EL Program: Smart Manufacturing Processes and Equipment

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Strategic Goal: Measurement science and standards for Smart Manufacturing, Construction, and Cyber-Physical Systems

Summary:

This program addresses measurements and standards necessary to develop next generation smart manufacturing processes and equipment that are optimized to enable cost effective and agile manufacturing of complex, technology-intensive, innovative, customized products of the future. The program will accomplish its objective through solution-enabling measurement science research and standards development on: (1) additive manufacturing, (2) smart machining, and (3) micro- and nano-manufacturing.

DESCRIPTION

Objective:

To develop and deploy advances in measurement science that will enable rapid, agile and cost-effective production of innovative, complex products through advanced manufacturing processes and equipment by 2016.

What is the problem?

Global economic and technological forces have created fundamental changes in U.S. manufacturing. Rapidly changing global market demands and competitive environment create pressure on U.S. manufacturers to respond more quickly and efficiently with innovative products and processes[1]. The future vision of U.S. manufacturing[2] includes innovative, technology-intensive products and processes requiring intelligent manufacturing equipment; customization of manufactured products to meet individual customer needs; and 'point-of-use' manufacturing capabilities based on proximity to customers that are highly responsive to rapidly changing needs. In a workshop[3] organized by NIST recently the following major industrial drivers were listed, among others: increasing pace of technological change; increasingly rapid product and process innovation; shorter time to market; continual push for higher quality, better performing

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[1] "*Understanding Changes in U.S. Manufacturing,"* Report prepared for the DoC Working Group on Manufacturing, Economics and Statistics Administration, June 10, 2009.

[2] L. Rhoades, "*The transformation of Manufacturing in the 21st Century*," The Bridge: National Academy of Engineering, Vol. 35, no. 1, 2005.

[3] "*Summary of the NIST Extreme Manufacturing Workshop*," Report prepared by IDA Science and Technology Policy Institute, March 29, 2011.

customized products; increasing productivity and reducing costs; and highly efficient unit-of-one production. Therefore, the ability to mass-customize products for a wide range of increasingly sophisticated and demanding customers and to produce them cost-effectively in any lot size will provide a competitive edge in the future. In fact, according to a new report by The Boston Consulting Group, products more attractive to produce in the U.S. include those made in small lots and those that involve multiple design changes[4]. Agile manufacturing processes, where the production is achieved by means of programmable action to create parts out of bulk or powder material with minimum specialized tooling, are therefore critical enablers for achieving U.S. competitive advantage.

Among the four fundamental manufacturing process categories (casting/molding, forming, machining, and joining), machining is by far the most basic and agile manufacturing process with a broad impact on other manufacturing processes (e.g., high-value dies and molds needed for forming and molding processes are produced by machining). According to a study by the Association for Manufacturing Technology (AMT)[5], the unmeasured contributions of machine tools and machining operations averaged nearly $200 billion per year over a five year period in the late 1990s. Although machining is a relatively mature technology, recent introduction of new high-performance materials (such as corrosion resistant titanium and nickel-based alloys) as well as new generation multi-axes complex machine tools create new challenges for machining industry to cost-effectively utilize this technology to respond rapidly changing customer demands. It has been reported that 10% increase in productivity can produce a return on investment of 1,000 times the original investment[6]. To improve productivity, machine tools must run at optimum operating conditions and autonomously avoid and correct processing errors while machining[7]. However, measurement science is lacking in **smart machining**. Specifically, due to uncertainty in material properties under machining conditions as well as highly complicated 5-axis machine structures, accurate process and machine performance models and in-process measurement techniques and robust optimization and adaptive process control are lacking to enable such autonomous operations.

There are also emerging new manufacturing technologies to address the manufacturing challenges mentioned above. Among them, Additive Manufacturing (AM) technology is a key enabler for agile manufacturing providing fast response to changes in customer demand and efficient and local production of specialized products directly from electronic communication of designs and design changes. Industry observers project the market for AM will grow to $7 billion by 2020[8]. It is predicted that biological and medical applications could make this market even larger. AM is expected to contribute to competitiveness in the quality of American designs, time to market for new designs, and is considered as enabling technology for new industries. Therefore, there is significant interest and focus on AM, including attention at the highest levels of corporate management and the federal government. However, the measurement science infrastructure needed to make **additive manufacturing** a strong alternative to other more

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[4] "*Small makes it big*," Cutting Tool Engineering, vol. 63, no. 6, June 2011.
[5] "*Producing prosperity – Manufacturing technology's unmeasured role in economic expansion*," Report by AMT, 2000.
[6] G. Ulsoy and Y. Koren, "*Control of machining processes*," ASME Journal of Dynamic Systems, Measurement, and Control, June 1993, vol 115, 301-308.
[7] M. Eugene Merchant, "*Twentieth century evolution of machining in the United States – An interpretive review*," Sadhana, Vol 28, Part 5, October 2003, 867-874.
[8] "*Manufacturing Trends 2010*," Report by Strategic Business Insights, March 2010.

established manufacturing processes is lacking. Specifically, processes and powder material are developed by machine vendors without any standard means of quantifying their performance. The lack of measurement methods and standards prevents quantitative comparisons among different AM processes, machines, and the metal powders used in these processes.

Micro-nano-manufacturing is also considered having high impact across a broad number of future manufacturing industries by a recent report identifying the manufacturing trends[8]. The same report states that manufacturers need design models, standards, and in-situ measurements in order to increase yield and reduce material waste in micro-nano-manufacturing. Measurement science is lacking in **micro- and nano-manufacturing**. Specifically, requirements for form tolerances of next generation micro products exceed the capabilities of existing machine tools producing them. New measurement science is needed to improve these capabilities. New measurement methods are also needed to characterize the dynamic performance of MEMS and NEMS which are widely used as oscillators and resonators in next generation electro mechanical systems. Considering the market for micro-nano products is expected to grow to $16-24 billion by 2020, solving this industry's measurement science problems is urgently needed.

In summary, to enable rapid, agile, and cost effective manufacturing of high-value complex products, measurement science is lacking to reduce trial-and-error process development, enable real-time performance optimization, improve quality and yield, and reduce risks of adoption for **additive manufacturing, smart machining,** and **micro- and nano-manufacturing** technologies.

Why is it hard to solve?

Additive Manufacturing: In AM, complicated material transformation processes by fast moving localized heat sources coupled with uncertainty in input powder metal properties and unknown relationship between powder properties and process and product quality makes it very difficult to control process variations and produce highly accurate and reliable products.

Smart Machining: Machining processes are very complicated interactions of workpiece material properties, tool material properties, as well as mechanical and thermal loading of these components. Due to harsh machining environment, there are many limitations on direct measurements of process making cause-and-effect relationships between process inputs and outputs very difficult to understand and model. Scientific understanding requires multi-disciplined approach, integrating diverse sources of information with substantial uncertainties, and sophisticated measurement methods and instruments. Similarly, manufacturing equipment consists of precisely interacting subsystems, rigorous characterization, measurement and control of which are highly complex and costly.

Micro- and Nano-Manufacturing: In the area of micro- and nano-manufacturing, in-process metrology must be implemented to improve the capabilities of processes and machines to meet the tolerance requirements of micro- and nano-scale products. But, measurement uncertainties of in-process measurement devices and instruments that are on the market today are close to the required form tolerances as well as ultra-high bandwidth and resolution of micro products. This creates significant challenges in integrating measurements with processes and machines.

How is it solved today, and by whom?

Some U.S. companies have made strategic decisions to gain and retain specific manufacturing capabilities for their high-value, high-technology content products and processes, thus protecting competitive advantage. For example big aerospace companies spend significant resources and efforts to learn how to process new non-conventional materials, such as titanium and nickel-based alloys, mostly by trial-and-error procedures, and keep the production of key components in house. However, for any advances in material technologies, they have to go through similarly large expenses to learn about processing these new materials. Furthermore, when they eventually subcontract some of these components to small and medium size second and third tier suppliers there is significant knowledge gap and this gap is filled with more trial-and-error type learning process.

Some other U.S. companies facing this problem choose to outsource their manufacturing operations to locations where these optimizations are done by many low-cost engineers. As an example, the late Apple CEO Steve Jobs said that there were 700,000 manufacturing contract workers in China making iPods, iPhones and iPads and the biggest problem facing Apple that prevents them manufacturing in the U.S. was finding "mid-level manufacturing engineers in the factory who are constantly tweaking and making sure the operations are functioning effectively[9]." Smart manufacturing processes and equipment will overcome this problem such that continuous adjustments will be achieved by machines incorporating all knowledge and real-time sensing about the process and adapting to changing conditions accordingly.

Why NIST?

This program is closely aligned with the EL mission to promote U.S. innovation and industrial competitiveness in technology-intensive manufacturing by anticipating and meeting the measurement science and standards needs of the U.S. manufacturing industry. The program is structured around the EL vision to be the source for creating critical solution-enabling measurement science and for critical technical contributions underpinning emerging standards that will be used by the U.S. manufacturing industry. The program has the following unique features that distinguish it from manufacturing research conducted in industry and academia: 1) emphasis on baseline performance metrics, metrology, and standards that can be applied to a broad class of measurement and manufacturing technology challenges, 2) effective use of NIST's demonstrated diverse interdisciplinary expertise, sustained commitment, and neutrality that are essential for the development of harmonized and unbiased national and international standards needed by broad sectors of industry. In short, NIST has the necessary expertise, program focus, and mission to address the high-priority measurement science challenges in smart manufacturing processes and equipment most needed by U.S. industry.

What is the new technical idea?

The new idea is to develop models, measurements, and standards enabling smart manufacturing processes and equipment by integrating models and measurements and converting them into effective decision making tools. In order to rapidly respond to changes in design, material and functionality of products the operation of these complex systems, interacting with each other, must be optimized rapidly and production should start without extensive period of operator adjustments. Multi-disciplinary measurement science capabilities are needed to capture the

[9] *Manufacturing News*, vol. 18, no. 4, March 8, 2011.

system complexities and interactions in real manufacturing environments such that these processes and equipment can be modeled accurately. Such robust predictive models are then used in process and equipment optimization eliminating the need for lengthy and costly adjustment prior to production. The measurement science contributions of the program will enable development of smart machines and processes, where most of critical decisions are taken and optimization carried out by the machines without significant operator intervention.

Additive Manufacturing: We will leverage our long standing expertise in measurement science in machining processes to develop measurement methods for validation and improvement of metal-based AM process models, to develop AM material (both powder and bulk) characterization methods and standards, and to develop test artifacts and measurement methods and standards to characterize the performance of AM processes and equipment.

Smart Machining: We will develop measurement methods and standards for integrating machining process and machine tool models with real-time measurements to optimize and improve machining processes and performance of complex 5-axis machine tools.

Micro- and Nano-Manufacturing: We will improve the quality and yield of micro-and nano-scale products through new measurement methods and improved processes by developing closed-loop process control using on-machine micro-form metrology tools for diamond turned micro optics, and by developing high-bandwidth, high-resolution optical displacement metrology system for wafer-based MEMs and NEMS.

Why can we succeed now?

There have been significant technological advances in machine controllers enabling execution of sophisticated control algorithms, in measuring instruments enabling performance measurements, and in sensors and imaging systems to enable investigation of process phenomena with more accuracy and resolution. Furthermore, in case of additive manufacturing, there is a ground swell of interest by U.S. manufacturing industry to improve the capability of this technology as evidenced by the recent initiation of an ASTM standards committee and the Additive Manufacturing Consortium. By leveraging industrial experience and knowledge, it will be feasible to develop better process models, performance evaluation methods and product quality metrics. The program staff has access to most modern manufacturing equipment, including 5-axis machine tools, ultra-precision diamond turning machine, and state-of-the-art metal-based laser sintering machine to conduct experimental studies in most efficient manner.

What is the research plan?

The program focuses on the manufacturing processes and equipment at the workstation level, which consists of the machine tool and its peripherals that convert powder or bulk material into finished parts using agile processes that can be controlled by software programmable actions. The complexity of products that are in consideration is associated with: geometry, material, size, tolerance, number of parts and functions, and the degree of customization. Within this scope, the program will accomplish its objectives by focusing on three thrust areas representing three unit processes, two of which are emerging high-impact manufacturing processes with significant potential to revolutionize U.S. manufacturing (metal **additive manufacturing**, **micro-nano-manufacturing**) and the other is by far the most basic manufacturing process (**smart**

machining) with a broad impact on other manufacturing processes (e.g., high-value dies and molds needed for forming and molding processes are produced by machining).

Additive Manufacturing: Leveraging long standing NIST expertise in material removal processes and machine tools, the program will address measurement science challenges of metal-based AM processes, equipment, materials, and system integration and optimization. Measurement methods and instruments will be developed to understand the fundamental process characteristics driving the related performance metrics and standards. Draft standards for performance evaluation methods will be developed for AM machines so that commercially available machines can be compared and selected by the users for optimum utilization as well as path for technology improvements can be identified and implemented. The system integration efforts will provide methods to integrate in-process measurement tools so that the process can be adaptively controlled to produce the parts with more and more stringent form and functional tolerances. In parallel to these efforts, the program will address measurements and standards needs for properties of powder metals used in AM as well as bulk metal properties produced by AM, to allow end users to confidently select their material and equipment suppliers.

Smart Machining: The program will develop and integrate the measurement science and relevant technologies and standards enabling smart machining. Since many of today's high technology products use advanced, non-conventional materials for improved efficiency and reliability (corrosion resistance, high temperature operations, etc), the program focuses on machining of non-conventional (hard-to-machine) materials, such as titanium alloys, nickel alloys, composites, etc. Working with a consortium of stakeholders, the program will identify high priority materials to be investigated. Machining process metrology using such materials will be demonstrated and relevant process parameters will be correlated to the measured process characteristics. The measurement data will be used to validate the physics-based models to improve the robustness and accuracy of these models such that they can be easily integrated to optimization algorithms for rapid decision making at the workstation level. Based on this research, the program will develop standard reference data representing machining process behavior for selected material-tooling combinations. In addition, smart machining systems require fully-developed machine tool performance characterization and modeling, involving complex motion of cutting tool with respect to the workpiece, in order to optimize machine operations. The new generation of multi-axes machine tools with high-speed spindles highlighted the limitations of existing machine tool standards for performance testing. The program will develop models to simulate performance testing of 5-axis machine tools, including testing under loaded (machining) conditions, assess multiple test strategies and develop data analysis methods to interpret test results. To integrate machine and process performance knowledge, the program will develop knowledge representations for machine and process performance data specifications. Such integration is targeted either within the standard smart machine numerical control (STEP-NC) environment or within commercially available Computer Aided Manufacturing (CAM) software packages. The program will partner with software developers as well as equipment vendors and end users for prototype implementation of such integration. Finally, in order to self diagnose and eliminate non-scheduled down time of machines, the program will develop measurement methods and data analysis to enable diagnostics through continuous real-time monitoring of machines and processes. The techniques and practices developed within the field of industrial equipment condition monitoring and prognostics will be adapted and tailored to machine tools and machining processes, leading to first ever machine tool and machining monitoring standards.

Micro- and Nano-Manufacturing: The program will address the challenges associated with manufacturing of miniaturized products, devices as well as miniaturized features on larger products. The size scale of interest is from nanometers to tens of micrometers, therefore the research activities address measurement science issues related to manufacturing of a broad range of manufactured products including microelectromechnical systems (MEMS), nanoelectromechanical systems (NEMS), complex micro optics, and micro mechanical systems. The cross-cutting issue in both micro- and nano-scales manufacturing is measurement methods with adequately low uncertainties that can be incorporated in the manufacturing environment for deterministic control of the manufacturing process. Due to size limitations and high bandwidth requirements, the measurement methods have to utilize non-contact instruments. This is especially true for manufacturing of micro optics with additional key requirement of protecting specular surfaces. The interactions of the instruments with the manufacturing equipment and the manufactured product have to be well characterized through modeling, uncertainty analyses and rigorous tests. This same approach will be used in the projects addressing both micro- and nano-scale manufacturing. In addition, since this thrust area is still an emerging area, a key strategy of the program will be to maintain continuous and extensive interactions with groups of stakeholders to identify changing needs and priorities and to adapt the research directions accordingly.

How will teamwork be ensured?

The program involves staff mostly from EL's Intelligent Systems Division. They have demonstrated effective team work during the execution of the previous research activities in this area. They have also established strong interactions with industrial partners over the years through periodic face-to-face and virtual meetings using telecommunication facilities. These interactions will be strengthened and leveraged to deliver maximum impact to our stakeholders. Interactions and information sharing among the project teams and team members will be encouraged through formal and informal meetings, division seminars, and utilization of common program share drive.

During the past year, due to these interactions, we have taken advantage of the synergies among the three thrust areas as evidenced by the development of AM test part using the concepts and criteria established in the development of machining test parts. Similarly plans for testing AM machine performance is being built based on the existing experience on machine tool performance testing. The instrumentation developed for machining process metrology will be the basis for developing new instrumentation for AM process metrology. In the coming years, we will be expanding the synergies between micro and nano-scale manufacturing by utilizing common ultra-precision motion metrology instruments and analytic methods.

What is the impact if successful?

Widespread implementation of program outcomes, along with the other smart manufacturing programs in Engineering Laboratory, will lead to broad benefits for the U.S. economy, give U.S. manufacturers a significant technological edge in rapidly evolving markets. Specific to the three thrusts of this program, the following future impacts are anticipated:

- Measurement science advances in the metal additive manufacturing area will enable accelerated adoption of metal additive manufacturing processes resulting in capability for art-to-part mass customization, and rapid production of high-value products including some that cannot be made by other manufacturing methods. U.S. aerospace, defense, and medical device industries and government agencies will benefit from such impacts.

- Widespread use of modeling and simulation combined with in-process measurements and associated standards, will result in realization of smart machining that will avoid costly trial-and-error practices and waste of resources, enabling optimized production of high-value products making U.S. manufacturers more competitive and innovative. U.S. aerospace, automotive, energy, imaging, and medical device industries will benefit from such impacts.
- Widespread use of measurement methods of MEMS/NEMS system performance will enable better control of nanomanufacturing processes resulting in high quality and high yield micro- and nano-scale products at low cost, leading to the realization of significant growth projections of such systems in the market place. U.S. MEMS and NEMS suppliers and users, instrumentation, optics and imaging system suppliers and users will benefit from such impacts.

Broad industry sectors will use the standards resulting from this program to:

- Reduce risks of technology adoption, make informed buy/sell decisions, and allocate resources efficiently
- Define and maintain process and equipment capabilities
- Conduct manufacturability analyses
- Optimize process and equipment performance

What is the standards strategy?

Sustained commitment and engagement with stakeholders is essential to develop consensus-based standards. The SMPE program will maintain and initiate standards leadership for the U.S. and provide critical technical contributions for development of high-impact standards within its scope. Top Standards Development Needs within the next five years to help achieve program objectives are identified as follows:

Additive Manufacturing:

- Performance metrics and measurement methods for AM systems
- Assessment metrics and methods for AM materials

Smart Machining:

- Performance metrics and measurement methods for complex 5-axis machine tools and their components (spindles, rotary heads, rotary tables, etc)
- Harmonization of national and international standards for representing machine and process capabilities and models
- Standards for measuring the performance of machine tools under loaded (machining) conditions

Micro- and Nano-Manufacturing:

- Standard methods for measuring the performance of non-contact, on-machine metrology systems for micro- and nano-scale products

Anticipated Impact: NIST measurement science research to develop measurement methods for AM systems and materials will be adopted by ASTM F42, Additive Manufacturing Technologies by 2015. These standards will be broadly used by the ever-expanding group of vendors and users of AM technology and AM products, particularly in medical and aerospace applications. Taking into account the fact that AM is a new and developing technology area, widespread adoption of standards for performance metrics and measurement methods for AM systems by industry is expected by 2020.

In the smart machining area, NIST measurement science results will be adopted by ASME B5, Machine Tools and ISO TC39, Machine Tools and incorporated into relevant standards. U.S. manufacturers of machined parts in automotive, aerospace, and heavy equipment industries, machine tool vendors, manufacturing software developers, third party service providers, system integrators, and the equipment maintenance industry will use these standards. Widespread adoption by industry is expected by 2020.

In the micro- and nano-manufacturing area, NIST results will be incorporated into standards adopted by ASME B5, Machine Tools and ISO TC39, Machine Tools by 2015. The optics manufacturing industry will be a primary user of these standards. The adoption by this industry and its suppliers is expected by 2018.

Broad industry sectors, including the automotive, aerospace, optics, heavy equipment, and medical device industries, will benefit from the standards resulting from this program. Companies will use these standards to make buy/sell decisions, define and maintain process and equipment capabilities, conduct manufacturability analyses, allocate resources, and optimize process and equipment performance.

Current and Alternate Standards Strategy: In the additive manufacturing area, substantial NIST experience in developing and structuring standards in other areas of manufacturing will be leveraged to accelerate progress in AM standards. The relevant project results will be submitted as technical contributions to the ASTM F42 Committee. The program staff will seek leadership roles in the working groups within ASTM F42. To ensure harmonization between national and international standards, program staff will also initiate interactions with the ISO committee on Additive Manufacturing (ISO TC261), through the U.S. Technical Advisory Group.

In the smart machining area, the program already has a significant leadership role in both national and international standards. NIST is a charter member of the ASME committees for machine tool performance testing (ASME B5 TC52) and related information technology standards (ASME B5 TC56). NIST also serves as the Secretariat of the ISO sub-committee for developing standard test conditions for metal cutting machine tools (ISO TC39/SC2). In this role, NIST has been instrumental in developing and maintaining more than 60 ISO standards related to machine tool performance testing (including turning, milling, drilling, grinding, and electro-discharge machining). SMPE program research will lead new standards and amendments to existing standards to address the needs of smart machine technologies.

The SMPE program will also expand its active participation in standards committees in industrial automation, condition monitoring, process control. The program also recognizes that technical specifications, technical reports, and best practices guidelines published by Standards Development Organizations (SDOs) are effective outcomes that augment formal standards to further spread standards-based solutions to small and medium size manufacturers.

The SMPE program will also initiate industry consortia and working groups to start new standards and other dissemination mechanisms in collaboration with stakeholders, including:

- Initiation of an industry consortium for machining non-conventional materials to disseminate NIST-developed robust methods for process performance
- Initiation of an industry working group in nanomanufacturing to prioritize and review standards activities
- Initiation of an industry working group in optics manufacturing for developing robust in-process standard measurement methods, as well as traceable reference artifacts

Fit to Criteria for Selecting Standards Development Involvement: The standards outlined above are high-priority needs for technology-intensive manufacturing processes and equipment and therefore fall directly in line with the EL mission. The broad industry sectors identified above play key roles in the development of these standards and will benefit from these standards by implementing smart manufacturing technologies that improve responsiveness, machine utilization, and productivity.

ASME and ASTM are the two primary SDOs that provide standards for manufacturing processes and equipment. The SMPE program will interact and collaborate with these organizations to result in efficient and effective development of needed standards. Involvement with related ISO committees in parallel with the national SDOs will speed the adoption of U.S. views in the international arena, which is critical for global competitiveness of U.S. manufacturers.

Actual Impact: NIST technical contributions and standards leadership have recently resulted in:

- First ever international standard on testing a machine tool's measuring capability (for on-machine measurements of parts) (ISO 230-10:2011)
- Revised, restructured, and harmonized international standard on geometric accuracy of machine tools (ISO 230-1:2012)
- First ever international standard on testing machine tool capability for batch production (ISO 26303:2012)

These standards are used by major U.S. manufacturers, including Boeing, Caterpillar, Pratt & Whitney, Hardinge, Precitech, Moore Tools, and their suppliers, to make machine tool buying/selling decisions, define equipment and process capabilities, and improve equipment and process performance. These standards also enable technology providers to develop generic measurement, analysis and process optimization tools that help manufacturers to achieve significant cost reductions and quality improvements.

In general, manufacturing process and equipment standards are not regulatory standards. Therefore they are not typically adopted by any level of government in the U.S. However, agencies such as DLA, DoE, and NASA use these standards for their production and procurement. The only regulatory use of these standards in the U.S. is in the context of export control regulations. Export control regulations are revised periodically to align with new manufacturing standards, as well as to address new manufacturing processes and equipment.

How will knowledge transfer be achieved?

The outputs and the knowledge generated from the program research activities will be disseminated to customers and stakeholders through participation in the standards committees and activities, through participation in academic and industrial conferences, through focused workshops, future technology road mapping activities, seminars and webinars, as well as through journal articles, NISTIRs and conference proceedings. For the areas where there are no active standard committees, stakeholder consortiums and consultative committees will be formed to enable intensive and continuous communications for effective exchange of research results and industry perspectives.

MAJOR ACCOMPLISHMENTS

In additive manufacturing:

Impacts

- ASTM F2792-10 *Standard Terminology for AM Technologies* to enable uniform use of terms among AM users, vendors, researchers, and media
- ASTM F2924-12 *Standard Specification for AM Ti64 with Powder Bed Fusion* used by the buyers and suppliers of such products for defining requirements and ensuring component properties

Outcomes

- New NIST/EL technical expertise/capability to produce complex parts using Direct Metal Laser Sintering (DMLS) metal additive process and to pursue research on AM.
- Obtained a leadership role in ASTM F42 by membership in Executive Board, proposed a, strategic approach, and framework for AM standards.
- New draft standard for test artifacts for assessment of AM machines and processes to enable vendors and users of AM technology making quantitative comparisons among different machines and processes, and reducing risks of selecting appropriate technology for the production needs.

In smart machining:

Impacts:

- First ever international standard on testing machine tool capability for batch production (ISO 26303: 2012) to enable users to identify the capability of machine tools producing a batch of products within specified dimensional tolerances.
- Revised and harmonized international standard on geometric accuracy of machine tools (ISO 230-1:2012) to be more applicable for checking machine's functional capability so the U.S. manufacturers' needs and requirements are represented in this international standard.
- First ever international standard on testing a machine tool's capability for on-machine measurements of parts (ISO 230-10: 2011) for in-process qualification of machined parts

Outcomes:

- Developed new draft of revised standard for testing geometric accuracy of axes of rotation (ISO 230-7) introducing new concepts applicable for machining complex parts using rotary tables and rotary heads, which were lacking in the original version of the standard.
- EL staff contributions resulted in the development of following Draft International Standards
    - ISO/DIS 230-2, "Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning of numerically controlled machine tool axes"
    - ISO/DIS 10791-6, “Test conditions for machining centres—Part 6: Accuracy of speeds and interpolations”
    - ISO/DIS 10791-7, "Test conditions for machining centres – Part 7: Accuracy of finished test pieces"
- New NIST Virtual Machine Tool model used by the international STEP-NC Manufacturing Group (KTH, Step Tools, Sandvik, GE Energy, University of Bath, IQL, ASME, Ameritech, Airbus, and Pratt&Whitney) to predict accuracy of machined parts.

- Smart Machining Consortium (Boeing, Pratt&Whitney, UTRC, GE Aviation, Lockheed Martin, BAE, General Dynamics, Kennametal, GM, Ford, Caterpillar, EWI, TWS, DP Technology, NCDMM, and CCAT) was established and accepted NIST experimental plan to generate reference data sets for titanium machining.

In micro- and nano-manufacturing:

Outcomes:

- Capability of diamond turning of optics to conduct research on closed-loop control of micro optics manufacturing with form accuracy of about 200 nm and surface finish of 40 nm.
- Improved capability for nano-scale motion microscopy for better characterization of MEMS/NEMS performance.
  - Upgraded with confocal detection, reducing measurement noise
  - Measurements of MEMS/NEMS displacement at vacuum (10^{-5} torr)
- NIST leading an industrial team (Alio, Lion Precision, Aerotech, Corning, Newport, Pratt&Whitney, nPoint, Kriterion, Precitech, 3M, Moore, Hardinge, and LLNL) developing new draft standard for testing ultra-precision positioning systems that are used in on-machine form metrology instruments.

Recognition of EL:

The project activities associated with the SMPE program provide significant NIST/EL visibility within the manufacturing community due to their continuous interactions with stake holders and timely delivery of critical technical solutions. The examples such recognition include membership in the Technical Advisory Group of the MTConnect Institute; various leadership roles in the standards committees including ASME B5 (Machine tools)- Chair, USTAG to ISO/TC39, ISO TC39 (Machine tools) – Secretary ISO/TC39/SC2, as well as growing leadership roles in ASTM F42 (Additive manufacturing); leadership roles of organizing 11th CIRP conference on modeling of machining operations (2008), 3rd International Conference on Micromanufacturing (2008), annual SME Micromanufacturing conferences (2008-2010), 9th International conference on machine metrology (2009), ASME Symposium on "Advances in micro-scale manufacturing and metrology systems" (2010), NIST Advanced Manufacturing Workshop (2009), and NIST Extreme Manufacturing Workshop (2011). Furthermore, the researchers of SMPE program have received various awards over the last several years including DoC Silver Medal (2006), NIST Bronze Medal (2008), Best Poster runner-up in NIST Sigma Xi postdoctoral poster presentation (2009), NAMRI/SME Outstanding Paper award (2009) as well as Certificates of Appreciation for dedicated service to ASME Codes and Standards (2009).

During the last year, new recognitions were added to the above list. S. Moylan received Society of Manufacturing Engineers (SME) 2012 Young Manufacturing Engineer Award. K. Jurrens joined the Executive Committee of ASTM F42 that establishes the guidance and direction to other F42 subcommittees. J. Slotwinski became the Task Group Lead in ASTM F42.01 Test methods subcommittee. K. Jurrens was invited to participate in the Joint Defense Manufacturing Technology Panel (JDMTP) for the development of DoD Roadmap for metal-based additive manufacturing. J. Slotwinski was invited to be a member of the Organizing Committee for the 2012 National Summit on Additive Manufacturing. J. Slotwinski and R. Ivester served as the Session Chairs in the 2102 ASME International Manufacturing Science and Engineering Conference (MSEC). A. Donmez served as an invited Panelist in the 2nd G. Salvendy International Symposium on Frontiers in Industrial Engineering at Purdue University. A. Donmez served as a member of the Ph.D. Committee in the Department of Mechanical

Engineering at Carnegie Mellon University. R. Fesperman received a letter of appreciation from Aerotech, Inc. for his efforts in ultra-precision motion metrology.

In addition, SMPE efforts in nanomanufacturing have received NIST-wide recognition as evidenced by invitation of Jason Gorman to be a panelist during the visit of the NIST Assessment Panel on Nanomanufacturing. Finally, MicroManufacturing trade magazine published an article by A. Donmez describing the SMPE program in its March/April 2012 issue.