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Ceramic Technology Project

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Office of Propulsion System Materials
Office of Transportation Technologies
Energy Efficiency and Renewable Energy
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Executive Summary

An assessment of needs for the manufacturing of ceramic gas turbine components was undertaken to provide a technical basis for planning R&D activities to support DOE's gas turbine programs. The purpose of the assessment was to determine the underlying technical issues that must be resolved in order to enable the cost effective manufacturing of ceramic turbine engine components in the relatively large quantities required for commercialization of the DOE turbine technologies. The manufacturing processes for ceramic turbine engine components were examined from design through final inspection and testing. The following technology needs were identified:

- Concurrent engineering early in the design phase to develop ceramic components that are more readily manufacturable.

- Additional effort in determining the boundaries of acceptable design dimensions and tolerances through experimental and/or analytical means.

- Provision, by the designer, of a CAD based model of the component early in the design cycle.

- Standardization in the way turbine components are dimensioned and toleranced, and in the way component datum features are defined.

- Rapid means of fabricating hard tooling, including intelligent systems for design of tooling and rapid prototyping of tooling.

- Determination of process capabilities by manufacturing significant numbers of parts.

- Development of more robust ceramic manufacturing processes which are tolerant of process variations.

- Development of intelligent processing as a means of controlling yield and quality of components.

- Development of computer models of key manufacturing steps, such as green forming to reduce the number of iterations required to manufacture in-tolerance components.

- Development of creep feed or other low-damage precision grinding for finish machining of components.

- Improved means of fixturing components for finish machining.

- Fewer and lower-cost final inspection requirements.

- Standard procedures, including consistent terminology and analytical software for dimensional inspection of components.

- Uniform data requirements from the U.S. turbine engine companies.

- An agreed-upon system of naming ceramic materials and updating the name when changes have been made.

Recommendations

- The desire to develop production-viable processes for manufacturing large quantities of components and the need to have engine quality hardware in small quantities but in a timely manner for testing are sometimes in conflict. It is suggested that both production-viable manufacturing processes, and more flexible processes for producing prototype quantities of parts be pursued in parallel. Small numbers of components for engine testing might be made most effectively by rapid prototyping methods such as green or bisque machining or, ultimately, by soft tooling approaches such as stereolithography for making the precision ceramic shapes.

- Manufacturing processes suitable for aerospace and stationary gas turbine quantities of components might be developed as an

intermediate step toward processes suitable for automotive quantities of components.

- It is important that a significant number of parts be manufactured to determine process capability. It is recommended that relatively large numbers of parts be manufactured, even if the number of specific components and designs manufactured is limited by available resources, i.e., make large quantities of a small number of components.

- The needs identified above are all important to a cost-effective manufacturing process for high-quality components and should be addressed in DOE's manufacturing programs for ceramic turbine engine components.

Introduction

An assessment of needs for the manufacturing of ceramic gas turbine components was undertaken to provide a technical basis for planning R&D activities to support DOE's gas turbine programs: the Office of Transportation Technologies' Hybrid Vehicles Program and the supporting programs, Hybrid Vehicles Turbine Engine Technology Support (HVTETS), the Ceramic Turbine Engine Demonstration Project and the Transportation Materials Program Ceramic Technology Project; and the joint Fossil Energy/Energy Efficiency (Office of Industrial Technology) Advanced Turbine Systems Program. The purpose of the assessment was to determine the underlying technical issues that must be resolved in order to enable the cost effective manufacturing of ceramic turbine engine components in the relatively large quantities required for commercialization of the DOE turbine technologies.

In the current and past DOE programs, the ability of the domestic ceramic suppliers to provide ceramic components meeting dimensional and mechanical behavior requirements in a timely fashion has often been viewed as a problem by the engine companies. Frequent complaints were the long time period between the initial design of a component and delivery of the first article, inability of the suppliers to meet dimensional requirements of the parts, and mechanical behavior of the components that was not consistent with that predicted from test bar data. The ceramic suppliers, on the other hand, complain that the orders for components are never for enough parts to establish process capability, and that the engine companies change the design of the components too frequently.

The engine companies typically want to procure components made using a production-viable process, even though the engine companies buy only a small number of parts that might be made more easily using a low-volume process.

The purpose of the present effort is to determine the underlying technical issues that impede efficient manufacturing of ceramic gas turbine components, and to recommend a technical approach for systematically solving those problems.

The approach taken in the assessment has been visits to the key participants in the DOE programs and interviews to determine the perception of each participant as to the critical technical issues. This report represents a summary of what was learned, and does not present the results broken down by participant. However, we did make distinctions between the needs of the various groups involved in the process: engine companies, ceramic suppliers, and machining companies.

The participants in the assessment were as follows: AlliedSignal Engines, Allison Engine Co., Solar Turbines, Inc., AlliedSignal, Inc. Ceramic Components, Kyocera Industrial Ceramics Corporation, and Norton Advanced Ceramics.

Summary of Findings

Differences in Manufacturing Processes for Metal and Ceramic Components

There are significant differences in the processes for manufacturing ceramic and metal gas turbine components. It is useful to examine the differences in the processes to understand some of the difficulties ceramic suppliers have had in providing hardware, e.g., in the DOE ATTAP program. Metal components, such as vanes and blades, are typically formed by investment casting. See, for example the ASM Handbook (1) for a description of the investment casting process. Ceramic components are formed by powder metallurgy processes: green forming followed by sintering, with or without gas pressure, or by hot isostatic pressing. These processes are described, for example, by Richerson (2) and are discussed in the section below on fabrication of the ceramic blank.

The engine companies play a significantly different role in the process for manufacturing metal components than in that for ceramic components. For example, with metal turbine blades, the engine companies buy the cast blades from a casting company and then have them coated and machined by other suppliers, or do the work themselves. In either case, the casting company usually has no responsibility for the finish machining and inspection of the cast blank. The engine company provides the drawing for the cast part, the finished part, and performs (or out sources) the final inspection.

Ceramic components are purchased as completed hardware, i.e., the ceramic supplier is responsible for fabricating the as-sintered part, as well as performing the finish machining, and final inspections. Thus, the ceramic supplier must determine his shrinkage factors (approximately 20% linear shrinkage) for densification of the green parts, develop the drawings for the green and as-sintered parts, order hard tooling for forming the components, then fabricate the as-sintered parts, machine the parts to final dimensions and perform the final inspections.

The machining and inspection of gas turbine components are sophisticated manufacturing skills (see the following sections on Design, Machining, and Inspection). One would not necessarily expect a ceramic component supplier to possess the machining and inspection skills, and, in fact, these operations are often out sourced. (Some engine companies feel it is desirable to have more vertical integration of the manufacturing by the ceramic supplier by, for example, bringing tooling fabrication and component machining in-house.) The relatively large shrinkage (20%) that occurs in densification of the green ceramic part, compared to 2% during the investment casting process for metal components, results in a significant potential for warpage in the sintered ceramic parts. This potential for warpage significantly confounds the machining and inspection steps.

At least one engine company now also buys new metal designs as finished components instead of castings. The trend seems to be toward procurement of finished components; thus, it is likely that the ceramic suppliers will continue to be required to furnish finished components.

The relationship between the engine companies and ceramic suppliers is also different with respect to concurrent engineering and establishment of fixed ceramic processes. For metallic components, the same superalloy composition can be procured from a number of sources via the same general process. The ceramic suppliers, on the other hand, each have unique, proprietary compositions and processes. Most processing problems encountered by the ceramic suppliers must be solved via resources within their own companies in order to protect trade secrets. In addition, little expertise pertinent to the ceramic supplier's specific composition and process exists outside the ceramic company as compared to the metals casting industry.

Design

Ceramic and metal components are designed to similar geometric and tolerancing requirements. The geometry of most of the ceramic blades and vanes we observed is similar to their metal counterparts, probably because metal components represent a known starting point to the designer or because the ceramic component is a retrofit. As a result, many of the ceramic components we observed were designed with dimensions and tolerances that are appropriate for metal components. This has resulted in low yields of in-tolerance ceramic components, since the behavior of ceramic materials is quite different from metals in most phases of the manufacturing process. More appropriate tolerances might be developed by concurrent engineering and by determining the effects of tolerances on performance by computer simulations and actual rig and engine tests. The engine companies are not supportive of this view, and point out that rig tests to evaluate the effects of tolerances are not possible in a meaningful way until the ceramic companies can make components that strictly meet the print. Modeling may be the only way to establish the effect of tolerances.

There is a fundamental lack of communication between designers, manufacturers and end users of ceramic components during the early design phase. The component manufacturer feels that he frequently has no meaningful input into the design of the product. In many cases, designs could be modified slightly to greatly improve manufacturability and reduce costs. Frequently, design changes occur well into the component manufacturing cycle, often as a result of fabrication difficulties encountered by the ceramic supplier or sometimes from rig test results. The result is added expense and schedule delays.

The designer does not always supply the component manufacturer with a correctly defined, computer-aided-design (CAD) based model of the component. This forces the manufacturer to spend additional time generating a model that is based on his own interpretation of the design drawing. When models are provided by the designer, they are often generated by a CAD system different from the one used by the manufacturer. Even though most CAD packages have the ability to translate information from one format to another, the results are far from perfect. (People familiar with word processors who have tried to read a Microsoft Word document with WordPerfect, or vice versa, will have an understanding of the problem.)

Component manufacturers who have a strong on-site CAD capability believe that the use of CAD models should be universal. They believe the model should be provided by the designer; it should be available *early* in the design cycle; the model should be used for tooling and fixture design, as well as machining and inspection programs; and the same coordinate reference system should be used throughout.

Another common complaint from component manufacturers is that designs are too aggressive and impractical to produce. From the perspective of component manufacturers, designers are conservative in specifying geometric dimensions and tolerances. There is often no experimental basis for this conservatism. Out-of-tolerance components subjected to engine tests have, in some cases, exhibited performance equal to that predicted by analytical models. From the point of view of the engine companies, the trend in new engine designs is toward more aggressive aerodynamic designs and the ceramic components must meet the aerodynamic requirements to be competitive. There is a need for additional effort in determining the boundaries of acceptable design dimensions and tolerances. This determination could be made through experimental or analytical means, or a combination of both.

There is a lack of uniformity in the way design drawings are defined and interpreted. Dimensional requirements for both ceramic and metal parts generally fall into the categories of *size, form, location* and *tolerance*. The standard that governs true-position dimensioning and tolerancing is ANSI Y-14.5. Although ANSI Y-14.5 attempts to provide a consistent method of defining dimensional requirements, it is an evolving standard and it is far from perfect. It is difficult to find two designers who always agree on interpretation of the Y-14.5 standard. It is nearly impossible to find a designer, machinist, inspector and end user who all interpret the meaning of a complex drawing in the same manner.

There is a general lack of standardization in the way that turbine blades and vanes are dimensioned and toleranced. The typical blade or vane drawings we observed were very complex and did not conform to the Y-14.5 standard. Furthermore, the standard applies only to the dimensioning and tolerancing of drawings — not to the manufacturing and inspection methods used to achieve those dimensions and tolerances. This situation is common to both metal and ceramic components, but is apparently a less serious problem in the metalworking industry.

A standardized methodology is needed for establishing coordinate reference systems on components. The definition and establishment of datum surfaces is also a problem that was common throughout the facilities we visited. A *datum* is a theoretical geometric element such as a plane, a line or a point. Datums are used to establish Cartesian coordinate systems relative to the surface of the component. This process is fundamental to dimensional metrology. Real components have physical geometric features that closely match the theoretical datum surfaces. However, because of real-world irregularities in the component, these physical features never agree exactly with the theoretical surfaces. This is true whether the component is in a machined or an as-sintered condition. However, unmachined surfaces tend to be even more irregular than machined surfaces. It is very difficult to measure an unmachined surface repeatedly and obtain reproducible results. Therefore, it is generally not practical nor advisable to use an unmachined surface to establish a datum.

Certain features of ceramic components are frequently left unmachined (typically the airfoil shape), while other features (such as the attachment surfaces) are machined to very small, i.e., demanding, tolerances. In some instances the designer specifies two separate sets of datum features — one for surfaces that are as-sintered and one for machined surfaces. Thus two distinctly different coordinate systems are defined for the component. In at least one instance, we observed that these two sets of datums were intermixed, causing confusion between the designer and the producer. A consistent, industry-wide method needs to be developed for defining blade and vane datum features.

Better tools are needed for predicting the effects of distortion and shrinkage due to sintering and other processing variables. This would reduce the number of tooling iterations required and would speed up the manufacturing process. In addition to rapid prototyping for tooling, discussed below, computer models of mold filling, including die fill and defects and stresses introduced are needed.

Manufacture of Blank Component

Introduction The ceramic component fabrication process begins with receipt of the raw material powders, being in all the cases studied herein both silicon nitride powder and sintering aid(s). These materials are normally purchased to a specification from the component manufacturer which has been worked out based on their experience in materials development. The sintering aid(s) are blended with the silicon nitride via some form of milling action, with the assistance of a liquid vehicle for forming a slurry. The liquid vehicle usually also contains a dispersing agent to maintain the powders in suspension, and a binder to provide some green strength to the formed part. The liquid is water, where possible, to minimize environmental and handling problems; alcohols and other organics may be used instead in some cases.

The suspension may then be cast into a mold: when performed without pressure (slip casting), a porous plaster mold to provide for water removal is normally used; when performed under pressure (pressure casting) to speed up the water removal, the process uses a stronger mold such as a porous plastic. Another process involves spray drying the suspension, followed by isostatic or uniaxial pressing, then green machining. Injection molding uses a suspension vehicle which is not aqueous but totally organic, such as a thermosetting or a thermoplastic polymer or wax, followed by forcing the suspension into a mold under pressure. A variant of this practice is often called "hybrid molding," in which the wax or polymer is mixed into an aqueous or organic vehicle and the whole forced into a mold under pressure, where the vehicle is solidified or removed. A final type of fabrication is known as gelcasting, wherein the powders are suspended in an aqueous medium containing a monomer which is heated to cause polymerization to occur. All of these forming processes, with the exceptions of bisque or green machining, require the design and fabrication of precision tooling. The tooling is often articulated to facilitate removal of the parts and may be quite complex mechanically. The dimensions of the tooling must take into account not only the precise shrinkage factors, but also the anisotropy in shrinkage due to orientation and thickness effects; failure to properly account for these factors will result in warpage and out of tolerance parts.

The next step is drying, for those processes utilizing water or a low-viscosity organic as the suspension medium. At this point, if the green shape has sufficient strength, some machining may be performed, commonly referred to as "green" machining. For other components, the binders/waxes/polymers may be burned out and a partial sintering performed prior to machining, which is then known as "bisque" machining. For components which are very near to net shape, no machining is needed.

The green part is then densified, by atmospheric-pressure sintering, if possible, thereby maintaining low cost for the process, or through use of a batch-type process such as gas-pressure sintering or HIPing. To modify the strength or toughness of the silicon nitride, some materials are subjected to an annealing process prior to the final grinding procedure. Many are also subjected to a post-machining process, to relieve machining-induced stresses and/or provide for surface crack healing/blunting and coating of the surface of the component with a coherent oxide protective film.

A large number of parameters are necessarily involved in manufacture of the component, based on the large number of steps just described. Incomplete understanding of some of these parameters, or the inability to control them, leads to problems in manufacture of components which meet the strength, performance, dimensional, and defect level specifications of the end-user. Poor knowledge of these parameters may also hinder timely delivery of first-article components. It also leads to low yields, and consequent long delivery times and high individual costs.

The following section is a critical analysis of these parameters, their sources, and effects on component manufacture.

<u>Parameters Affecting Ceramic Turbine Component Fabrication</u> The ceramic raw materials are purchased under a specification defined by the user, within the product definitions provided by the suppliers. Commonly used specification parameters for the silicon nitride powder include particle size and range, specific surface area, oxygen content, and impurity content. There may be others, but these predominate, as they are known to affect the fabricability and ultimate strength performance of the component. Unfortunately, it has proven impossible to specify a powder completely enough that a user can determine from these data alone whether the powder will perform to expectations. That is, powders with apparently identical values for the specified parameters will perform differently in the manufacturing process. Thus the user is forced to perform a "goodness" test, usually involving the complete manufacture of a number of test components. (The counterpart in the metals industry is the master heat qualification). This need adds to the time to manufacture the components, and adds cost. Another problem arises when the raw material supplier is unable to prepare powders to the "tightness" of the specification, requiring them to select only certain batches of material to fill the requirement. This problem keeps the cost of the powder high. In the event that the user is sophisticated enough to know the effect of using powders with varying values of the specification parameter, then they may use the powder but will have to modify either the powder or the manufacturing process in some way.

In general, the same problems hold for the sintering aid(s), which are normally oxides or oxide precursors. However, less is known about the effects of lot-to-lot variances in these materials, as the silicon nitride powder has normally been much more aggressively studied. Of course, this depends on the ceramic company's experience in the field.

Incomplete knowledge of these variations in the characteristics of the raw materials, or their effects, complicates the manufacturing process in several ways. One of their major effects is on the ability of the suspension or powder to form a shape within which the particle density is constant from point to point. If this does not occur, the component will distort during densification, as the less dense portions of the component will shrink more than higher density portions. Even when it is known that this density variation may occur within a specific component, two other problems may arise: (1) the point-to-point variation may not be constant, leading to part-to-part differences in the distortion, and (2) the effect will be different for components of other sizes or shapes and for different compositions, so that the component manufacturer cannot predict *a priori* how a component of a new design will distort.

Consequently, new designs require several iterations of mold or die procurement, which can be costly and result in long lead times for first article preparation. A separate problem which is often confronted at this stage is the inability of die- or mold- manufacturers to prepare the requisite die or mold cavity in speedy fashion. Delivery times may range from a few weeks to several months, depending on the complexity of the mold. The inadequate knowledge of the shrinkage factors on the part of the ceramic manufacturer may require a second, or even third, round of die fabrication. Among the tools needed are an expert system for tooling design and an inexpensive and reliable rapid prototyping capability for tooling.

Drying and binder burnout do not appear to be as critical to the overall process capability as the previous process steps. However, at least one of the manufacturers interviewed pointed out specific difficulties in these areas: there is a strong effect on part yield when the process is pushed too rapidly (cracking, distortion) or too many parts are placed into the furnace at one time. Not enough attention has been placed on this problem, because, in general, not enough parts have been fabricated to gather a database on the process. For cost reasons, it is desirable to minimize the time spent drying and bisque firing.

Those companies that do a green or bisque machining appeared to feel that these processes are under good control, possessing the ability to reliably produce a high yield of in-specification parts.

Densification, on the other hand, is a known major source of problems. In general, because of the high temperature requirements for densification of turbine component grade silicon nitride, a pressure sintering approach is utilized: either gas pressure sintering (GPS) or hot isostatic pressing (HIPing). The batch nature of these processes necessarily adds to process cost. Loading of the furnace has an effect on component distortion and overall density, which is poorly to moderately well understood by the various companies. Low yield is a common result of the densification process, but it is not all due to the process itself. That is, it is after densification that problems which were introduced into the component earlier will appear. Density variations introduced in the forming stage and/or incipient cracking or even surface irregularities not removed prior to sintering in the drying/bisque firing stage will develop into noticeable defects after the densification step.

Commonly, the ceramic manufacturer has not fabricated large numbers of the specified component, or a similar type of component, so that the knowledge of the overall process capability, and of the individual steps in the process are inadequate. Several parameters affect this capability: raw material variations, shelf life ("aging") of prepared batches, stability of forming equipment, wear of machinery and molds or dies, and effects of furnace loading and part position within the furnace, as well as those described above. In general, it is concluded that the ceramic manufacturers need more experience in fabricating turbine components in order to build up a process database, and thus better define their process capabilities.

A common problem associated with fabrication processes for advanced materials, such as silicon nitride turbine components, is that the individual steps and the overall process have been developed to provide optimum fabricability and strength of the component, based on tightly specified materials and processes. When variations in the materials, process equipment, ambient conditions, personnel, or other factors occur, the process typically results in less than optimal performance. More "robust" processes are needed, which will be more tolerant of normally occurring variations. This type of process development has not been utilized widely in the ceramics field, but is to be strongly encouraged, as it will lead to fabrication processes which will produce consistently high quality components.

Another need in the advanced ceramic component manufacturing arena is intelligent processing. It requires a well developed process model, preferably described via a set of statistically designed experiments. Given statistical knowledge of the effects of raw material or process variability, intelligent process controls can be utilized to provide feed-forward or feedback control. For instance, if it is known that a specific amount of variation in the oxygen content of a silicon nitride powder will affect the formability by a known amount, then either the powder can be treated to provide the nominally specified oxygen content (feedback control) or the slurry preparation process can be modified to accept the powder as-is (feed-forward control). It is recognized by the authors of this report that generation of the data to provide for such a process model, and the control systems to allow intelligent processing, are time-consuming and costly. However, the benefits of having such a model and control system are well worth the time and effort to obtain, consistently yielding reliable, in-specification components.

Machining

Introduction Grinding of ceramic materials requires the utilization of superabrasive grinding media, primarily diamond. Diamond grinding wheels are relatively expensive, and some degree of expertise is required of the machine operator if the machining operation is to be accomplished effectively and economically. This expertise is frequently not available either inside the ceramic company or within the available job shops.

If a ceramic company does not desire to do the machining on the ceramic blanks there are a very limited number of outside companies that will agree to take on contour grinding of a complex ceramic component. This is due to either a lack of existing previous experience, or to an undesirable conflict with their existing businesses. There are concerns that job shops are getting the bulk of the experience at present, but will not be doing the production jobs when markets develop.

The condition of the ceramic component surface, once ground, is of great importance not only to assure good fit with mating surfaces but more importantly, to insure an acceptable level of retained strength in the ceramic material. Cracks and subsurface damage have a significant effect on brittle materials like ceramics. If there is substandard strength in the material, then there is no utility in the part, and use of the part may, in fact, create a safety hazard.

The actual stock material removal process (generally a grinding or other abrasive operation) may not be as serious a problem to a machine shop as the perception of what the machined surface should look like and where it should be located. The engineering drawings are not always as clear and definitive as one would like. There appears to be little concurrent engineering and consultation with available manufacturing expertise when the initial designs are determined. As the machining is often outsourced, the machining expertise is not always brought into the early design process. This causes numerous manufacturing problems once the ceramic blanks reach the shop floor. In some cases, there has been poor understanding of the designer's intent with respect to datum surfaces, resulting in significant problems with fixturing.

The small numbers of parts ordered under the present programs present problems in machining, just as they do in other parts of the manufacturing process; the small numbers of parts do not allow development of cost-effective processes. Manufacturers must, in some cases, try to get the small number of parts out on a timely basis by rapid prototyping processes such as slip casting or gelcasting followed by green or bisque machining. The rapid prototyping is a good approach for meeting engine test schedules, but does little to develop high volume, cost effective processes.

Another problem common to machining as well as other unit operations is low yields, which result from manufacturing processes that are not, at present, well developed. Yields less than 90% seem to be a factor in each production step from initial powder preparation and casting through to final machining and certification. This series of 50 to 80 percent yields incurred in each successive step can ultimately result in overall yields as low as 5 to 10 percent for the finished, certified, and marketable component. This is completely unacceptable in high volume production of any component and illustrates the need for a program to develop manufacturing technology for gas turbine components.

R&D Needs for Machining Diamond grinding is the only viable machining process for ceramic materials; however, there are choices or alternative grinding processes that might be used to improve the results currently obtained. Typically, creep feed grinding is claimed to have increased stock removal capability over conventional grinding processes, while also producing improved surfaces in terms of surface finish and subsurface damage. This machining concept is already used for grinding of metal blade attachment surfaces. Obviously, work would be required to develop the optimum grinding parameters for the surfaces and contours of the ceramic parts, but this approach has a relatively high probability of success and should be pursued. As previously mentioned in the machining introduction section, existing subsurface damage and cracks have a very large impact on material strength and consistency of load carrying capability. The choice of optimum machining parameters would have to consider the resultant subsurface damage to be a major criteria in evaluation of these parameters.

There is, of course, a need for improved, more rapid, lower cost stock removal processes for ceramic components. There are ongoing programs which address these problems, e.g., the Cost Effective Ceramic Machining effort in the Ceramic Technology Project and the DOE Cost Effective Machining of Ceramics program which is a joint effort by three DOE programs. However, the unique problems encountered in machining complex, high-precision gas turbine components should be addressed in a complete component manufacturing program. For example, intelligent machining processes utilizing closed loop feedback controls to monitor acoustic emissions and machining stresses might be used to optimize the machining rate without damaging the components.

Design of fixturing for positioning of the blank during machining is a major consideration from several view points. First, the blank must be held securely so that it will not move or be damaged by the heavy loads imposed during the machining operation. At the same time, the blank cannot be broken by unbalanced clamping forces which might be used to hold the blank in position during machining. Frequently, castable fixturing is used to deal with this requirement, but castable fixturing has a number of problems that can cause difficulties in high volume production. This type of fixturing doesn't readily allow in-process inspection, and it can be a time consuming operation, a cost inflator for high volume production.

The fixturing must also hold the blank in the correct position relative to the existing datum locations so that the machined surfaces can be correctly placed on the blank. These machined surfaces will thereafter become the new *de facto* datum surfaces since they are what will position the air foil surfaces relative to the air or gas flow. If these machined surfaces are not properly located, then the air foil will lose effectiveness and not perform properly. In order that the to-be-machined areas of the blank are properly located, the fixturing which necessarily grips the air foil surface must be capable of repeatedly positioning the blanks correctly.

The variability of actual as-processed surface datums make accurate positioning difficult. There is a need for fixtures which accommodate variability and there is a need for a means to quickly accomplish adjustments in positioning. The design of fixturing which will both securely hold and position the blank for machining and contribute to cost-effective, high-volume production operations is a necessity. Then machining tests must be conducted to develop and prove the fixturing concept. This will require a considerable number of blanks being machined into parts that can be inspected and certified as to air foil location. This exercise will also push existing expertise a little higher up the learning curve and assist in establishing a production process that is effective for higher-volume production of ceramic components. The fixturing developed may be somewhat part specific as far as database establishment is concerned, so a number of different geometry blanks will be required to determine appropriate machining fixtures for various parts needed for different engine designs.

A far greater number of parts than ordered in the past will be required to establish high volume production techniques for ceramic engine components. The above tests, if conducted, would satisfy that need whether the machining is done by the ceramic company or by a subcontractor.

As an added recommendation, if hard tooling for casting or forming ceramic blanks continues to be a significant long-delivery item, particularly with changing designs, the blank supplier may want to consider establishing an in-house capability for making this tooling. If the supplier is considering establishing better fixturing and grinding capability for the ceramic blanks, then an added capability for also machining hard tooling would not be a great additional extension of capability.

Nondestructive (and Destructive) Evaluation

Inspections performed during fabrication are essential to developing a database of process capability, as well as providing knowledge of where specific problems such as inclusions or cracks or distortions occur. An additional benefit is that unsuitable components can be rejected before additional costs have been allocated to their manufacture, but it is presumed that for mature, well-defined processes, this benefit is minimal. That is, non-destructive examination (NDE) will not be required to "weed out" defective parts: it will be used for intelligent process control. Application of NDE is extremely beneficial during process development for the purpose of determining problems associated with specific process steps.

Commonly used destructive examination (DE) techniques are chemical and physical analysis of raw or in-process materials, metallographic examination of dense specimens, and mechanical property testing of materials, including proof-testing. NDE techniques include visual or microscopic inspection; dimensional inspection; fluorescent penetrant inspection; x-ray, gamma-ray, or neutron radiography; ultrasonic examination; and others which are less commonly utilized.

The companies surveyed for this report appeared to be well equipped, in general, for DE and NDE testing. All would like, of course, for the equipment and materials (film, for instance) to be less costly and for the techniques to yield higher resolution, but this area does not appear to present any significant problems. Another need noted was for increased automation, both to lower costs and to remove the variability brought about through human interpretation. What is needed is experience in applying these techniques to production processes, and lowering the total inspection cost through minimizing the amount of inspection performed. The latter requires a well developed and understood production process.

Inspection

There are differences in inspection results, depending on the inspection method used. The ceramic component industry is plagued by a problem that is universal to *all* manufacturing facilities engaged in machining and inspecting components. The problem is the apparent lack of agreement between inspection results obtained by different methods and on different equipment. Some vendors and/or end users rely on functional gauges to determine if a component is within tolerance. Other vendors/users rely almost exclusively on CMM inspection data.

Functional gauging has the advantage of quickly determining whether a part is functionally good or bad — hence the name *functional gauging*. This technique is also well suited for in-process inspection, where the process is robust and well understood. However, functional gauging does not supply easily analyzed numerical data. Functional gauges are also very expensive and must be modified each time the design of a component is changed. CMMs are slower than functional gauges, which makes them expensive sampling tools. However, they provide quantitative numerical results that can be statistically analyzed to establish process control charts. The CMM is also a wonderful diagnostic tool that can pinpoint geometric problems with both as-sintered and machined components. CMMs require a large initial capital investment and an investment in skilled personnel for programming and operation.

Some vendors and end users do not have an in-house inspection capability. They must rely on the integrity and skill of third-party inspection houses. It becomes difficult for them to use the CMM effectively as a diagnostic tool because of the inspection turnaround time and the expense of using a third-party inspection service.

There are differences in results obtained through functional gauging and those obtained on a CMM. This is partially because a functional gauge deals with *maximum material* surfaces while a CMM deals with *average* surfaces. For example, when a functional gauge is used to measure the location of a geometric plane, it comes into physical contact with the three highest points on the surface being measured. (Three points, not in a straight line, will uniquely determine a plane.) On the other hand, a CMM can use as few as three points or as many as several hundred points to establish a plane. In most cases, an average, best-fit surface will be computed by the CMM software. However, there is no definitive standard for doing this, and techniques vary from manufacturer to manufacturer. Deciding how many inspection points are required to represent the surface adequately is usually left to the CMM programmer.

In some cases, the industry has developed its own pseudo-standards for inspecting blades. When a component does not meet the allowable drawing tolerance for size and/or location, an additional allowance is sometimes provided in the form of *bow, twist* and *lean* tolerances. Unless a consistent terminology and consistent analytical software are adopted industry wide, such complex tolerancing strategies are likely to cause confusion and make it more difficult to determine if a component is in tolerance and a process is in statistical control.

Data Requirements

An extensive database of mechanical properties measured at ambient and high temperatures from test bars co-processed with components and from test bars cut out of components is required of a ceramic material to be used for turbine engine components. The data requirements are not uniform from one engine company to another, requiring some duplication of effort on the part of the ceramic suppliers. The ceramic materials are, in some cases, evolving and improvements are made in the materials, but the material designation is not changed. Thus, the database for a particular material may become obsolete because of changes in the composition or processing of the material. There is a need for uniform data requirements from the users. There is also a need for an agreed - upon system of naming ceramic materials and updating the name when a change has been made that affects the mechanical behavior of the material.

A final problem area noted by the ceramic manufacturers was that of the cost and handling difficulties engendered by the huge data packages required by the engine companies. Much of the data is detailed reports of inspections on each component. The large paper requirement for each component is expensive. There is a need for significantly less paperwork attached to each component for production quantities of parts.

Much of the paperwork to date has been associated with documenting discrepancies. If the hardware meets print, little documentation is required. However, if the hardware is discrepant, and the supplier submits the hardware for evaluation rather than make new parts, detailed inspection results are required to make a disposition. Consequently, design and process improvements will greatly reduce the paper work needs.

Since low yields currently dictate 100 percent component inspection, significant reductions in data acquisition and reporting are also expected following establishment of well controlled processes. Initially, improved yields will permit the use of sampling plans. Eventually, SPC data will be used to eliminate the need for some inspections altogether.

Routine data collection and report generation in production can be automated though the use of computer-based relational databases. Commonality in data requirements between engine manufactures should reduce the cost of data collection and reporting, as well as increase the effectiveness of the statistical process control techniques. Reports generated through computerized databases will create opportunities for paperless communication.

Scale Up, Cost, and Learning

If the technical needs identified in the present assessment are adequately addressed by a comprehensive program of engineering and R&D, the industry can expect a predictable and quantifiable reduction in cost as the number of components manufactured is increased. Learning curves may be used to quantify the cost-quantity relationship. First used in the airframe industry in the 1930s (3), empirical data from many industries have shown that the cost-quantity relationship can be expressed by a simple relationship (4):

$$Y = pX^q$$

where Y is the cost of the Xth unit, p is the cost of the first unit, and q is the index of learning, which can be expressed as

$$q = \ln(\text{fractional learning})/\ln 2$$

The concept is that product costs decline by a constant factor each time the volume doubles. The cost reduction is a result of learning during the manufacturing process and associated improvements in yield and efficiency. For example, with a 70% learning curve the cost per part would be reduced by 30% each time the volume doubled; by the cumulative millionth part, the cost would be reduced by three orders of magnitude from the cost of the first part. The slope of the learning curve can be estimated from experience with similar parts from the same industry or company. Ceramic gas turbine components are very early on the learning curve, and, thus, offer great potential for improvement.

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