545-5264
Email: jdmorse@research.umass.edu

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Background

Initial projections of the economic impact of nanotechnology from as far back as 2001 predicted a 25% yearly growth in revenues from nanotechnology enhanced products, with a total market exceeding one trillion USD by 2015[1-3]. Thus far, industry growth has followed these predictions, predominantly in nanocomposites and nanointermediates. However, the economic downturn has hit key nano-enabled product segments hard: in particular, auto, construction, and electronics. Lower output and slower technology adoption in these industries will ripple up the value chain to nanointermediates and nanomaterials, leading to total revenue from products incorporating nanotechnology to be down 21% from previous projections[4]. The changes will place challenges and economic constraints on large corporations to develop new technologies, and further constrain startup company opportunities with demands for rapid return on investment, thereby requiring creative action from governments in order to keep the necessary innovations by researchers in nanotechnology on track for transitioning to commercialization. This becomes especially challenging as private investment will require higher levels of maturity for technology in order to see return on investment in short order.

The Interagency Working Group of the National Science and Technology Council in its report, *Manufacturing the Future (March 2008)* points out that, "There are technical barriers to high-volume and predictable nanomanufacturing.... While some manufacturing knowledge may be drawn from existing manufacturing enterprises, much of the future manufacturing paradigms will require new science and engineering knowledge…".[5] Similar conclusions are drawn by the NIST White Paper on Manufacturing regarding nanomanufacturing, stating, "Robust and reliable production methods with correct control and measurement for consistent features and no waste at the atomic scale are needed for consistent features."[6]

With a strategic, coordinated effort, the U.S. has a timely opportunity to address these challenges and, as a result, create significant economic and societal value. The acceleration of nanomanufacturing processes for the manufacture of flexible electronics, photovoltaics, batteries, water purification media, information storage media and sensors will directly address these issues by providing process developments that can make these devices more economically attractive thereby ensuring the Nation's competitive position in developing innovative new products and revitalizing the domestic job market. Under the current economic conditions and because of the high-risk nature of this research, U.S. Industry is unlikely to be able to solely fund and undertake this fundamental nanomanufacturing process research. Consequently, it falls to the academic community in close collaboration with interested industrial partners, both large and small, to perform this high-risk, high-reward research.

Critical National Needs

In order to facilitate paradigm shifts in how key problems of critical national needs will be solved, the key societal challenges requiring government support to facilitate transformational approaches must be addressed. The Obama administration and the Office of Science and Technology Policy[7] is committed to advancing a comprehensive technology and innovation plan that will develop new clean energy sources, next generation manufacturing technologies, critical civil infrastructure, reduction/elimination of greenhouse gases, and the evolution of green, environmentally friendly manufacturing processes to address these critical needs and application areas. One key technology topic impacting all of these areas, along with additional highly leveraged industry sectors, is nanomanufacturing.

These key national needs have reached critical levels due to a combination of overlapping economic, industrial, and environmental issues that have evolved over many years, and more recently have gained attention through a global economic crisis. As such, the opportunity exists now as it has never before to exact real and sustainable change on a national and global scale addressing these issues. New clean energy generation and storage technologies must become available to industry and the public providing sustainable market driven products immune from the manipulations and economics of fossil fuels and foreign governments. New and expanded infrastructure must provide clean water sources for future generations. Affordable carbon dioxide capture and conversion must maintain and balance greenhouse gas production. Finally, a new manufacturing base must be established supporting existing infrastructure, yet establishing a new work force base sustained by expanded education and training.

Societal Challenges and Impact

The above discussion and points are not new by any means. Enacting these concepts takes a critical mass of economic, political, industrial, and public support, effecting a synergistic production enterprise in order to be successful by realistic and sustainable measures. Energy is particularly challenging in that competitive technologies have existed for decades, and will ultimately depend on the limited availability of low cost fossil fuels to gain market share. This has been difficult since the cost of oil and coal can be manipulated, thereby making these energy options more costly and less attractive. While recent swings in the cost of oil to historic highs have heightened awareness of this issue, the public's sentiment still tracks economic trends, and has become more relaxed as prices have receded. To counter this, cost-competitive sustainable energy options must be provided to the masses. Given these choices, the public is at a crossroads where decisions regarding future spending on replacement energy sources would lean towards new green energy sources and would chart new directions if the choices were available. Future projections of global economic growth further support these trends as oil becomes a primary commodity sustaining growth in emerging economies, the Nation's costs will only increase.

Similarly, other critical national needs such as water resources, manufacturing, and reduction of greenhouse gases face the same challenges of economic impact making it difficult to achieve market entry, as well as justification for the necessary investment, whether public or private, to achieve sustainability. While new investment into these areas continues, time to market remains a serious consideration for sustaining the investment and, in most cases, can only be justified for the largest markets. In this scenario, only mature, low risk technologies will make an impact, being capable of riding out economic oscillations through a combination of niche market sales revenues and private investment. In the case of the high risk, less developed technologies and markets, technology maturation and market entry will be adversely impacted by these scenarios and mentality. These are the areas where selective investment of public funds makes sense and will have the most impact. To enhance the impact of such investment, models employing regional and local collaboration, common goals cutting across industry sectors, and establishment of pilot lines demonstrating the necessary economy of scale will facilitate broader market adoption thereby extending this impact to other manufacturing bases.

Nanomanufacturing: Benefits and Challenges

Nanomanufacturing is the vehicle by which society will realize the benefits of nanotechnology[8-11]. These benefits will result through enhanced performance of products in a wide range of industries including aerospace, automotive, communications, energy, environmental remediation, information, medical, pharmaceutical, and power. At the same time, realizing the promise of nanotechnology through the development of practical manufacturing methods will likely lead to industries and products yet to be imagined. For application of nanomanufacturing to critical national needs in energy, manufacturing, civil infrastructure and reduction of greenhouse gases, nanomanufacturing methods must provide a paradigm shift in the way these products are designed and manufactured, and, ultimately, enhance the performance such that the properties demonstrated at the nanoscale are truly scaled to large volume manufacturing lines and processes. Furthermore, these methods and materials must achieve the necessary economy of scale in order to be a disruptive and competitive approach for the critical national needs. Additional benefits include economic growth through the establishment of new education, training and employment opportunities that will eventually spill over to other industrial sectors. Peripheral benefits include growth in the materials supply chain, nano-intermediates, equipment, and instrumentation markets as these new methods gain foothold and acceptance within specified industrial sectors.

Nanotechnology is viewed throughout the world as a critical driver of future economic growth and as a means to solving some of humanity's most vexing challenges. Because of its incredibly broad range of prospective uses, nanotechnology has the potential to impact virtually every industry from aerospace and energy to healthcare and agriculture. The inherent limitation of nanotechnology's impact in both economic and societal terms has been the transition of nanoscience breakthroughs in the laboratory, having increased at an incredible rate over the past decade, into consumer products and applications. While there are significant examples of these transitions, most have been through existing infrastructure in the form of composite materials and semiconductor electronics manufacturing.

Nanomanufacturing is the utilization of value-added processes to control matter at the nanoscale in one, two, and three dimensions for reproducible, commercial-scale production. It remains the essential bridge between the discoveries of the nano sciences and real-world nanotechnology products, and encompasses bottom-up directed assembly, top-down high resolution processing, molecular systems engineering, and hierarchical integration with macro-scale systems. Advancing nanotechnology from the laboratory into high-volume production ultimately requires careful study of manufacturing system issues including product design and development, manufacturing process integration, supply chain management, and standards for measurement, processing, and safe handling[8].

Nanomanufacturing introduces an inherently multi-disciplinary set of problems for working with structures in the 1-100 nm regime. Critical research and technological challenges include controlled assembly of three-dimensional heterogeneous systems, quality processing of nanoscale structures in high-rate/high-volume manufacturing systems, and ensuring the long-term reliability of nanostructured systems. Realizing this potential depends on progress on many fronts of science and engineering. Ultimately, it will require reliable tools and processes for precisely manipulating and assembling the basic building blocks of nanotechnology products, cost-effectively producing these products in large quantities, and integrating them into systems spanning nanoscale to large-scale dimensions. In addition, nanotechnology could have profound structural implications for the manufacturing sector in general.

In order to impact the critical national needs mentioned above, acceleration of nanomanufacturing processes must be addressed including production for the following;

1. Clean energy sources - photovoltaics, Li-ion polymer batteries, fuel cells, ultracapacitors
2. Civil infrastructure - water desalination, remediation, and filtration
3. Manufacturing - flexible electronics, displays, data storage, and sensors
4. Greenhouse gas reduction - industrial scale separation and conversion of carbon dioxide

An effective nanomanufacturing R&D effort will directly address the scale-up production issues of specific technology approaches employing nanostructured components, devices and system approaches via process developments that can make these devices more functional and economically attractive. In achieving these goals, new methods must be established that eliminate by-products, wastes, and impurities associated with manufacturing processes that hinder acceptance and adoption in commercial applications.

Emerging Nanomanufacturing Technologies

Emerging nanomanufacturing techniques include top-down processes and tools, such as nanoimprint lithography (NIL), and bottom-up processes, such as self-assembly using block copolymer blends and surface functionalization. These techniques are at the forefront of research since there remains a great deal of understanding to be developed and further refined as the envelope of dimensional limits and tolerances is pushed. While the literature includes a wealth of information in these and other nanomanufacturing process related to areas exhibiting the promise of nanotechnology methods and materials, examples of the research described are either focused on very specific industry sectors, or are still seeking specific market and product sectors to support. The key aspect limiting the broader adoption of emerging processes and tools for specified market and industrial sectors is manufacturing infrastructure, including tools, equipment, materials, supply chain, and work force. For a major industrial sector, it is typical that significant investment has been made in establishing tools, processes, and standards for effective manufacturing. In assessing the impact of emerging processes and tools as a solution extending the technology roadmap, the manufacturer must also consider the impact of upstream and downstream process steps in making a decision to incorporate new process steps, let alone to adopt completely new processes. In this context, the barriers to entry for these emerging processes are substantial, and in many cases require a completely new manufacturing line.

In this context, examples of emerging nanomanufacturing technologies transcending to targeted applications include directed assembly of block copolymer templates to form master mold patterns for NIL of patterned media data storage. This has proven to be one of the more cost effective process approaches to achieve the goals of the industry roadmap for magnetic data storage. Another example is in the area of functional nanocomposite materials where companies have developed coating tools for the deposition of carbon nanotube sheets at large scales. The carbon nanotube sheets have a range of military and commercial applications and the process established to provide sufficient reproducibility for manufacturing. In either case, the application does not require complex integration issues and may be the only cost effective means to achieve the desired goal in the available timeframe.

In order to extend these examples to viable industry sectors and applications, processes and tools must be explored that increase the complexity of the system through process integration. As such, new levels of control and functionality are engineered into the nanocomponents, which are then scaled accordingly through mass production processes. As an example, one might envision directed and coordinated self-assembly techniques to be incorporated to create atomically precise positioning of nanocomposite architectures to achieve three-dimensional functional structures. This may be integrated with existing mass production infrastructure via roll-to-roll processes, incorporating various methods of thin film deposition or coating to control surface morphology, dispersion, and functionality, along with nanoimprint lithography techniques providing the patterns for directed assembly, and integrated interface to the macroscopic elements with the integrated architecture. Considering the above example further, while the literature is filled with papers addressing the individual process steps mentioned, several critical unmet needs must be further demonstrated to make this approach competitive. These research issues include the development of low-cost, commodity scale materials suitable for directed assembly at both single wafer batch processes, as well as high rate roll-to-roll processes. In this examples, the key research focus must consider designs needed to transfer the technology from the laboratory to the necessary manufacturing platform and may include;

- Generating low-cost, commodity scale materials sets,
- Demonstrating precision cooperative assembly
- Utilize surface directed/guided assembly of critical features via imprint stamping
- Demonstrate fabrication of ordered hybrid nanocomposites at high rates
- Develop suitable online metrology

Integrated Nanomanufacturing Processes

In order to demonstrate nanomanufacturing processes for more sophisticated and complex applications areas, process integration and hierarchical design methodologies must be investigated[12]. Critical national needs and specified technologies relevant to energy, power, water resources, and greenhouse gas reduction would all benefit from these approaches. Furthermore, by exploiting the high throughput roll-to-roll process infrastructure, production needs and cost requirements for these industry sectors can be addressed at an early stage via an existing manufacturing base. Incorporating hierarchical process methodologies to address the optimization of nanoscopic elements, along with the upstream and down stream process steps, whether nano, micro, or meso scale, enables multiscale system functionality to be addressed from the inception of the manufacturing process. The importance of transitioning laboratory proof-of-concept batch processes to continuous high-rate roll-to-roll processes cannot be understated. Ultimately achieving the high-rate manufacturing for which these methods are capable will drive the cost for these high value technologies to be cost competitive, thereby opening up early stage markets within the various sectors described. To succeed will require the detailed scientific and engineering research regarding process kinetics, heterogeneous material interfaces, process measurement and control, precision process tool development, process-property relationships, materials performance data, rapid roll-to-roll prototyping, cost optimization and best practices in accelerated technology development.

Nanomanufacturing Testbeds: Unique Opportunities for Industrial-Academic-Government Collaborations

Nanomanufacturing testbeds provide a critical platform bridging the gap between innovations in the laboratory and implementation into production lines and consumer products. As such, researchers involved in a broad range of science and technology enabled through nanoscale materials and phenomenon are reporting discoveries and innovations with increasing frequency. As these breakthroughs involve academia, industry and government researchers, the next step in many cases is to understand who the stakeholders are and the range of applications that would benefit from the research results. While the applications and benefits may be obvious, it is not always as straightforward as developing a business plan, or partnering with an industry leader to take a technology to the next level. Very typically, the innovation must be further developed such that design, manufacturing, reliability and yield issues are addressed to achieve the necessary economy of scale in order to realize a competitive product. This is especially true for technologies for which there does not yet exist a proven manufacturing platform. In this context, inherent risk is involved regardless of the makeup of the stakeholders that may add capital expense or scaled performance limitations that detract from the benefits provided by the innovation.

While these concerns may not be unique to the field of nanotechnology and nanomanufacturing, several aspects are. These involve existing infrastructure, capabilities, tools, and capacity enabling further investigation and development of the range of technologies being reported by research laboratories worldwide to better understand the financial and societal benefits provided therein. One model that addresses these issues is that of the testbed. The goal of a nanomanufacturing testbed is to translate outstanding fundamental research on nanoscale science and engineering to realizable manufacturing processes and devices. An effective testbed project quickly establishes feasibility and performance data to guide the decisions necessary for ramped-up development and a long-term technology roadmap. Most academic research centers include testbed programs at some level, as well as government laboratories, which may have a focus towards mission critical applications. While some industry sectors do sustain testbed programs, the focus has a tendency to be limited to core products, and additionally encounters competitive entanglements that may limit the broader exchange of information to the community of interest. In these instances, the testbed may specify some common goal of demonstrating the feasibility and scaling of a process or device concept in order to generate metrics through which demonstrable performance results can be measured and compared. For a testbed to be successful ultimately requires input from stakeholders and industry relative to important parameters, issues, and concerns specific to their manufacturing platforms, thereby enabling direct evaluation of new processes and device technologies with present state-of-the-art.

To extend the utility and benefits of a testbed further requires a partnership between government, industry and academia to identify the key contributors and beneficiaries of such programs, as well as involve the key researchers in the field. The importance of this partnership varies depending on the technology maturity, complexity, and existing infrastructure that represents the status quo. As an example, consider the semiconductor industry over the years where industrial consortia have been established in collaboration with government and academic organizations to investigate and develop new capability for the entire industry. In most cases, the technology being validated was a new tool or capability that would replace existing tools having significant foothold within the industry. As such, the commitment of long term, industrial sector driven partnerships has clearly demonstrated the benefit of the testbed program. As new paradigms are being established in how nanotechnology is being applied to manufacturing challenges of the future, these issues become significantly more complex as many industries face the prospect of establishing partial or completely new infrastructures to extend the manufacturing capability for the future. In this context, the testbed programs provide additional benefits including cost sharing of the expense for feasibility demonstration and scale-up.

National Nanomanufacturing Testbed Program: Learning from History

A coordinated testbed program on nanomanufacturing technologies has numerous benefits enabling transformational impacts addressing key societal challenges. Historically, nanoscience breakthroughs in the laboratory have experienced the "valley of death" when innovators attempt to commercialize the technology. In order to enhance the success rates in transitioning these key breakthroughs in the laboratory to commercial production, a platform is necessary wherein production techniques can be demonstrated prior to making significant capital investment into equipment and facilities. In that sense, a nanomanufacturing testbed program offers benefits of a user facility for stakeholders to determine the feasibility of yet unproven, high risk processes and equipment for their specific needs. In some sense, this would enable the benefits of accessibility as the NNIN user facilities have provided, yet with a different focus. The hands-on portion would be in the context of a virtual nanomanufacturing facility wherein stakeholders, members, or participants would have access to the critical expertise, research, and facilities to focus on their specific problems and needs.

Commitment to such a concept is expected by large technology based companies and technology industry-based consortia. Research institutions would also likely participate. Additional research institutions around the U.S. would further contribute specific expertise in core research and transition to scaled manufacturing. Finally, numerous small companies in the technology areas including batteries, energy storage, fuel cells, photovoltaic's, water desalination, and sensors can be anticipated to participate in such a program.

In order to be successful, a National Nanomanufacturing testbed must provide the best of both worlds: innovations at the research institutions, and timely transition and scale-up to address production level issues in a timely fashion. To further the success of such a program, new models of doing business must be established, including providing an intermediate platform through an industrial partner to facilitate the scaled R&D efforts without the encumbrances of intellectual property issues and concerns. Companies would provide input to the project specifying the issues for given processes that are important to them. After addressing these issues and demonstrating feasibility towards their needs, the companies can then provide additional funding to continue development under more proprietary conditions. While these types of issues are not trivial, the benefit must outweigh the concerns such that industry can participate in an open manner to establish the criteria that are important to them for testbed process demonstrations.

Summary: Opportunities in Nanomanufacturing

The realization of nanotechnology enabled materials, devices, and systems requires the realization of low-cost materials and systems, which combined with high speed manufacturing processes represents a water-shed event which would smoothly address the critical national needs as specified above. Nanomanufacturing testbeds offer a unique opportunity to accelerate progress in these emergent areas of nanomanufacturing by providing a pre-competitive environment that includes buy-in, direct participation, and guidance from industry, yet exploits the leading edge research of key academic centers and organizations. While many emerging areas of nanomanufacturing have not yet been discussed, the examples cited above provide a set of the more mature technologies. The key research will ultimately address the integration issues and challenges in transitioning the emergent technologies.

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