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**THE CERAMIC MANUFACTURABILITY CENTER—
A NEW PARTNERSHIP WITH U.S. INDUSTRY**

V. J. Tennery and T. O. Morris

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THE CERAMIC MANUFACTURABILITY CENTER— A NEW PARTNERSHIP WITH U.S. INDUSTRY*

V. J. Tennery and T. O. Morris†

ABSTRACT

The Ceramic Manufacturability Center (CMC) is a new facility at the Oak Ridge National Laboratory (ORNL) established as a direct response to current U.S. industry needs. It was created as part of a highly integrated program jointly funded by the U.S. Department of Energy Defense Programs, Energy Efficiency and Renewable Energy, and Energy Research divisions. The CMC is staffed by personnel from ORNL and the Y-12 Plant, both managed by Martin Marietta Energy Systems, Inc. (Energy Systems). Its mission is to improve the technology needed to manufacture high-precision ceramic components inexpensively and reliably. This mission can be accomplished by strengthening the U.S. machine tool industry and by joining with ceramic material suppliers and end users to provide a path to commercialization of these ceramic components.

1. BACKGROUND

Ceramic materials have been developed to the point where their properties are sufficient to be seriously considered for use in advanced engine applications. Use of these materials, particularly silicon-based ceramics including silicon nitride and silicon carbide, in vehicular propulsion engines can provide higher fuel economy, greater engine reliability, greater fuel tolerance, adaptability to alternate fuels, and reduced petroleum imports and lower emissions. The essential materials science research and development (R&D) necessary to demonstrate the required mechanical and physical properties

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has been extremely successful due to Department of Energy (DOE) efforts that have been highly focussed in U.S. companies during the past 10 years. This has occurred due to substantial U.S. government support and leadership through DOE programs such as the Ceramic Technology Program (CTP). Engineering evaluations of ceramic components in a variety of advanced heat engines have clearly shown the performance advantages these materials can provide to diesel, gasoline, and gas turbine engines.

The production of cost-effective ceramic components is heavily dependent on the machine tool industry. Since effective ceramic machining involves the use of new higher stiffness machine tools, the health of the U.S. machine tool industry impacts ceramic machining. Unfortunately, the U.S. machine tool industry has experienced a long-term decline in market share because of aggressive foreign competition and diminishing technical advancement among a reduced number of U.S. companies. This decline of the machine tool industry and the vulnerability to petroleum supply are also important in light of the recent world changes leading to the elimination of nuclear weapons production in the United States. An effort to maintain national manufacturing capabilities will be critically dependent upon the machine tool industry. Further, many special skills and capabilities have been developed in the weapons production organizations over the years of classified component production, which are particularly relevant to helping solve the problems of the machine tool industry and the advanced materials industries. Y-12 Plant management has dedicated funding and personnel to the Ceramic Manufacturability Center (CMC) in order to maintain manufacturing capability and to assist the above industries by transferring advanced manufacturing technology to them.

The transportation sector's almost total dependence on petroleum contributes heavily to the resulting U.S. need for imported oil and the negative balance of trade. This, in turn, creates a major adverse impact on the nation's economy and results in an already demonstrated vulnerability to petroleum supply disruptions. Substantial improvements in the fuel economy of engines can reduce this dependence upon petroleum imports. Significant improvements in the fuel economy of vehicle engines will require substantial changes in the materials used and, in some cases, the basic design of these engines. Structural ceramics have been demonstrated to provide major improvements in the fuel economy of both internal combustion and gas turbine engines. A major impediment to the use of these materials in current types of vehicular engines is the high cost of ceramic engine components relative to metal components and the uncertainty of large-scale manufacturability. A major contributor to these current costs is the machining or finishing process required to make the part comply with the specified surface and dimensional

specifications. Recent analyses have shown that the cost of machining a typical ceramic engine component can represent as much as 70% of the manufacturing cost.

The Secretary of Energy was recently directed to assess the capabilities of the national laboratories relative to the machine tool industry and to recommend appropriate action for enhancing interactions to further promote the competitiveness of this critical industry. Oak Ridge National Laboratory (ORNL) is well known for research in materials and material characterization. One of the prime avenues of interaction with U.S. industry has been through the High Temperature Materials Laboratory (HTML), which has been operational at ORNL since 1987. It currently includes six user facilities which contain a complete suite of instruments for characterizing the surfaces, structure, and properties of materials. The CMC is located in the HTML to take advantage of the existing material characterization capability and expertise of the User Center staff in working with U.S. industry. In addition, ORNL has been a leader for over a decade in U.S. government-sponsored research on structural ceramics, with primary emphasis on properties of these new materials, which are critical to their engineering use in advanced engines.

2. U.S. INDUSTRY NEEDS

An Energy Systems needs analysis was recently conducted to determine the areas in which major advances are required to improve the economics of manufacturing structural ceramic components. The most significant needs identified in an off-site analysis meeting, in priority order, are:

1. **A basic understanding of the grinding process and other high-speed materials removal processes is needed before orderly and systematic advances can be made in reducing ceramic machining (material removal) costs.**

There are several relatively new material removal processes that should be applicable to machining structural ceramics. These processes are distinctly different from conventional grinding, which uses superabrasive grinding wheels. These wheels have diamond or cubic boron nitride grit bonded onto their rims using a matrix such as a resin, a vitrified ceramic, or a metal. Other unconventional machining methods, such as abrasive jet machining, use an abrasive that is carried in water or a special liquid. This mixture impinges upon the workpiece at very high velocity in the form of a jet. In another type of system, an ultrasonically driven head vibrates very close to the workpiece as an abrasive-filled liquid is carried

to the surface of the workpiece around a desired shaped tool. The high-frequency vibrations of the head and the abrasives erode the ceramic to the desired dimensions. Other newer techniques include the use of very special cutting fluids and the application of an electric field in the vicinity of the wheel-workpiece contact area. For many material systems, these so-called "electrochemical and/or electrodischarge-assisted" processes are reported to provide relatively high rates of material removal. Also, use of laser energy to heat a ceramic material immediately in front of a cutting tool has been reported to be capable of greatly accelerating high material removal rates, while providing minimal surface damage.

Areas for better understanding and optimization include: grinding media (wheels, abrasives, matrix media for the abrasives, and coolants, for example); machine tool and grinding wheel properties (stiffness definitions, quantitative requirements, and measurement standards and protocols); structural ceramic uniqueness in machining processes (specific understanding of how the composition and, more importantly, how the microstructure and the phase composition relate to the optimum machining parameters); and optimum ways of using laser energy to greatly accelerate the machining process.

2. **There is a major need for automatic, in-process inspection of both the workpiece being machined and the cutting component, i.e., grinding wheel, cutting tool, etc., and implementation of appropriate feedback and control systems on the machine tool that automatically bring the workpiece to the required dimensions.**

The ideal situation for rapid and accurate machining of structural ceramics is a completely automated system in which the critical dimensions are continuously measured in real time while the component is being produced. This requires the ability to measure dimensions of an object while mounted in the machine tool with an accuracy of $<0.5 \mu\text{m}$ and a repeatability of $<0.25 \mu\text{m}$. It also requires that the abrasive carrier, i.e., the grinding wheel or cutting tool, etc., must have the same accuracy and repeatability. These requirements place major demands upon the dimensional stability of the machine tool itself, in addition to the abrasive carrier, such as a grinding wheel. Such accuracy and repeatability have only been achieved to date on a few experimental machines in the United States, Japan, and Germany. It is anticipated that major effort will be required to achieve the required control in a reliable and cost-effective manufacturing system.

3. **Overall Intelligent Processing (IP) is required to achieve robust manufacturing systems, i.e., systems that are to a great degree self-correcting when deviations from nominal conditions occur during the manufacturing process. The development and application of IP systems is viewed as a long-term objective in the structural ceramic manufacturing industry. Such systems are mandatory if high-volume economical production of ceramic products is to be achieved.**

This objective includes the incorporation of sensors that monitor the operation of the machine tool so that operating parameters can be adjusted automatically to produce components to the required dimensions. The goal is to achieve dynamic adjustment during machining via use of mathematical and heuristic (rule-based) models. These models incorporate the effects of all the measured variables into the fabrication of the workpiece. IP has been shown to be a powerful manufacturing optimization tool for the production of a wide range of products made from metals and polymers. Its application to structural ceramic manufacturing requires understanding of the relationships between all of the major variables which determine the attribute that is to be controlled in the manufacturing process. The knowledge required to accomplish this is not currently available for various machine tool classes, nor for different types of structural ceramics, such as silicon nitride, silicon carbide, alumina, and zirconia. IP can only realistically be applied after the successful accomplishment of Nos. 1 and 2 discussed earlier. It is viewed as the final stage of development in a manufacturing process, where sufficient information is available to truly optimize a manufacturing process.

3. STRATEGY AND INDUSTRY PARTICIPATION

It is necessary to create an environment in which a broad range of people from government, educational institutions, and industry, who are skilled in ceramic manufacturing and in machining difficult materials, such as special metal alloys, can work together to rapidly respond to the industrial needs cited previously. This is accomplished by identifying key process variables, by determining how machine tools and computer control systems must be modified for the cost-effective machining of structural ceramics, and by expanding experimental systems into full-scale manufacturing systems in other locations such as industrial facilities or manufacturing centers at the Y-12 Plant. The ultimate goal is to quickly reduce the relatively high ceramic component machining costs. Major progress is required within the next 2 years to meet foreign competition. This time frame is critical, due to the fragile condition of the U.S. structural ceramic industry. The CMC has been created in the HTML at ORNL to provide close proximity to the User Center staff and the large array of materials characterization instruments located in the present six HTML User Centers. The CMC is being equipped with state-of-the-art material removal equipment and dimensional characterization instruments. This equipment complements the existing material and surface characterization equipment already available in the HTML.

The staff of the CMC will work with U.S. companies, educational institutions, and other government facilities where appropriate, via special working arrangements called Cooperative Research and Development Agreements (CRADAs), through the existing HTML User Centers via User Agreements, and through the CTP via Cost-Shared Subcontracts. The objective is to identify specific ceramic manufacturing problems of highest priority and to mutually develop appropriate solutions to the problems. U.S. industry involvement is critical to the success of the program. Most of this work will be specifically targeted at making major improvements in the ability to machine and dimensionally characterize structural ceramics. The full capabilities and expertise of the facilities at ORNL and the Y-12 Plant are available to use within this framework, but most R&D work required for the solutions to the identified ceramic problems will be conducted either in the CMC or at the industrial partner's facility. The desire is to create a strong interrelated program dedicated to meeting U.S. industry needs.

4. PROGRAM ELEMENTS

This program plan, as shown in Fig. 1, includes three major program elements: (1) fundamental machining technology, (2) machine control technology, and (3) ceramic component characterization.

Fig 1. Ceramic Manufacturability Center program elements.

4.1 FUNDAMENTAL MACHINING TECHNOLOGY

Understanding and controlling the machining processes are critical to the success of ceramic components being introduced into U.S. industry. Basic aspects of the machining processes must first be understood before the optimization process can begin.

4.1.1 Traditional Abrasive Techniques

The traditional abrasive techniques portion of the program establishes the baseline for comparison of all other material removal processes. The initial objective is to understand the basic interactions of the superabrasive grit (diamond or cubic boron nitride) and the machining fluid with the ceramic material being machined, so that the major variables which dominate the rate of material removal and the initiation of surface damage are clearly identified and their functional relationships demonstrated for a minimum of three U.S.-produced structural ceramics. The existence of damage will be determined quantitatively using atomic force and acoustic microscopy in addition to statistical analyses of specimens machined under varied conditions, then fractured followed by 100% fractography using scanning electron microscopy. The unique combination of machining research capabilities with the broad range of material characterization capabilities in the HTML User Centers is ideal for efficiently determining the required relationships in this subelement.

Equipment being acquired for this research includes state-of-the-art machine tools for cylindrical grinding, centerless grinding, and surface grinding, plus extensive instrumentation for measuring machine tool and workpiece behavior during the machining process under a variety of controlled conditions. Major attention is being focussed on characterizing the grinding media, including wheel structure, and particularly how the diamond and cubic boron nitride wheels can be designed and constructed to more exacting tolerances than currently possible. This provides much more predictable cutting behavior and life. Silicon nitride, silicon carbide, and alumina ceramics are the materials being used for the initial studies.

Major research thrusts include:

1. Determine values for major machine tool variables providing maximum material removal rates with minimum surface and subsurface damage including microflaw generation, residual stress, fracture statistical parameters, and wear parameters. Use the results as a standard for comparison to other material removal processes.

2. Demonstrate machine tool accuracy of $<1\ \mu\text{m}$ and repeatability of $<0.5\ \mu\text{m}$ over the volume of a typical ceramic heat engine component.

4.1.2 Creep Feed Grinding

This new method of high-speed material removal requires a very stiff machine with a high torque spindle. A variant of this process is to use an electrically conductive wheel and coolant to augment the material removal by creating an electrical potential between the wheel and the workpiece. This process keeps the grinding wheel structure open and allows more aggressive grinding. In some instances, this technique offers faster material removal rates and better surface finish when compared to conventional machining. A creep feed surface grinder is a major new machine tool addition in the CMC. This process will be critically compared with those in subelement 4.1.1 for the same three types of structural ceramics.

Major research thrusts include:

1. determine values for major machine tool variables providing maximum material removal rates with minimum surface and subsurface damage, including microflaw generation, residual stress, fracture statistical parameters, and wear parameters; and
2. demonstrate machine tool accuracy of $<1\ \mu\text{m}$ and repeatability of $<0.5\ \mu\text{m}$ over the volume of a typical ceramic heat engine component.

4.1.3 Ultrasonic Machining

There are many new applications of structural ceramic components in which small holes and threads are required. State-of-the-art ultrasonic machines in the CMC will be used to determine the critical values of variables necessary to produce small holes and threads in structural ceramic components. These machines will be instrumented so that machine-induced deformations will be known and can be controlled to increase dimensional accuracy and reduce surface and subsurface damage. A major goal is to achieve repeatable dimensions that are an order of magnitude better than currently possible. A wide range of nitride-, carbide-, and oxide-based ceramics will be studied under various ultrasonic machining parameters to determine maximum tolerance capability and maximum material removal rates as a function of surface finish and damage.

Major research thrusts include:

1. determine values for major machine tool variables providing maximum material removal rates;

2. demonstrate machine tool accuracy of $<1\ \mu\text{m}$ and repeatability of $<0.5\ \mu\text{m}$ for holes and threads in a typical ceramic heat engine component;
3. study the integrity of internal and external threads in ceramic components; and
4. study the residual stress caused by ultrasonic drilling over a range of major machine tool variables, including frequency, amplitude, coolant chemistry, abrasive type and chemistry, coolant flow, and structural ceramic type and microstructure.

4.1.4 Hydroabrasive Processes

This machining research involves a newly emerging material removal process which is an alternative to conventional grinding. Its potential has not been demonstrated for structural ceramics such as silicon nitride, silicon carbide, or alumina. It is anticipated that existing hydroabrasive machine tools located at industrial partners' facilities can be used for this study. Little is known regarding the state of surface damage or surface stress caused by this fast cutting process. The fluid dynamics, and the effects of the abrasive grit on the hydrodynamics, must be understood to determine the lowest tolerances possible with this type of machine tool, while at the same time achieving maximum material removal rates. Again, this is done for a minimum of the three structural ceramic classes described earlier in subelement 4.1.1. It is also important to understand how surface finish is maximized while subsurface damage in the machined surfaces is minimized.

Major research thrusts include:

1. demonstrate machine tool accuracy of $<5\ \mu\text{m}$ and repeatability of $<2.5\ \mu\text{m}$ over the volume of a typical ceramic heat engine component;
2. model the hydroabrasive machining process, including the role of all major parameters in determining optimum cutting conditions while minimizing surface damage; and
3. demonstrate the use of this technique to perform machining of complex geometry components to realistic engineering tolerances in the major classes of structural ceramics, plus thin coatings of some of these ceramic materials deposited upon engine alloys.

4.1.5 Laser-Assisted Processes

It has been reported that the application of laser energy in the vicinity of the workpiece and cutting tool interface on a machine tool can markedly increase the material removal rate on some classes of ceramic materials while at the same time generating minimal surface damage. Considerable work has been done in Germany in this new machining area. Achievable tolerances and material removal rates as a function of machine tool parameters and laser type, power density, beam uniformity, and exact point of application on the workpiece are unknown at this time. Initial experiments will be conducted to determine the operating envelope of one of these systems in Germany on a new U.S. silicon nitride. If these results are promising, a laser system could be installed in one of the laboratory modules in the CMC. Rotational axis machine tools will be the first candidate systems for evaluating this new ceramic machining method with industry.

Assuming that the preliminary experiments in Germany are successful, research thrusts include:

1. parametric modeling of the process for a range of silicon nitride ceramic compositions and microstructures;
2. comparison of material removal rates in the same machine tool without laser assistance; and
3. empirical relations between surface finish and subsurface damage in machined ceramics, as a function of major machine tool parameters for different types of ceramic materials, i.e., silicon nitride, silicon carbide, and alumina.

4.1.6 Ductile Grinding

This method of material removal requires a machine tool that has ultimate stiffness and precision movement. In this process, either a single-point diamond tool or a grinding wheel is very carefully fed into a ceramic workpiece at such speed and accuracy to only produce ductile mode chip formation. There are no plans to acquire this type of machine tool in the CMC, but we will collaborate with Energy Systems personnel who are conducting research in this area at the Optics Manufacturing Operations Development and Integration Laboratory (MODIL) at ORNL. This facility was constructed for the Strategic Defense System to fabricate high-precision ceramic mirror components. Many educational facilities and government facilities, such as the National Institute of Standards and Technology (NIST), are also involved in ductile grinding.

Major research thrusts include:

1. determine values for major machine tool variables providing maximum material removal rates with minimum surface and subsurface damage, including microflaw generation, residual stress, fracture statistical parameters, and wear parameters; and
2. demonstrate machine tool accuracy of <10 nm and repeatability of <5 nm over the volume of a typical ceramic heat engine component.

4.2 MACHINE CONTROL TECHNOLOGY

Identifying and controlling critical machine operating parameters is a must if high material removal rates are to be achieved while maintaining dimensional control to machine tool accuracy of <1 μm and repeatability of <0.5 μm over the volume of a typical ceramic heat engine component. At the same time, surface deviations of only a few micrometers from nominal, with minimal surface damage, are desired. For "conventional" material removal processes, wherein a grinding wheel is brought into contact with the workpiece while the pair is flooded with coolant, the initial contact between the part and the abrasive (diamond) is a critical event. Excessive mechanical stress causes heating of the diamond/matrix system and irreparably changes the properties of the grinding wheel. Vibrations induced in the machine tool or workpiece during machining have a severe negative effect upon the ability to achieve high dimensional accuracy and at the same time generate subsurface cracks and residual stresses in machined surfaces of ceramic materials. These complicated interactions cannot be detected without instrumentation such as force monitors and accelerometers. Therefore, automatic control of the machine tool via computers and instrumentation is the only way to minimize variability in this delicate process and is a major aspect of this subelement.

4.2.1 Part Modeling and Machine Programming

A complete solid model of the part geometry is required to represent the engineering design objective of a ceramic component. Geometry and tolerance representation algorithms are evaluated for accuracy, efficiency, and ease of interface with computerized numerical control (CNC) machine tools. They are demonstrated on a variety of machine tools by translating the solid model into machine code and then producing a number of duplicate components. These groups are then critically characterized via coordinate measuring machine (CMM) techniques to determine the algorithms which provide the minimum variance in key dimensions and surfaces in these prototypical parts. Both ability to translate from solid model to machine code and representation of measured geometry will be tested.

4.2.2 Real-Time Control of Machines

Robustness is a highly desirable characteristic of any manufacturing process. It is the ability of the process to continue to operate within a specified range of one or more critical output parameters, such as part dimension, in spite of deviations of the manufacturing parameters. In order for a manufacturing process to be robust, i.e., not sensitive to environmental and process variables, it must be capable of adjustment of several of the manufacturing input parameters in real time. First, this requires the ability to measure one or more critical output parameters, such as a key dimension on a part, while it is located in the machine tool, and preferably during the material removal process. This must be done in the presence of vibrations, coolant spray, and other disturbing variables. Therefore, robust sensors must be mounted in the machine tool and be able to measure the required variables to high accuracy and precision in spite of the disturbances from the machine operation. Second, high-speed control systems must link the sensors and the operation of the machine tool itself to provide useful real-time control. Sensors and software are developed and evaluated to convert the signals into machine tool commands and movements.

Some research thrusts include:

1. evaluation of sensor technology suitable for application in an operating machine tool environment for measuring vibration, linear dimensions, and diametrical dimensions;
2. study of sensor/computer interface technology to identify the optimum control approach for feed-back and feed-forward control of machine tools; and
3. demonstration of a sensor/computer system on a surface and cylindrical grinder and demonstration of machine tool accuracy of $<1\ \mu\text{m}$ and repeatability of $<0.5\ \mu\text{m}$ over the volume of a typical ceramic heat engine component.

4.2.3 In-Process Inspection

The final stage of deciding if a machining process has adequately produced a component feature is measuring and verifying the dimension. It is most desirable that this be done prior to removal of the component from the machine tool. Such a procedure is highly cost effective and significantly reduces the need for off-line inspection, which is particularly expensive. This procedure also ensures that the process remains in control and that no defective components are allowed to be produced.

Some research thrusts include:

1. Study of candidate-sensing systems having sufficient spatial resolution for high-accuracy dimensional measurements. One candidate approach is laser-speckle interferometry. Other techniques will be evaluated and compared. After selection of the best candidate system, a prototype system is installed on a machine tool in the CMC, demonstrated while producing component parts from the candidate structural ceramics, and then used with industrial teams.

4.3 CERAMIC COMPONENT CHARACTERIZATION

Surface and structural integrity are critical to satisfying design requirements of machined ceramic components considered for use in heat engines. Also, friction and wear are largely dependent on surface finish, plus subsurface damage. Fatigue life and load-bearing capability are greatly affected by subsurface flaws and residual stress induced during machining. Computer hardware and software algorithms are evaluated for rapid characterization of complex geometry components, the most efficient systems identified, and a prototype system of the best identified software/computer combination installed and used to determine effectiveness of the entire system. The major dimensions are compared with results obtained from a calibrated CMM.

4.3.1 Dimensional Characterization

Current state-of-the-art equipment for dimensional characterization is a CMM. An optimally set up device can operate to an accuracy of $<0.1 \mu\text{m}$ and repeatability of $<0.05 \mu\text{m}$ over the volume of a typical ceramic heat engine component. A state-of-the-art CMM is available in the CMC. This machine is used as a general tool for characterizing the geometry of complex parts, as well as providing input for reverse engineering of one-of-a-kind models scanned by the CMM. This will be useful in determining the green-state dimensions required to produce the final part dimensions after firing of the ceramic component. This is needed for near-net-shape forming of ceramic components. It is also used for establishing algorithms for CMM use in characterizing complex geometry parts. It is important to evaluate the native language software and determine its accuracy in detecting known deviations from geometrically perfect features.

4.3.2 Surface Integrity

Surface integrity is generally critical to the operation of a ceramic component where contact loads occur in operation. Surface finish, which is the classical means for quantifying the "quality" of machined surfaces, is totally inadequate for most structural ceramic materials. An entirely new way of measuring these machined surfaces is required, and this approach must account for damage that is introduced into the material under the physical surface. Nondestructive methods which are easy to apply and that are actually usable in a manufacturing environment are critically needed. The depth of subsurface damage from a particular machining operation depends also upon the ceramic material, including its fracture toughness, strength, and various microstructural features. Depending upon the specific structural ceramic under consideration, this region can extend up to 100 μm under the physical surface. In addition, methods for quickly measuring the geometrical perfection of a machined surface over lengths of at least several thousand micrometers with a vertical resolution down to a few micrometers, and providing the data quickly in a friendly format, are particularly needed at this time.

4.3.3 Structural Integrity

Structural integrity of the ceramic component is also of prime consideration. Residual stresses and subsurface flaws can dramatically reduce the mechanical properties of ceramic parts by creating stress concentrations. In brittle materials, this is an initiation point for cracks that can propagate under stress and cause catastrophic failure. Techniques are studied for evaluating the structural integrity without the need for destructive evaluation. As discussed earlier, these techniques must be able to measure the critical parameters that have been shown to relate directly to either fracture strength or mechanical fatigue by nondestructively scanning or probing a machined surface.

5. SCHEDULE FOR CMC OPERATION

The overall objective of the CMC is to demonstrate substantial reduction in the time required to machine ceramic components of high quality. The result will be a design data base that will allow the manufacture and implementation of ceramic components into the heat engine industry. The CMC schedule is shown in Fig. 2.

Fig. 2. Ceramic Manufacturability Center schedule.

6. PROPOSED (CURRENT) DOE AND INDUSTRY FUNDING

The CMC will be funded in part from three divisions of DOE and from U.S. industry private sector funds through CRADAs. The divisions of DOE are Defense Programs (DP), Energy Efficiency (EE) and Renewable Energy, and Energy Research (ER). The DOE funds also support the HTML User Centers, the CTP, and CRADAs that are located in locations other than the CMC. The estimated budget and time frame are shown in Table 1. Approximately one-third of the funds will be spent in the CMC.

Table 1. Proposed (current) DOE and industry funding

	FY 1994	FY 1995	FY 1996
DP CHADAS	\$ 5.6M (3.0M) ^a	\$ 7.0M (4.0M) ^a	\$ 8.4M (5.0M) ^a
ER CRADAS	1.25M (.25M) ^a	1.5M	2.0M (0) ^a
Increased DOE CRADA funding	3.6M	4.5M	5.4M
Total DOE CRADA funding	6.85M	8.5M	10.4M
Industry like-kind funding	8.15M	9.8M	9.7M
EE Program	<u>5.6M (3.1M)^a</u>	<u>7.0M (3.6M)^a</u>	<u>8.4M (3.6M)^a</u>
TOTAL	\$20.6M	\$25.3M	\$28.5M

^a () Current funding.

7. COST-EFFECTIVE CERAMIC MACHINING

The CMC fully supports activities in the area of cost-effective ceramic machining (CECM), as shown in Table 2. CECM activities span several programs including the CMC; the HTML User Centers; and the CTP, CECM Initiative.

Table 2. Cost-effective ceramic machining

1.0 ENVIRONMENTAL SAFETY AND HEALTH ASPECTS OF MACHINING

1.1 Sampling and Analysis of Ceramic Grinding Fluids (ORNL)

2.0 TECHNOLOGY ASSESSMENT AND FUTURE NEEDS

2.1 Workshop on Cost-Effective Ceramic Machining (ORNL)

2.2 Ceramic Machining Needs Assessment (Industry/ORNL/Y-12 Staff)

2.3 Workshop on Superabrasives and Grinding Wheel Technology (ORNL)

2.4 Survey of Japanese Ceramic Machining Technology (U. of N. Dakota)

2.5 Survey of Internal/European Machining Technology (Fraunhofer IPT)

3.0 ADVANCED MACHINING METHODS DEVELOPMENT

3.1 High-Speed, Low-Damage Grinding (Eaton Corp., U. of Mass.)

3.2 Development of the Next-Generation Grinding Wheel (St. Gobain - Norton)

3.3 COMMEC Grinding System (ORNL/Y-12)

3.4 Chemically Assisted Ceramic Grinding (NIST)

3.5 Ceramic Machining Consortium (NIST)

4.0 CERAMIC MANUFACTURABILITY AND RELATED PERFORMANCE

4.1 Repeated Impact Test for Valve Materials (ORNL)

4.2 Development of a Compact Grindability Test System (Chand Kare Tech. Ceramics)

5.0 STRUCTURE AND SURFACE QUALITY OF MACHINED CERAMICS

5.1 Structure of Machined Surfaces (ORNL)

8. ACKNOWLEDGMENTS

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APPENDIX A – WORK BREAKDOWN STRUCTURE

APPROACH

The approach used in this program to accomplish the objectives is to organize the technical work within a work breakdown structure (WBS), based on three major program elements: fundamental machining technology, machine control technology, and ceramic component characterization, as shown in Fig. A1. Each of these major program elements is, in turn, organized into major subelements.

Fig. A1. Program elements of Ceramic Manufacturability Center.

WBS 1.0 – FUNDAMENTAL MACHINING TECHNOLOGY

Understanding and controlling the machining process are critical to the commercial success of ceramic components being introduced and used on a large scale in products such as advanced diesel engines and eventually in gasoline and alternate fueled engines in automobiles.

This program element is organized as shown in Fig. A2 and includes five subelements: (1) traditional abrasive techniques, (2) creep feed grinding, (3) ultrasonic machining, (4) hydroabrasive processes, (5) laser-assisted processes, and (6) ductile grinding. Each subelement, along with process characteristics, is described in the following.

Fig. A2. Subelements of fundamental machining technology.

WBS 1.1 – TRADITIONAL ABRASIVE TECHNIQUES

This subelement establishes the baseline for comparison of all other material removal processes included in this program. The initial objective is to understand the basic interactions of the abrasive grit with selected ceramic materials so that the appropriate major material removal parameters and the resulting stock removal rates can be modelled and optimized while minimizing surface damage in the structural ceramic. Machine tool accuracy of $<1\ \mu\text{m}$ and repeatability of $<0.5\ \mu\text{m}$ over the volume of a typical ceramic heat engine component are a thrust of this subelement. The unique combination of material removal and material characterization capabilities found in the HTML makes it an ideal facility for conducting this function. This subelement is a part of the Fundamental Machining Technology Element; see Figs. A1 and A2.

This program subelement is organized as shown in Fig. A2 and includes eight process characteristics: (1) abrasives, (2) matrix, (3) wheel structure, (4) coolants, (5) machine characterization, (6) basic chip formation processes, (7) environmental aspects, and (8) machinability data base. Each subelement is described in the following.

WBS 1.1.1 – Abrasives

This process characteristic includes work which determines the fundamental relationships between abrasive properties in different classes of grinding configurations, such as wheels or core drills, and the material removal process. Important factors include superabrasive type, such as diamond or cubic boron nitride; particle friability or fracture toughness; particle size distribution; particle shape; and particle distribution within the wheel rim, for example. Different loading conditions exist between the use of grinding wheels and core drills, which can greatly affect wear. Diamond particles are harder than cubic boron nitride, but the fracture toughness is generally lower depending on the crystal imperfections, which can be tailored to meet customers' needs. For example, high-fracture-resistant particles are better for grinding low-fracture-resistant materials, and vice versa. Particle shape and distribution can also greatly affect wear of the grinding tool.

WBS 1.1.2 – Matrix

This process characteristic includes work which establishes the role of the matrix that holds the abrasive particles in place in a grinding wheel or core drill. This relationship of the matrix properties to the grinding process will be analyzed for a class of materials in specific types of machine tools. Important factors include material type such as polymer resin, vitrified ceramic, or metal matrices; material hardness; material stiffness; and thermal resistance. Polymer

resins offer good vibration damping but cannot hold tight tolerances or resist overheating. Vitrified or metal matrices can resist heat and hold tight tolerances but cannot withstand large vibrations.

WBS 1.1.3 – Wheel Structure

This process characteristic includes work which determines the combined effects of the abrasive, matrix, and hub of the wheel. The hub can include materials such as aluminum, cast iron, steel, or vitrified ceramic. The stiffness and vibration absorption of the hub material have dramatic effects on the wheel characteristics, which are currently poorly understood. The thickness and composition of the matrix material and the distribution of abrasive in the matrix have a major performance effect on the wheel. It is important to determine the range of operating conditions of the wheel as it relates to the type of machine tool being used.

WBS 1.1.4 – Coolants

This process characteristic includes work which establishes the effects of different coolants and their chemistry on the machining of ceramics. Important factors include lubricity, flow rate, chemical reactions, chip removal effectiveness, thermal conductivity, and environmental impact (disposal). Lubricity relates to the wetting characteristics of the fluid and can influence the friction between the wheel and workpiece. Flow rate has a dramatic effect on chip removal effectiveness, while chemical reactions can also affect material removal rates and workpiece surface condition. Very high temperatures can occur at the wheel and workpiece interface that can damage the ceramic component. Finally, some trade-off between coolant effectiveness and biological impact may be necessary.

WBS 1.1.5 – Machine Characterization

This process characteristic includes work which determines the important design and construction elements required to make a highly reproducible machine tool for machining ceramic components. The goal is to develop a model of machine tools, which includes all of the major variables that control the spatial stability of the abrasive delivery system relative to the workpiece mounted in the machine tool, during the machining process. This information is urgently needed by the machine tool industry. Important factors include stiffness, accuracy, repeatability, vibration spectrum, and tool speed range and uncertainty. This work includes finite element modeling of the machine tools and measurements of selected machines with vibration sensors, force sensors, and laser interferometers to quantify machine behavior. Part dimensional accuracy is used as final verification of the machine characteristics.

WBS 1.1.6 – Basic Chip Formation Processes

This process characteristic includes work which establishes basic understanding of the machining process. In this effort, well-characterized machines are instrumented with various sensors, and machining studies are conducted to determine machining parameters which produce the ceramic components in the shortest time while minimizing surface damage. Important variables studied include wheel rotation speed, part rotation speed, wheel infeed, wheel crossfeed, wheel trueness, wheel dress condition, role of spindle movement and vibration (for both wheel and workpiece), and coolant properties and flow. This information will be collected into a data base and made available to U.S. industry.

WBS 1.1.7 – Environmental Aspects

This process characteristic includes work which determines the environmental, health, and safety aspects of machining ceramics. It includes understanding and controlling airborne hazards from ceramic materials, coolants, and grinding wheels. It includes control of liquid chemical reactants as well as biological hazards. It also includes liquid and solid waste disposal of ceramic powders and environmentally compatible filters to separate solid wastes from coolants.

WBS 1.1.8 – Machinability Data Base

This process characteristic includes work which establishes the machinability of various ceramic materials using traditional grinding processes. This data base will form the basis for comparisons with other material removal processes. Instrumented grinding equipment is necessary for the measurement of grinding parameters.

WBS 1.2 – CREEP FEED GRINDING

This subelement includes work which determines effectiveness and processes operating during creep feed grinding. This method of grinding differs from traditional grinding in that the wheel is strongly forced into the workpiece and proceeds at a very slow crossfeed rate. Optimum operation results in faster material removal rates compared to conventional grinding. An increase in material removal rate of one order of magnitude over traditional abrasive techniques, while maintaining the same machine tool accuracy and repeatability, is the goal of this effort. The machine tool must be very stiff and have exceptional torque to accomplish this type of rapid material removal. The final shape is produced in one tool traverse, and the wheel can be continuously electrochemically dressed at the region near the wheel and part interface. This

procedure produces several important enhancements including dressing of the wheel, removal of swarf (ceramic chips), and chemical reaction with the ceramic part.

This program subelement is organized as shown in Fig. A2 and includes eight process characteristics: (1) abrasives, (2) matrix, (3) wheel structure, (4) coolants, (5) machine characterization, (6) basic chip formation process, (7) environmental aspects, and (8) machinability data base. Each process characteristic is described in the following.

WBS 1.2.1 – Abrasives

This process characteristic includes work which compares the abrasive properties in creep feed grinding to those found in traditional material removal processes. Important factors include abrasive type, such as diamond or cubic boron nitride; particle friability or fracture toughness; particle size distribution; particle shape; and particle distribution within the wheel rim, for example. In creep feed grinding, larger overall forces are experienced; however, due to more wheel surface area exposure, the forces on the workpiece are lower. The effect of these different loading conditions on the abrasive particles must be determined.

WBS 1.2.2 – Matrix

This process characteristic includes work which establishes the effects of the matrix that holds the abrasive particles in place. In creep feed grinding, the wheel composition is usually electrically conductive to take advantage of beneficial electrochemical reactions. This means that the wheel matrix is usually made of cast iron but can be made of other electrically conductive materials such as bronze. Other important factors include material hardness, material stiffness, and resistance to heat. Since creep feed grinding requires higher overall forces, the wheel matrix must be stiffer than in traditional grinding.

WBS 1.2.3 – Wheel Structure

This process characteristic includes work which determines the combined effects of the abrasive, matrix, and hub of the wheel. In the case of creep feed grinding, the core and the matrix containing the abrasive are usually made of cast iron or another electrically conductive material so that continuous dressing by electrochemical discharge can be achieved. The stiffness and vibration absorption of the wheel material are studied, since they can have dramatic effects on the wheel characteristics. The thickness and composition of the matrix material, and the distribution of abrasive in the matrix, have a major performance effect on the wheel.

WBS 1.2.4 – Coolants

This process characteristic includes work which determines the effects of coolants and their chemistry on creep feed grinding of ceramics. In the case of creep feed grinding, the coolant is usually electrically conductive. Important factors include lubricity, flow rate, chemical reactions, chip removal effectiveness, thermal conductivity, electrical conductivity, and environmental impact. Lubricity relates to the wetting characteristics of the fluid and can influence the friction between the wheel and workpiece. Flow rate has a dramatic effect on chip removal effectiveness, while chemical reactions can also affect material removal rates and workpiece surface condition. Very high temperatures can occur at the wheel and workpiece interface that can damage the ceramic component. Finally, some trade-off between coolant effectiveness and biological impact may be necessary.

WBS 1.2.5 – Machine Characterization

This process characteristic includes work which determines the important design and construction elements required to make a highly reproducible machine tool for creep feed grinding of ceramic components. The goal is to develop a model of machine tools, which includes all of the major variables that control the spatial stability of the abrasive delivery system relative to the workpiece mounted in the machine tool, during the machining process. This information is urgently needed by the machine tool industry. Important factors include stiffness, accuracy, repeatability, vibration spectrum, and tool speed range and uncertainty. This work includes finite element modeling of the machine tools and measurements of selected machines with vibration sensors, force sensors, and laser interferometers to quantify machine behavior. Part dimensional accuracy is used as final verification of the machine characteristics.

WBS 1.2.6 – Basic Chip Formation Process

This process characteristic includes work which establishes basic understanding of the machining process. In this effort, well-characterized machines are instrumented with various sensors, and machining studies are conducted to determine machining parameters which produce the ceramic components in the shortest time while minimizing surface damage. Important variables studied include wheel rotation speed, part rotation speed, wheel infeed, wheel crossfeed, wheel trueness, wheel dress condition, role of spindle movement and vibration (for both wheel and workpiece), and coolant properties and flow. This information will be collected into a data base and made available to U.S. industry.

WBS 1.2.7 – Environmental Aspects

This process characteristic includes work which determines the environmental, health, and safety aspects of machining ceramics. It includes understanding and controlling airborne hazards from ceramic materials, coolants, and grinding wheels. It includes control of liquid chemical reactants as well as biological hazards. It also includes liquid and solid waste disposal of ceramic powders and environmentally compatible filters to separate solid wastes from coolants. In this case, electrochemical reactions may cause unforeseen hazards by forming more reactive by-products.

WBS 1.2.8 – Machinability Data Base

This process characteristic includes work which establishes the machinability of various ceramic materials using creep feed grinding processes. This data base will be compared with other material removal processes. A machine will be instrumented to measure the grinding parameters.

WBS 1.3 – ULTRASONIC MACHINING

This program subelement provides the capability to machine ceramics with high accuracy, including holes and threads in ceramic components. The goal is to accomplish the machining at an order-of-magnitude increase in material removal rate over traditional abrasive techniques and with improved quality. Current methods include drilling and tapping with diamond-coated tools. The machining method is very slow and cannot always produce adequate features. Ultrasonic machining will extend the capabilities of the CMC.

This program subelement is organized as shown in Fig. A2 and includes six process characteristics: (1) abrasives, (2) coolants, (3) frequency, (4) amplitude, (5) environmental aspects, and (6) machinability data base. Each process characteristic is described in the following.

WBS 1.3.1 – Abrasives

This process characteristic includes work which determines the effects of abrasive type on the material removal process. Important factors include abrasive type, such as diamond, cubic boron nitride, or garnet; particle friability or fracture toughness; particle size; and particle shape. In the case of ultrasonic machining, the abrasives can be free flowing or imbedded into the tool. When free flowing, the abrasives are pumped to the workpiece through or around the tool. Ultrasonic vibrations of the tool cause abrasion of the workpiece around the tool. When the abrasives are imbedded in the tool, abrasion of the tool

against the workpiece removes material. In this case, higher accuracy is achievable since the abrasive is not allowed to flow around the tool.

WBS 1.3.2 – Coolants

This process characteristic includes work which establishes the effects of different coolants and their chemistry on ultrasonic machining of ceramics. In ultrasonic machining, the coolant can be used as a carrier fluid for abrasive particles or as a coolant to flush chips from the work area. The coolant acts as a carrier when the abrasive is free flowing and as a flushing agent when the abrasives are imbedded in the tool. Important factors include lubricity, flow rate, chemical reactions, chip removal effectiveness, thermal conductivity, and environmental impact. Lubricity relates to the wetting characteristics of the fluid and can influence the friction between the tool and workpiece. Flow rate has a dramatic effect on chip removal effectiveness, while chemical reactions can also affect material removal rates and workpiece surface condition. Very high temperatures can occur at the tool and workpiece interface that can damage the ceramic component. Finally, some trade-off between coolant effectiveness and biological impact may be necessary.

WBS 1.3.3 – Frequency

This process characteristic includes work which determines the optimal vibration frequency for ultrasonic machining. Models are developed that relate material removal rate to the frequency of the head on the machine tool for selected geometries of parts. The vibration frequency is highly dependent on the size and location of the tool.

WBS 1.3.4 – Amplitude

This process characteristic includes work which establishes the desired amplitude for optimum material removal for a selected set of structural ceramic materials. The goal is to include the amplitude in a parametric model to quantitatively predict material removal rates for this technique while producing minimal surface damage. Amplitude is a function of power input and tool geometry.

WBS 1.3.5 – Environmental Aspects

This process characteristic includes work which determines the environmental, health, and safety aspects of machining ceramics. It includes understanding and controlling airborne hazards from ceramic materials, coolants, and grinding tools. It includes control of liquid chemical reactants as well as biological hazards. It also includes liquid and solid waste disposal of ceramic powders and environmentally compatible filters to separate solid wastes from coolants.

As in the case of creep feed grinding, electrochemical reactions may contribute to the hazardous environment by breaking down stable solutions to form more reactive by-products.

WBS 1.3.6 – Machinability Data Base

This process characteristic includes work which establishes the machinability of various ceramic materials using ultrasonic machining. This data base will be compared with other material removal processes. The type of sensors needed to measure the process parameters is undetermined at this time. It is hoped that the machine and the material removal process can be modeled.

WBS 1.4 – HYDROABRASIVE PROCESSES

In this program subelement, fast removal of material from the workpiece is critical. The goal is two orders of magnitude increase in material removal rate compared to traditional abrasive techniques, while maintaining machine tool accuracy of $<5\text{ }\mu\text{m}$ and repeatability of $<2.5\text{ }\mu\text{m}$. In this subelement, detailed comparisons are conducted that compare the surface finish and subsurface damage in selected structural ceramics with what is achievable with traditional grinding.

This program subelement is organized as shown in Fig. A2 and includes six process characteristics: (1) abrasives, (2) fluids, (3) machine characterization, (4) hydrodynamic processes, (5) environmental aspects, and (6) machinability data base. Each process characteristic is described in the following.

WBS 1.4.1 – Abrasives

This process characteristic includes work which determines the effects of abrasive type on the material removal process. Important factors include abrasive type, such as diamond, cubic boron nitride, or garnet; particle friability or fracture toughness; particle size; and particle shape. In the case of hydrodynamic machining, the abrasives are mixed in a carrier fluid and pumped to the workpiece through a nozzle at supersonic speeds. In this case, wear of the nozzle becomes an important consideration in the choice of abrasive.

WBS 1.4.2 – Fluids

This process characteristic includes work which establishes the desired optimum properties for the carrier fluid used to transport the abrasives to the workpiece at high velocity. The composition of the fluid and the type and distribution of abrasive are critical elements in the flow pattern through the

nozzle. This, in turn, influences the jet diameter and shape. Consistency of the jet geometry and standoff distance largely determine the accuracy of the machining process.

WBS 1.4.3 – Machine Characterization

This process characteristic includes work which determines the important design and construction elements required to make an "effective" machine tool for machining ceramic materials using hydroabrasive methods. In the case of hydrodynamic machining, the tool head consists of an abrasive jet mounted where a wheel normally would be mounted. This effort will include finite element modeling of the machine tools and measurements with vibration sensors and laser interferometers to confirm predicted machine responses. Important factors include accuracy, repeatability, and vibration characteristics. This information is invaluable to the machine tool industry. Actual part dimensional accuracy will be a final verification of the machine characteristics. It may also be possible to combine a grinding wheel with an abrasive jet to take advantage of the fast material removal and the fine control of the grinding wheel.

WBS 1.4.4 – Hydrodynamic Processes

This process characteristic includes work which establishes a basic understanding of the hydrodynamic machining process. The velocity and the abrasive particle distribution greatly affect the cutting efficiency of the jet. The type of abrasive and carrier fluid viscosity also affect the size of the jet and amount of spreading of the jet after leaving the nozzle. Wear of the nozzle is a big factor in useful life of the cutting head. A basic understanding of the operating parameters must exist in order to optimize the process. It is also very important to determine the unique effects of the abrasive jet on the surface finish and subsurface damage introduced in the ceramic component, since this form of machining is mostly due to erosion and impact of the abrasive on the part.

WBS 1.4.5 – Environmental Aspects

This process characteristic includes work which determines the environmental, health, and safety aspects of machining ceramics. It includes understanding and controlling airborne hazards from ceramic materials, carrier fluids, and abrasive grit. It includes control of liquid chemical reactants as well as biological hazards. It also includes liquid and solid waste disposal of ceramic powders and environmentally compatible filters to separate solid wastes from carrier fluids. In this case, the abrasive grit used in the process may contribute significantly to waste disposal problems.

WBS 1.4.6 – Machinability Data Base

This process characteristic includes work which establishes the machinability of various ceramic materials using hydroabrasive processes. This data base will be compared with other material removal processes. Instrumentation of a machine tool to measure the machining parameters may not be possible. A machine and material removal model is needed to understand the complex interactions between the cutting fluid and the workpiece.

WBS 1.5 – LASER-ASSISTED PROCESSES

This program subelement concentrates on fast material removal with the goal of minimizing subsurface damage in the ceramic component. The goal is to increase the material removal rate two orders of magnitude over traditional abrasive techniques while maintaining a machine tool accuracy of $<1\text{ }\mu\text{m}$ and repeatability of $<0.5\text{ }\mu\text{m}$ over the volume of a typical ceramic heat engine component. The Fraunhofer Institut Für Produktionstechnologie (IPT) in Aachen, Germany, will be a partner in this area. Other areas within Energy Systems are conducting research in laser machining, and research is also being conducted at other national laboratories. Research is also done toward combining laser machining and grinding or hydroabrasive machining in one machine.

This program subelement is organized as shown in Fig. A2 and includes five process characteristics: (1) power, (2) application geometry, (3) tool/coolant interaction, (4) environmental aspects, and (5) machinability data base. Each process characteristic is described in the following.

WBS 1.5.1 – Power

This process characteristic includes work which determines the required power level to most rapidly machine ceramics while minimizing damage. The laser beam power (avg.) and the beam power spectrum plus absorptivity of the structural ceramic are major interacting variables. Thermal stresses induced by the laser beam cause subsurface damage in the ceramic components that must be minimized.

WBS 1.5.2 – Application Geometry

This process characteristic includes work which establishes the specimen geometry that can be machined by using laser-assisted turning of selected structural ceramics. It is expected that cylindrical geometries will be appropriate

for this type of machining. With a 5-axis control system, more complex geometries can be machined, such as turbine rotors. In this case, a conventional grinding wheel is replaced by a diamond-coated milling tool.

WBS 1.5.3 – Tool/Coolant Interactions

This process characteristic includes work which provides a basic understanding of the interaction of laser beam, cutting tool, structural ceramic, and coolant. In this work, laser-assisted turning is studied. This is when a laser beam is directed onto the workpiece just prior to the coolant jet and cutting tool. The desired effect is to heat the ceramic material to sufficient temperature until plastic deformation in the immediate vicinity of the cutting tool will occur during the machining process. This will change the basic chip formation process and minimize subsurface cracking.

WBS 1.5.4 – Environmental Aspects

This process characteristic includes work which determines the environmental, health, and safety aspects of machining ceramics. It includes understanding and controlling airborne hazards from ceramic materials, coolants, and grinding tools. It includes control of liquid chemical reactants as well as biological hazards. It also includes liquid and solid waste disposal of ceramic powders and environmentally compatible filters to separate solid wastes from coolants. In this case, high temperatures from laser beams may cause the breakdown of stable chemicals into more reactive by-products. The laser beams themselves are a hazard that must be contained.

WBS 1.5.5 – Machinability Data Base

This process characteristic includes work which establishes the machinability of various ceramic materials using laser-assisted processes. This data base will be compared with other material removal processes. Use of the laser provides greater flexibility and additional material removal capability. It is important to model the laser and material interactions in order to minimize surface and subsurface damage.

WBS 1.6 – DUCTILE GRINDING

This method of material removal requires a machine tool with an order of magnitude of stiffness and precision movement as compared to traditional grinding. The process can either incorporate a single-point diamond tool or a grinding wheel. Machine tool accuracy of <10 nm and repeatability of <5 nm over the volume of a typical heat engine component are required. Collaboration will be made with existing facilities conducting research in this area.

This program subelement is organized as shown in Fig. A2 and includes eight process characteristics: (1) abrasives, (2) matrix, (3) tool structure, (4) coolants, (5) machine characteristics, (6) basic chip formation processes, (7) environmental aspects, and (8) machinability data base. Each process characteristic is described in the following.

WBS 1.6.1 – Abrasives

This process characteristic includes work which determines the fundamental relationships between abrasive properties in different classes of grinding configurations, such as wheels or single-point turning. Important factors include abrasive type, such as diamond or cubic boron nitride; particle friability or fracture toughness; particle size distribution; particle shape; and particle distribution within the wheel rim, for example. Diamond particles are harder than cubic boron nitride, but the fracture toughness is generally lower depending on the crystal imperfections, which can be tailored to meet customers' needs. For example, high-fracture-resistant particles are better for grinding low-fracture-resistant materials, and vice versa. Particle shape and distribution can also greatly affect wear of the grinding tool.

WBS 1.6.2 – Matrix

This process characteristic includes work which establishes the role of the matrix that holds the abrasive particles in place in a grinding wheel or on a tool. This relationship of the matrix properties to the grinding process will be analyzed for a class of materials in specific types of machine tools. Important factors include material type, such as polymer resin, vitrified ceramic, or metal matrices; material hardness; material stiffness; and thermal resistance. Polymer resins offer good vibration damping but cannot hold tight tolerances or resist overheating. Vitrified or metal matrices can resist heat and hold tight tolerances but cannot withstand large vibrations. In the case of ductile grinding, the tightest tolerances must be maintained.

WBS 1.6.3 – Tool Structure

This process characteristic includes work which determines the combined effects of the abrasive, matrix, and hub of the wheel. The hub can include materials such as aluminum, cast iron, steel, or vitrified ceramic. The stiffness and vibration absorption of the hub material have dramatic effects on the wheel characteristics, which are currently poorly understood. The thickness and composition of the matrix material and the distribution of abrasive in the matrix have a major performance effect on the wheel. It is important to determine the range of operating conditions of the wheel as it relates to the type of machine tool being used. Single-point diamond tools will also be evaluated.

WBS 1.6.4 – Coolants

This process characteristic includes work which establishes the effects of different coolants and their chemistry on the machining of ceramics. Important factors include lubricity, flow rate, chemical reactions, chip removal effectiveness, thermal conductivity, and environmental impact (disposal). Lubricity relates to the wetting characteristics of the fluid and can influence the friction between the wheel and workpiece. Flow rate has a dramatic effect on chip removal effectiveness, while chemical reactions can also affect material removal rates and workpiece surface condition. Very high temperatures can occur at the wheel and workpiece interface that can damage the ceramic component. Finally, some trade-off between coolant effectiveness and biological impact may be necessary.

WBS 1.6.5 – Machine Characterization

This process characteristic includes work which determines the important design and construction elements required to make a highly reproducible machine tool for machining ceramic components. The goal is to develop a model of machine tools, which includes all or the major variables that control the spatial stability of the abrasive delivery system relative to the workpiece mounted in the machine tool, during the machining process. This information is urgently needed by the machine tool industry. Important factors include stiffness, accuracy, repeatability, vibration spectrum, and tool speed range and uncertainty. This work includes finite element modeling of the machine tools and measurements of selected machines with vibration sensors, force sensors, and laser interferometers to quantify machine behavior. Part dimensional accuracy is used as final verification of the machine characteristics.

WBS 1.6.6 – Basic Chip Formation Processes

This process characteristic includes work which establishes basic understanding of the machining process. In this effort, well-characterized machines are instrumented with various sensors, and machining studies are conducted to determine machining parameters which produce the ceramic components in the shortest time while minimizing surface damage. Important variables studied include wheel rotation speed, part rotation speed, wheel infeed, wheel crossfeed, wheel trueness, wheel dress condition, role of spindle movement and vibration (for both wheel and workpiece), and coolant properties and flow. This information will be collected into a data base and made available to U.S. industry.

WBS 1.6.7 – Environmental Aspects

This process characteristic includes work which determines the environmental, health, and safety aspects of machining ceramics. It includes understanding and controlling airborne hazards from ceramic materials, coolants, and grinding wheels. It includes control of liquid chemical reactants as well as biological hazards. It also includes liquid and solid waste disposal of ceramic powders and environmentally compatible filters to separate solid wastes from coolants. In this case, electrochemical dressing of the grinding wheels may be required to maintain accuracies. Again, stable chemicals may be decomposed into more reactive components by these reactions.

WBS 1.6.8 – Machinability Data Base

This process characteristic includes work which establishes the machinability of various ceramic materials using ductile grinding. This data base will be compared with other material removal processes. This process produces superior surface finishes and minimum subsurface damage in the ceramic component. The material removal process is fundamentally different than traditional grinding. It involves shear and ductile fracture instead of brittle fracture. The material removal process needs to be modeled for better understanding.

WBS 2.0 – MACHINE CONTROL TECHNOLOGY

In this program element, a Silicon Graphics workstation with solid modeling, finite element modeling, numerical control (NC) programming, and simulation software is utilized. The workstation is linked to the machine tools so that part programs and results can be exchanged. The entire system is integrated into a closed-loop feedback system that sends machine tool command and movement sequences to all computer-controlled machines and collects sensor data for compensation and part verification. All data are handled electronically to reduce operator effects and to ensure rapid turnaround.

This program element is organized as shown in Fig. A3 and includes three subelements: (1) part modeling and machine programming, (2) real-time control of machines, and (3) in-process inspection. Each subelement is described in the following.

Fig. A3. Subelements of machine control technology.

WBS 2.1 – PART MODELING AND MACHINE PROGRAMMING

This program subelement includes work relating to component model creation and machine tool programming. A solid model of the desired part geometry is created, and all machine tool motion is programmed from this reference geometry. All necessary information is stored in the solid model to completely define the material properties and methods required to manufacture the component from the starting geometry. Simultaneous optimization of the geometry and expected operating conditions allows for improved designs to be developed prior to manufacture of the component. Rapid programming of the machine tools and machine tool motion verification is implemented prior to material removal.

This program subelement is organized as shown in Fig. A3 and includes three process characteristics: (1) part geometry, (2) machine code, and (3) simulation and verification. Each process characteristic is described in the following.

WBS 2.1.1 – Part Geometry

This program process characteristic includes work involving the creation of a solid model of the desired part geometry, which is used to drive downstream applications. A complete model of the part captures knowledge about the functional requirements of the part and makes this knowledge available for later use. This standardizes the design requirements and allows for optimization based on expert knowledge. This knowledge is then made available to other users without requiring them to become material experts. The knowledge captured in the solid modeling work can be used to improve the efficiency and capabilities of industrial partners.

WBS 2.1.2 – Machine Code

This program process characteristic includes work involving the creation of the NC tool path required for machining the part geometry. The tool paths can be generalized on a family of part geometries, which would allow for easy modification. Knowledge can be captured, which will be based on the machining parameters required to produce satisfactory ceramic components, allowing users that are not experts in machining to function as well as more experienced users. The knowledge can be transferred to industrial partners.

WBS 2.1.3 – Simulation and Verification

This program process characteristic includes work dealing with simulating and verifying the NC machine code prior to execution on the machine tool. This will eliminate errors that could cause loss of the starting material or injury to operating personnel. Reduced operating costs, scrap reduction, and safety are major benefits.

WBS 2.2 – REAL-TIME CONTROL OF MACHINES

This subelement includes work which links the machine tools to the programming workstation and sensor feedback computers. It allows for error correction and program adjustment in a closed-loop system. Setup speed and increased accuracy are prime reasons for this work.

This program subelement is organized as shown in Fig. A3 and includes three process characteristics: (1) direct numerical control (DNC) network, (2) sensor feedback, and (3) real-time software. Each process characteristic is described in the following.

WBS 2.2.1 – DNC Network

This process characteristic includes work which links all machine tools to a DNC network. It allows for direct communication from programming computers to machine controllers. This eliminates data storage and transfer by slow, inefficient processes. It also increases reliability by allowing several machine tools to be capable of accepting programs from a common source and allows for uninterrupted backup of data.

WBS 2.2.2 – Sensor Feedback

This process characteristic includes work which allows for sensor feedback and control at each machine tool. The types of sensors include strain gages to measure forces, accelerometers to measure vibrations, acoustic emission to measure part contact, and laser interferometers to measure displacement. The information is essential to understanding the basic machining processes. The basic understanding of machining processes will only be accomplished by measuring all operating variables and correlating them to resulting effects on the ceramic component.

WBS 2.2.3 – Real-Time Software

This process characteristic includes work which integrates the sensor feedback signals into machine control movements. It allows for more accurate manufacturing of parts based on adaptive control and reduction of uncontrollable operating variables. The benefits of real-time feedback control will only be realized with the development of software that uses the sensor data. It allows for corrections to be made before the part is removed from the machine tool. Demonstration of a working real-time feedback control system incorporating many types of machine tools and sensors will be important to U.S. industry.

WBS 2.3 – IN-PROCESS INSPECTION

This program subelement includes work which verifies final part dimensions prior to removal from the machine tools. It reduces the number of final inspections required to maintain consistent dimensional control of manufactured ceramic components. By reducing final inspections, which are very time consuming, a net reduction in operating cost is realized. The process can be continuously monitored, and control can be maintained.

This program subelement is organized as shown in Fig. A3 and includes three process characteristics: (1) contact probing, (2) optical measurement, and (3) laser interferometry. Each process characteristic is described in the following.

WBS 2.3.1 – Contact Probing

This process characteristic requires on-the-machine probing to accurately locate stock material prior, during, or after machining. In this case, a calibrated spherical-tipped probe is used to touch the part and calculate the location and size of the part. It can be used to adjust the machining starting locations or to verify that the final part meets specifications. Measurement of the location of the part to an accuracy of $<0.1\ \mu\text{m}$ and a repeatability of $<0.05\ \mu\text{m}$ over the volume of a typical ceramic heat engine component is the goal. Setup time is reduced, and expensive after-manufacturing costs are minimized.

WBS 2.3.2 – Optical Measurement

Work on this process characteristic involves optical measurement of the part or tool/wheel used to machine the part. It is non-contact and therefore faster than contact probing. An order-of-magnitude increase in measurement speed, while maintaining the same accuracy and precision, is the goal. Corrections must be made for environmental effects such as coolants and surface irregularities. Once the optical inspection process has been certified, it will save considerable time.

WBS 2.3.3 – Laser Interferometry

Work on this process characteristic involves the use of a laser interferometer to measure the part prior to removal from the machine tool spindle. It is very sensitive to surface contours on precision components. This technique is being applied at Argonne National Laboratory to provide subsurface flaw detection capability for selected translucent ceramic materials. This technique provides early quality control methods for these ceramic materials that could save the expense of machining unusable materials.

WBS 3.0 – CERAMIC COMPONENT CHARACTERIZATION

Understanding the effects of machining on the final ceramic components is critical to the successful implementation of machining processes. The ceramic component must have the required dimensions, surface characteristics, and internal strength to meet all application requirements. Product life is determined by the final condition of the part. The important factors are dimensional control, surface integrity, and structural integrity.

This program element is organized as shown in Fig. A4 and includes three subelements: (1) dimensional characterization, (2) surface integrity, and (3) structural integrity. Each subelement is described in the following.

Fig. A4. Subelements of ceramic component characterization.

WBS 3.1 – DIMENSIONAL CHARACTERIZATION

This subelement includes work which determines the hardware and software capabilities of a state-of-the-art CMM. The CMM is one of the most widely used instruments today for dimensional characterization. Accuracy of $<0.1\text{ }\mu\text{m}$ and a repeatability of $<0.05\text{ }\mu\text{m}$ over the volume of a typical ceramic heat engine component can be held for an optimally set up machine. This work also allows for the integration of the CMM into a near-real-time feedback control system with machine tools in the CMC. This will enhance the certification and process control ability in the CMC.

This program subelement is organized as shown in Fig. A4 and includes four process characteristics: (1) native language capability and comparison, (2) programming and simulation, (3) machine characterization, and (5) near-real-time feedback control. Each process characteristic is described in the following.

WBS 3.1.1 – Native Language Capability and Comparison

This process characteristic involves studying the new feature-based and intuitive capabilities of the native programming language of the CMM. The software will also be compared to other software packages such as the NIST Algorithm Testing System (ATS) standard geometry representation data sets and the Dimensional Inspection Techniques Specification (DITS) from Computer Aided Manufacturing-International (CAM-I). In-house-developed inspection routines from the Automated Inspection Metrology Program will be used as a comparison. This will determine the native language's ability to detect known deviations from geometrically exact feature definitions. It will give an accurate comparison of this software's evaluation algorithms with standard algorithms.

This process characteristic also involves performance studies on geometric form measurement by rapidly traversing the part and sampling data points. In scanning, many points are measured as the probe maintains contact with the part. Inspection speed is increased while more data points are collected and statistically analyzed. Important objectives include speed, accuracy, and comparison of analysis data to conventional scanning and point-to-point techniques.

WBS 3.1.3 – Programming and Simulation

This process characteristic involves programming and simulation of the CMM programs on a Silicon Graphics workstation using the Pro/ENGINEER solid modeler and Cimstation programming and simulation software. The solid modeler is fully integrated with the programming software so that all data and

imbedded knowledge are retained from the model and used in downstream applications. The output of the Cimstation programming system is an American National Standards Institute (ANSI) standard data format known as Dimensional Measuring Interface Specification (DMIS), which was developed by CAM-I. The DMIS format program is automatically converted into the native language of the CMM. Dynamic simulation of the CMM and part program confirms that no errors are present. The solid modeling software can also be linked to a stereolithography system for rapid prototyping and part fixture construction.

WBS 3.1.4 – Machine Characterization

This process characteristic involves instrumenting the CMM with sensors to measure temperature linear displacement very accurately. Accuracy of $<0.1\ \mu\text{m}$ and a repeatability of $<0.05\ \mu\text{m}$ over the volume of a typical ceramic heat engine component will be maintained. The ability to use very small (less than 1-mm-diam) spherically tipped probes for measurement of small holes will be tested. This subelement also involves testing the CMM with loads varying from smallest possible to maximum machine capacity. It is important to determine the effect on machine accuracy due to load. Finite element modeling will also be applied to predict the machine response to loads. This is important because it simulates real-world conditions that the CMM will see and gives the manufacturer information that will allow for the reduction or compensation of loading effects.

WBS 3.1.4 – Near-Real-Time Feedback Control

Work on this process characteristic involves linking the CMM to machine tools and being able to send dimensional part data back to the machine control and programming systems. This will complete the closed-loop feedback system, which will allow for rapid design to machining to inspection capabilities within the CMC. It also involves development of near-real-time adaptive control of machine tools via direct link to the CMM. The goal is to use the CMM as a process auditor, updating the position registers of the machine tool's CNC during a specific manufacturing function. In this case, accurate part machining corrections can be automatically made based on measurement of the previously machined part. It will serve as a complementary control system to the in-process inspection system. The complete system will be made available to industrial partners.

WBS 3.2 – SURFACE INTEGRITY

This subelement includes work which determines the appropriate equipment to use for surface integrity measurements. Both a surface profilometer and an

atomic force microscope (AFM) will be compared to determine the capabilities of each device in correlating the as-machined surfaces to the mechanical strength of the ceramic components. The surface profilometer is capable of measuring both surface roughness and waviness on a large scale, while the AFM is capable of the same measurements on a much finer scale. The relationship of peaks to valleys on the surface of a part significantly affects the wear and life of the part. Many peaks will wear faster, while many valleys will actually hold lubricants and increase part life. Too many, or very deep, valleys will be sites of fracture initiation and will reduce part life.

This program subelement is organized as shown in Fig. A4 and includes two process characteristics: (1) macro-scale structure, and (2) micro-scale structure. Each process characteristic is described in the following.

WBS 3.2.1 – Macro-Scale Structure

This process characteristic is determined by using a surface profilometer to characterize the machined surfaces of ceramic components. Important factors include the average groove depth, the maximum groove depth, and the distribution of grooves. One limiting factor in surface profilometer measurements is the size of the diamond probe tip and its ability to penetrate narrow grooves. The surface profilometer is a fast measurement device, but it is limited in the ability to resolve characteristics of the surface of a part.

WBS 3.2.2 – Micro-Scale Structure

This process characteristic is dependent on the capabilities of an AFM in characterizing the machined surfaces of ceramic components. In this case, the probe tip is much smaller than in a surface profilometer, but the maximum size of groove that can be imaged is limited. The device is slower and more sensitive to rough surface finishes than the profilometer. It may be necessary to use both types of instruments to completely characterize machined ceramic surfaces.

WBS 3.3 – STRUCTURAL INTEGRITY

This subelement includes work which determines the structural integrity of machined ceramic components and correlates the integrity with mechanical strength. The subsurface flaws and damage induced by machining must be minimized in order to achieve acceptable structural ceramic components. Brittle materials are very sensitive to stress concentration initiation sites, which will lead to rapid failure by fracture. Reliable methods must be established to detect and quantify structural flaws.

This program subelement is organized as shown in Fig. A4 and includes five process characteristics: (1) residual stress, (2) microstructure, (3) subsurface flaws, (4) mechanical strength, and (5) design data base. Each process characteristic is described in the following.

WBS 3.3.1 – Residual Stress

This process characteristic involves measurement of residual stresses induced in the final part by machining. Residual stresses can be present in the initial ceramic from forming processes or can be produced during machining. Large stresses will cause tensile loads just below the surface of the ceramic component that will initiate crack growth. An X-ray technique is utilized which can resolve residual stresses just below the surface of the component.

WBS 3.3.2 – Microstructure

This process characteristic involves analyzing the microstructure of the ceramic component in a transmission electron microscope (TEM) and the fracture surface of the ceramic component in a scanning electron microscope (SEM). The information obtained will help determine the effect of machining on the subsurface structure of ceramic components. The TEM will give bulk material properties, while the SEM will detect fracture initiation sites. If the fracture initiates on the surface or near the surface of the ceramic, it can be caused by machining. If the fracture site is deep within the material, it is due to internal flaws.

WBS 3.3.3 – Subsurface Flaws

Measurement of this process characteristic involves applying acoustic wave microscopy in detecting subsurface flaws in ceramic components. Some of the flaws may be inherent to the material, while others are introduced during machining. Acoustic wave will penetrate the surface of the ceramic and detect flaws below the surface. The method is quick and inexpensive when compared with TEM or SEM.

WBS 3.3.4 – Mechanical Strength

This process characteristic is determined by machining flexure bars by different machining methods and determining the degradation of fracture strength by four-point bend testing. The machining method will be correlated to fracture strength. This test method is quick but not as reliable as tensile testing. Since bending puts tensile stresses just below the surface of the specimen, it is very sensitive to surface and subsurface condition caused by machining. It can be used as a screening process for machining grindability tests. Work in this area also involves machining tensile specimens by different machining methods and

correlating the machining damage to tensile strength. Tensile strength is intended to give bulk material properties. It is very reliable but is more expensive to conduct than bend testing. Bending moments must be minimized during tensile testing. If the failure site is indicated to be near the surface by SEM, it is probably due to machining effects. This work will be conducted in the existing HTML User Centers.

WBS 3.3.5 – Design Data Base

This process characteristic is intended to develop a data base for design of ceramic components. The data base will include material properties and design requirements such as probabilistic failure based on the component geometry and mechanical strength. Actual ceramic heat engine components will be designed with the Pro/ENGINEER solid modeler and COSMOS/M finite element analysis software. The Ceramic Analysis and Reliability Evaluation of Structures (CARES) probabilistic failure software from National Aeronautics and Space Administration (NASA)-Lewis Research Center will then be used to predict the probability of failure using the finite element model and the material mechanical strength. Models will be verified by laboratory tests to prove the modeling accuracy.

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