SMART MACHINING RESEARCH
AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

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ABSTRACT

This paper presents an overview of collaborative research activities conducted by staff of the Manufacturing Engineering Laboratory at the National Institute of Standards and Technology to address the enabling metrology and standards infrastructure needed for smart machine tools and smart machining processes. The research highlighted in this paper is directly applicable to the context of Small Lots Intelligent Manufacturing and contributes to technology advancements that will improve the productivity and competitiveness of U.S. manufacturers. Machining processes, such as milling and turning, are a critical infrastructural competence, enabling the manufacture of products ranging from consumer goods to airplanes. Improvements in machining technologies have a highly leveraged impact on the economy and national security. Advanced machining processes and machine tools enhance productivity and product quality, while allowing for the manufacture of ever more complex parts. U.S. manufacturers are facing numerous challenges in the area of machining, such as higher accuracy requirements, shorter lead times, smaller batch sizes, outsourcing, and intense global competition. This environment does not allow for costly and time-consuming trial runs, off-line part inspections, and on-going adjustments to achieve required part accuracies and process efficiencies.

To remain competitive, manufacturing requires accurate and reliable machines and processes whose characteristics are known and guaranteed for a wide variety of tasks and conditions. Productive, high-quality manufacturing will increasingly rely on smart machining: the ability to produce the first and every subsequent part on time and to specification through a science-based understanding and monitoring of the available machining processes and equipment with no significant time spent on process development or setup.

INTRODUCTION

Increasing international competition and the rising costs of operations force today's machining industry in the United States to pursue higher levels of efficiency and effectiveness. Additionally, machining businesses must cope with more complex parts, more expensive equipment, advanced new engineered materials, higher accuracy requirements, finer surface finish requirements, smaller inventory objectives, smaller batch sizes, and pressure for shorter time to market. To successfully compete in this marketplace, manufacturers require flexible, adaptable, accurate, and reliable machine tools and machining processes with known, optimized, verifiable behavior. Specifically, this means being able to produce complex parts in small lots to known geometries and tolerances without resorting to costly and time-consuming trial runs, off-line part inspections, or on-going adjustments. To achieve this goal, machine tool users must be able to predict and compensate for the many sources of error that change over time and are often task specific. Productive, high-quality manufacturing will increasingly rely on the concept of "smart machining," defined as the ability to produce the first and every subsequent part on time and to specification through a science-based understanding and monitoring of the available machining processes and equipment with no significant time spent on process development or setup. Research aimed at developing the necessary infrastructural capabilities to realize this capability is presented in this paper. The "first part correct" vision of the smart machining research has direct application to the concepts needed for Small Lots Intelligent Manufacturing.

This paper presents an overview of collaborative research activities conducted by staff of the Manufacturing Engineering Laboratory (MEL) at the National Institute of Standards and Technology (NIST) to address the enabling metrology and standards infrastructure needed for smart machine tools and smart machining processes. MEL research activities for smart machining cover four broad areas of technical development: machining knowledge, adaptive process planning, predictive modeling, and monitoring and adaptive control of machining. MEL organizes these activities as components of three research programs: Smart Machine Tools [1], Predictive Process Engineering [2], and Intelligent Open Architecture Control [3].

Within these programs, MEL researchers contribute to the four technical areas listed above through the development of measurements, methods, and testbeds, as well as through leadership and participation in industry forums and standards bodies. Measurements research addresses the development and provision of metrology expertise and state-of-the-art instrumentation for measurements relevant to manufacturing, including form and dimension, force, vibration, temperature, and material properties. Additionally, developments of methods provide enabling technology to improve the machining process, part accuracy, and machine reliability. Testbeds provide a means to validate standards specifications and to benchmark proposed models and methods. Participation in industry forums through the attendance and organization of workshops and conferences assists in the identification of industry needs and in fostering collaborations. NIST activities in the areas of machine tool metrology, manufacturing process metrology, open architecture control, condition-based monitoring and maintenance, and smart sensor systems will be discussed, as well as how these contribute to a future vision of smart machining and Small Lots Intelligent Manufacturing.

SMART MACHINING

Smart machining encompasses a broad range of capabilities with complex interrelationships. In a workshop jointly sponsored by NIST and the National Science Foundation (NSF) [4] in December 2002, a wide range of participants from government, industry, and academia were brought together to define the expected capabilities of a smart machine tool and to outline priorities and next steps for achieving this vision. While this paper cannot present the full guidance put forward during the workshop, a summary and representative sampling are provided to establish the context for the remainder of the paper.

The following wish list of machining capabilities would alleviate many of the difficulties faced by machine tool users and enable them to meet the challenges presented in today's manufacturing marketplace. Machining companies must be able to make parts better, faster, and cheaper. The possibility for crashing a machine tool must be completely removed. Setup time must be completely eliminated as a cost factor. The need for human intervention in machining processes must be eliminated. Machine tools must be able to calibrate themselves and compensate for inaccuracies automatically. Machine tools must be able to monitor and diagnose themselves autonomously and communicate this information in a standardized unambiguous way. The need for preventative maintenance must be monitored directly by the machine tool and scheduled accordingly. The quality of parts produced on a machine tool must be measured, determined, and certified directly on the machine tool during or immediately following machining operations. In an ideal world, a machine tool would be capable of electronically receiving part drawings and automatically producing parts of certified acceptable quality ready to ship without requiring human labor. This machine tool would know its own capabilities in terms of performance, availability, and condition and be able to communicate these capabilities, determining whether it can machine a particular part and at what cycle time. The machine tool would be capable of determining how to machine a part in an optimal manner, including determination of the necessary setups, fixturing, tools, and elementary machining steps with optimal process parameters and tool change policies. The machine tool would monitor, diagnose, and optimize itself using smart sensors with standardized interfaces to monitor and control machine and process conditions, diagnose problems, and compensate for errors. The machine tool would know the quality of its work by developing in-situ part inspection strategies based on part geometry and required tolerances, and estimating the resulting part tolerances from in-process data and in-situ part measurements. Finally, the machine tool would learn by incorporating new information through a modular architecture with standardized interfaces, using data obtained during and after machining in combination with additional information from external sources to achieve required capabilities.

MACHINING KNOWLEDGE

To assist in developing the required capabilities for smart machining, MEL staff perform collaborative research in measurement methods and standards addressing the capability and condition of machine tools as part of the Smart Machine Tools program. This research encompasses characterization of machine performance, predicting part tolerances from performance characterizations, and standardized machine tool performance data formats to enable universal exchange of machine tool capabilities [5].

Through leadership in national (ANSI) and international (ISO) standards development in the area of characterization of machine performance, NIST contributes to the development of models, parameters, and tests for specification, evaluation, and validation of the performance of machine tools. Specific performance criteria of machine tools covered by these standards include geometric errors, thermal errors, stiffness, hysteresis, machine dynamics, axis of rotation, contouring, noise, and reliability. These capabilities will enhance companies' abilities to specify, evaluate, accept, and compare machine tool performance capabilities, resulting in improved decision-making capability for machine tool purchases. Through monitoring and control of machine performance and compensation for systematic errors, control of part quality can be improved directly on the machine tool.

Through the development of methods and models for linking machine tool performance parameters to expected part tolerances, effective analysis of the capability of a particular machine tool to achieve required tolerances for a particular part can be achieved. Using these methods and models, designers and planners can collaborate through simulation and virtual machining to pull together many diverse error sources and effectively determine the complex task-specific effects on part accuracy. By adjusting the design, machining process plan, machine setup, fixturing, tooling, environmental control, and process selection, designers and planners can effectively determine the best combination of processes, materials, and machine settings to achieve the required level of part accuracy without performing costly on-machine experimentation.

Virtual machining capabilities are facilitated by the expression of machine tool performance data in standardized Extensible Markup Language (XML) formats, which can then be communicated across intranets or the Internet. These standardized XML formats contribute to improved capability in a variety of related areas, including electronic commerce, resource allocation, performance tracking, and maintenance. In the absence of these formats, systems and applications cannot exchange machine tool data, and large companies frequently waste precious resources on duplicate and incompatible efforts to address different aspects of larger problems. Through leadership in the national standards arena, MEL researchers initiated and are developing standardized, unambiguous XML data formats to describe and communicate machine tool properties, such as footprint, configuration, and performance capabilities, as well as machine tool performance test data, results, and setups. In the future, these standards will facilitate the ability for machines to autonomously identify and develop knowledge of their own capabilities.

ADAPTIVE PROCESS PLANNING

MEL research directed at improving process planning capabilities for smart machining encompasses the development of standardized data formats for communication with machine tools as part of the Intelligent Open Architecture Control program, as well as the development of standardized process knowledge and process specification formats under the Predictive Process Engineering program.

To develop a process plan, the process planner must determine the required elementary machine tasks from a high-level description of the part. This task includes determining the required setups, fixturing, and tools. Furthermore, the planner must determine appropriate process parameters, such as cutting feeds and speeds, as well as an effective tool change policy. Traditionally these tasks are not completed in a fully integrated manner. In the future, these decisions will be completed autonomously. To facilitate this transition, the formats by which this information is communicated must be standardized so that successful communication can occur across a wide variety of participants. These standardized formats must be enriched to communicate more information than today's conventional numerical control (NC) code includes.

Through leadership in standards communities for controller technology, MEL researchers contribute to the development of the ISO 14649 standard [6], commonly known as STEP-NC (STandard for the Exchange of Product model data – Numerical Control). STEP-NC provides a rich description of the product and process data, including the geometry to be realized, tolerances to be achieved, part and tool properties, as well as design-related information such as designer intent and product functionality. These data enrichments provide the machine tool controller with the necessary information to implement smart machining capabilities. MEL researchers are working to ensure broad acceptance of STEP-NC results through participation in the Open Modular Architecture Controller (OMAC) industry users group.

Through leadership in standards communities for process knowledge and process specification, MEL researchers developed and contribute to the standardization of the Process Specification Language (PSL), formally standardized as ISO 18629 [7]. PSL provides a standard, rigorously defined data representation for manufacturing process information. Through development, prototype implementation, and standardization of PSL, MEL provides an exchange language that allows for the representation of all relevant manufacturing process information independent of any specific application and that defines unambiguous and rigorous semantics for the concepts being represented. PSL consists of a modular, extensible data model that captures the concepts required for process specification. The data representations and integration methods will provide necessary components to enable complete use of manufacturing knowledge and process-related data throughout the product lifecycle.

PREDICTIVE MODELING

Replacing conservative handbook data with optimized tooling solutions and cutting parameters obtained through predictive modeling dramatically improves the ability for controlling and adapting process behavior at the machine tool. This capability requires decision making from a more fundamental scientific basis, rather than the typical handbook data and empirical investigation approach commonly used today. Some of the scientific understanding of machining addressed by the MEL Predictive Process Engineering program includes complex process dynamics in high-speed machining and chemical-thermal-mechanical aspects of machining process behavior. Through the combination of models based on these scientific understandings and appropriately placed sensors, the controller can make decisions autonomously and process parameters can be adjusted adaptively based on measurements of process behavior. This combination enables dramatically more aggressive machining strategies to be developed offline and implemented in the controller while avoiding the potentially disastrous consequences of operating on the edge of machine and process capability.

The dynamic stability of long-overhang cutting tools for high speed machining provides one example of this type of modeling capability. As spindle speeds increase during machining, the frequency of engagements of individual cutting tool teeth into the workpiece often exceeds the critical vibration frequencies for long cutting tools. With the increasing complexity of machined parts, some part features may require long-overhang cutting tools to avoid damaging other part features or to minimize the number of required setups. To effectively use moderately long cutting tools, it is necessary to attain an analytical understanding of the cutting tool response to the frequency of the tool-workpiece engagements. In a manner analogous to the natural frequency of a tuning fork, a cutting tool has a natural frequency at which it will vibrate. By selecting spindle speeds such that the frequency of tool-workpiece interactions is an integer multiple of the tool's natural frequency, the tool will vibrate in a stable manner. This stable vibration is essentially a standing wave along the length of the tool. As such, the endpoints of the tool remain more or less stationary. If the tool-workpiece engagement frequency deviates from one of these critical values, the tool will chatter. If the tool chatters, potentially disastrous consequences can occur, including severe damage to the spindle bearings. High-speed spindles often have ceramic bearings instead of the more common steel bearings. Ceramic bearings are more likely to fail catastrophically than steel bearings. So maintaining the correct frequency or spindle speed is critical to maintaining proper machine operations at high removal rates in most high-speed machine tools.

Through careful measurement of the dynamic response of the combination of a particular cutting tool mounted in a particular spindle, it becomes possible to construct a stability diagram as shown in Figure 1. In this diagram, the white region indicates combinations of process parameters that result in stable cutting, while the gray regions result in unstable cutting (i.e., chatter). Using a stability diagram, it is possible to determine the maximum safe axial depth of cut for a given spindle speed. Since adjusting the length of the tool overhang (as mounted in the tool holder) moves the location of the stable regions, or "stability lobes," to the left or right, it is possible to adjust the length of the tool overhang so that the peak of the stability lobe occurs near the maximum speed of the machine tool spindle. This relationship can lead to counter-intuitive results. Lengthening the overhang of a cutting tool would normally make one believe that the tool would be more likely to chatter. However, this adjustment could also shift the stability lobe to a preferred spindle speed matching the dynamics of that machine tool. Therefore through use of dynamic measurements and a stability diagram, it becomes possible to select an optimal combination of tooling, tool overhang length, spindle speed, and axial depth so as to maximize material removal rate.

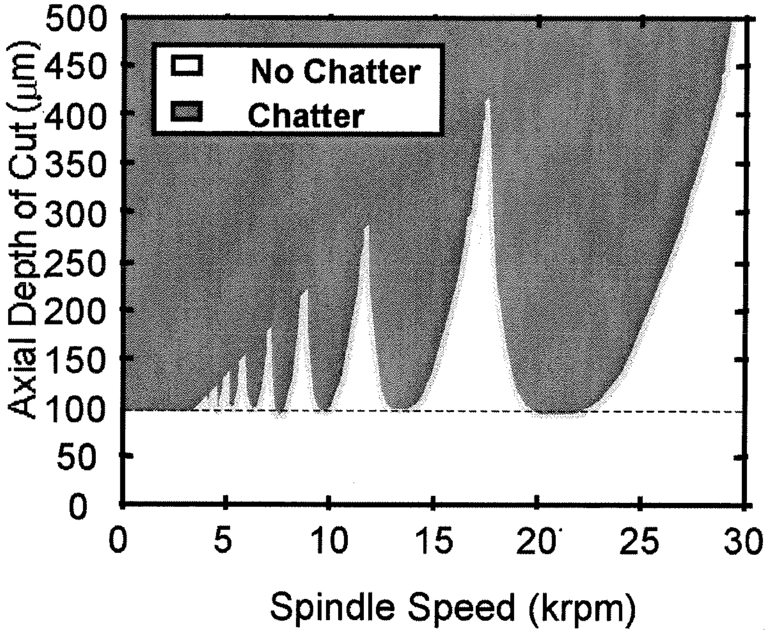

Figure 1. Sample stability lobe diagram for a milling process.

Through application of a technique called Receptance Coupling Substructure Analysis (RCSA) to the modeling of dynamic response, MEL researchers have demonstrated the capability to predictively model the dynamic behavior of a milling process based on an offline, independent measurement of the dynamic response of the machine spindle and the cutting tool. As such, the benefits of dynamic analysis can be realized without needing to perform new measurements every time the overhang length of a cutting tool is adjusted in the toolholder. Based partly on these research results, a collaborative project with the U.S. Navy demonstrated dramatic cost reductions in the fabrication of submarine propellers with one-third the total cycle time and ten times the maximum material removal rate in comparison to prior fabrication techniques [9].

Further research at MEL is aimed at achieving a better understanding of material behavior under the high strain-rates and high heating-rates typical of machining operations. This scientific understanding will enable development of an improved capability to model and predict thermal aspects of material removal. NIST has developed a unique measurement facility called the NIST Pulse-Heated Kolsky Bar for high strain rate, high temperature material properties to enable acquisition of the necessary scientific understanding of material behavior during machining [10]. Direct measurement of material properties at high strain-rates (10^4 s^{-1} to 10^6 s^{-1}) and high heating-rates (5,000 °Cs^{-1} to 10,000 °Cs^{-1}) provides a proper scientific foundation for building accurate modeling and simulation capabilities for machining processes. Additionally, through the Precision Machining Testbed, NIST has developed unique capabilities for microscopically (2 μm to 5 μm per pixel) measuring cutting zone temperatures synchronously with visual spectrum high-speed (2500+ frame per second) camera observations of chip formation. This capability combined with force measurements provides the ability to validate material model-based simulations of machining based on data from the Kolsky Bar. The results of high-resolution simultaneous infrared and visual high-speed video cutting experiments together with transmission electron microscopy (TEM) observation of grain transformations in cut chips and workpieces provides further validation of the cutting models [11]. This research will provide the necessary scientific foundations for reliable predictive modeling of the machining process for a broad range of materials, tools, and machines, in order to eliminate the need for costly and time-consuming on-machine experimentation for process development.

MONITORING AND ADAPTIVE CONTROL OF MACHINING

Enabling research in the MEL Smart Machine Tools program lays the foundation for machine tools that can monitor, diagnose, and optimize themselves using smart sensors with standardized interfaces to monitor and control machine and process conditions, diagnose problems, and compensate for errors. This research aims to eliminate the need for off-line quality control through development of in-situ part inspection strategies based on part geometry and required tolerances, and methods for estimating the resulting part tolerances from in-process data and in-situ part measurements. Additionally, based on the results of this research, the machine tool would be capable of monitoring its condition, detect impending failure, diagnose problems, and react appropriately to avoid breakdowns or damaged parts.

MEL research in the areas of smart sensor systems, sensor integration, and sensor networking works to provide sensors with standards-based plug-and-play interfaces for self-identification, dynamic networking capability, and robust data processing. MEL efforts to initiate and develop standardized solutions for these capabilities through the IEEE 1451 set of smart sensor interface standards have enabled new capabilities for more than 2000 sensor manufacturers to communicate with more than 50 different network protocols. MEL has implemented prototype solutions based on the IEEE 1451 standard for such applications as remote monitoring of the operating characteristics of a machine tool spindle. Further research in related areas for improved techniques for analysis of sensor data will impact applications such as monitoring of machine health (for condition based monitoring and maintenance). A joint project with industry and academia is focused on "smart spindle" capabilities to minimize machining errors due to spindle motions and to prevent spindle failure.

For the development of on-machine part inspection and certification strategies, MEL researchers plan to pursue advancements on several fronts as a future activity. This is an area of future growth for the program. In particular, several approaches are relevant to this topic, including use of on-machine part probes to detect errors due to setup and machining processes, use of a reference part for providing traceability of part measurements through comparisons, and realization of fully independent measurement systems using robust, fast, independent measurement techniques with high point densities for complex geometries. The ultimate aim is to develop capabilities for machine self-calibration and modeling of errors to reduce the number of part measurements and scrap of expensive parts.

Finally, through the development of modular architectures with standardized interfaces allowing for seamless system enhancements, together with the ability to obtain additional information from external sources, a smart machine tool of the future would be able to learn new capabilities based on experiences and outside development of new techniques.

CONCLUSION

Now is an opportune time for the development and realization of smart machining capabilities. Several critical enabling technologies are now available or under development. Cheap sensors and computing power together with simplified networking, internet, and wireless capabilities are now available. PC-based open-architecture machine controllers with standardized interfaces are becoming capable of accepting high-level product descriptions providing rich information about the task to be accomplished. Standardized data formats throughout the manufacturing enterprise dramatically facilitate effective interoperability. Physics-based models with associated sensors and identification techniques are being developed, and advanced simulation techniques are being validated. These technical developments provide a strong foundation for the realization of smart machining. Furthermore, industry faces demands for improved accuracy, productivity, and reliability, which provides further support for the strong demand for these capabilities. This is a critical, pivotal time for the U.S. manufacturing industry in general, and machine tool builders and users in particular. Through carefully coordinated collaborative research efforts such as those discussed in this paper, the U.S. machining industry stands on the brink of a new era of efficient, effective, flexible capabilities for successful competition in the increasingly global marketplace.

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