THE CERAMIC TECHNOLOGY PROJECT: TEN YEARS OF PROGRESS

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ABSTRACT

The Ceramic Technology Project was initiated in 1983 for the purpose of developing highly reliable structural ceramics for applications in advanced heat engines, such as the automotive gas turbines and advanced heavy duty diesel engines. The reliability problem was determined to be a result of uncontrolled populations of processing flaws in the brittle, flaw-sensitive materials, along with microstructural features, such as grain boundary phases, that contribute to time dependent strength reduction in service at high temperatures. The approach taken to develop high reliability ceramics included the development of tougher materials with greater tolerance to microstructural flaws, the development of advanced processing technology to minimize the size and number of flaws, and the development of mechanical testing methodology and the characterization of time dependent mechanical behavior, leading to a life prediction methodology for structural ceramics.

INTRODUCTION

Ceramics have been actively investigated as materials for advanced heat engines since about 1970. The interest in ceramics for automotive engines has resulted from a desire for higher fuel efficiency, concern over exhaust emissions, a need for greater fuel tolerance and adaptability to alternate fuels, and a need for higher performance and more reliable engines. The energy-saving potential of ceramics in automotive engines is based on higher operating temperatures and reduced friction, weight, and inertia stemming from the mechanical and physical properties of ceramics.

The Ceramic Technology Project was begun in 1983 for the purpose of developing an industry technology base for reliable, high temperature ceramics for use in advanced engines, particularly automotive gas turbine and low-heat-rejection heavy duty diesel engines.

An industry-needs assessment was conducted to obtain the information required to develop a program plan consistent with industry requirements. The assessment concluded that the major need was a substantial increase in the reliability of current materials and the development of new materials and processes with much higher reliability. The industry-needs assessment resulted in the first Program Plan for the Ceramic Technology Project.

While the Ceramic Technology Project has been comprehensive in the development of ceramic technology for heat engine applications, the present review will concentrate on the development of high reliability silicon nitride ceramics via increased fracture toughness and by improved processes to eliminate the sources of strength limiting flaws. The characterization of time dependent high temperature strength and ceramic life prediction methodology will be briefly discussed.

BACKGROUND

Ceramics are brittle, notch sensitive materials. Ambient temperature mechanical behavior is normally elastic up to catastrophic failure. Stress is stored as elastic energy in the material until the stress concentration at a flaw exceeds the fracture strength. The Griffith equation, eq. 1, relates the strength to the inverse square root of a critical flaw:

\[ \sigma = A(\gamma/c)^{1/2} \]

where \( \sigma \) is the applied tensile stress, \( A \) is a constant that depends on specimen and flaw geometries, \( E \) is Young's modulus, and \( \gamma \) is the fracture energy.
modulus, γ is the surface energy, and c is the critical crack length required to cause failure. The critical flaw is typically a flaw introduced during the processing of the material: a pore, a foreign inclusion, a large grain, a surface pit or scratch. For very high strength structural ceramics, the critical flaw size is only a few micrometers. Processing flaws are typically introduced inadvertently and in an uncontrolled manner during the manufacturing of the ceramic part. For example, hard agglomerates or foreign inclusions present in the powder may be incorporated into the part. Metal process equipment, such as mixers, compounders, extruders, etc., may be rapidly worn by abrasive ceramic powders, resulting in the introduction of metal particles into the ceramic. Chips and scratches may be introduced during finish machining.

As a result of the brittle, flaw-dominated mechanical behavior, the expected strength of a ceramic specimen becomes a statistical function, which is determined by the population, size and spatial distribution of the flaws. The Weibull equation, eq. 2, describes the failure strength of a unit volume of material in terms of a distribution function, m, which is called the Weibull modulus, and a scaling parameter a^:

\[ P_f = 1 - \exp[-((\sigma - \sigma_u)/\sigma_0) \cdot m \cdot dV] \]  

where \( P_f \) is the probability of failure, \( \sigma \) is the applied stress, \( \sigma_u \) is a threshold stress, below which failure will not occur (for \( \sigma < \sigma_u, \ P_f = 0 \)). In the ceramics community, \( \sigma_u \) is usually taken to be 0, resulting in what is called the 2-parameter form of the equation. The Weibull behavior infers a volume effect for the mechanical strength, which is dependent on the Weibull modulus, m:

\[ \sigma_1/\sigma_2 = (V_2/V_1)^{1/m} \]  

where \( \sigma_1 \) and \( \sigma_2 \) are the strengths of specimen populations having effective volumes \( V_1 \) and \( V_2 \). Thus, it follows that for materials of relatively low Weibull modulus the strength measured on small test specimens will not be representative of the strength of larger components. The test bar strength will be higher than the component strength. If the Weibull modulus is increased, by modifying the population of strength-limiting flaws, the strength will be less volume sensitive. A particular ceramic material composition can have different strengths and Weibull parameters for different forming methods, e.g., a slip cast component may have a different flaw population than an injection molded part.

The mechanical behavior of ceramics is further complicated by time dependent behavior, e.g., slow crack growth, in which an existing flaw grows under stress at a subcritical rate until it becomes a flaw of critical size and catastrophic failure occurs; or creep, in which high temperature deformation occurs, accompanied by the accumulation of damage in the form of small cavities, which eventually link up to form a crack of critical size, followed by catastrophic failure. These time-dependent failure mechanisms may be influenced by the atmosphere in which the part is exposed. For example, the presence of water vapor has long been known to promote slow crack growth in oxide ceramics.

Silicon nitride ceramics represent a family of materials consisting of approximately 85-95% silicon nitride, with the balance consisting of oxide sintering aids that are introduced to facilitate the densification of the parts by liquid phase sintering. The resultant material typically consists of silicon nitride grains embedded in a grain boundary phase of glassy or crystalline material (Fig. 1). Silicon nitrides have a relatively high fracture toughness as a result of this microstructure. However, the high temperature behavior of the material is dominated by the distribution and properties of the grain boundary phase, which is not as refractory as the silicon nitride grains.
whiskers into the ceramic, or by growing silicon nitride grains in situ into elongated grains that behave like whiskers. To control flaw populations in monolithic silicon nitride, nondestructive inspections have been used throughout the manufacturing process to identify the sources of processing flaws for subsequent elimination or minimization. A deliberate approach to process improvement by the use of statistical process control (SPC) and in-process inspections has been taken. In parallel with the development of improved materials, the time dependent strength of candidate heat engine materials was characterized and models were developed to explain the influence of the ceramic microstructures on the mechanical behavior. A comprehensive effort, still underway at present, was introduced to develop and demonstrate a life prediction methodology for high temperature heat engine components.

DEVELOPMENT OF HIGH TOUGHNESS CERAMICS

The Griffith equation, eq.1, can be written in terms of the critical mode I (tension) stress intensity factor, $K_c$, as shown in eq. 4:

$$\sigma = K_c/(\sqrt{C})$$

where $C$ is a dimensionless term. $K_c$ is referred to as the fracture toughness. The usual interpretation of eq. 4 is that $K_c$ is a material constant, and the equation relates the fracture strength to the inverse square root of flaw size. However, the equation also indicates that, if $K_c$ is increased via deliberate changes in the microstructure, then (other things being equal) the strength is higher for a given critical flaw size, i.e., the tougher material is more flaw tolerant.

Whisker toughened ceramics have been extensively developed in the Ceramic Technology Program. We found that the incorporation of silicon carbide whiskers into alumina or mullite substantially increased the strength and toughness over that of the monolithic ceramic (Fig. 2). The mechanisms of toughening were extensively studied and the means of optimizing the processing of the composites were determined. Crack deflection around the elongated whiskers was found to be largely responsible for the increased toughness. It followed, and was demonstrated that it is important that the whisker be only loosely bonded to the matrix in order for the crack deflection to occur. Whiskers that are smooth and uniform in diameter have been found to be preferable to those with uneven cross sections. In general, larger diameter whiskers result in higher strength and toughness, up to a limit, after which the large whiskers become the source of microcracks which result from the differential in thermal expansion of the whisker and matrix. Impurities in the whiskers may react with the ceramic matrix and result in tight bonding of the whiskers and loss of the toughening mechanism. Debris introduced along with the whiskers, or clumps of whiskers that were not dispersed in the matrix prior to forming may become Griffith’s critical flaw and result in lower strength in the composite than that of the monolithic ceramic.

Silicon carbide whiskers in alumina have also been found to improve the high temperature strength and creep resistance. Of course, the beneficial high temperature effects can be mitigated by impure, irregular, or poorly dispersed whiskers, similar to the case at ambient temperature. A number of non-engine related applications for the whisker toughened oxide ceramics have developed, particularly in the areas of cutting and wear resistance.

A substantial effort was spent in studying the effects of silicon carbide whiskers on strength and toughness of silicon nitride. While both the strength and fracture toughness were increased by the addition of 20-30% by volume of the whiskers, the relative magnitude of the increase was not as great as that observed with alumina. Moreover, the results at high temperature have been mixed. While high temperature strength and toughness were improved, evidence of enhanced creep damage due to the accumulation of voids along the whiskers during creep testing was also seen. Overall, the beneficial effects of the whiskers did not seem to outweigh the increased cost due to the high cost of the whiskers, nor the additional cost of handling the potentially dangerous whiskers. The SiC whiskers are similar in size to asbestos fibers, and limited experiments suggested the whiskers may be at least as dangerous as asbestos.

Fortunately, it was found that long acicular grains of $\beta$ Si$_3$N$_4$ can be grown in situ in the silicon nitride matrix. The resulting material exhibits substantially enhanced strength and toughness, greater than achieved with the whisker toughened material
The measurement of $K_{IIc}$ with Weibull modulus of 20; 1370°C tensile strength of 500 MPa of a liquid phase during sintering. One benefit of these compositions is that they can be densified by gas pressure sintering or even sintering at one atmosphere of nitrogen, as opposed to hot isostatic pressing (HIPing), which is required for the most refractory compositions. The in situ toughened silicon nitrides can be quite creep resistant up to 1200°C, but tend to creep rapidly at higher temperatures, due to the less refractory grain boundary phase, which is present in significant volumes.

These materials have been shown to exhibit what is called R-curve behavior by the fracture mechanics community. The measurement of $K_{IIc}$ as a function of crack length indicates an increasing fracture toughness as the crack grows, up to a limiting value. Development of the in situ toughened silicon nitride requires the addition of significant quantities of sintering aids, as the elongated grains apparently grow in the presence of a liquid phase during sintering. One benefit of these compositions is that they can be densified by gas pressure sintering or even sintering at one atmosphere of nitrogen, as opposed to hot isostatic pressing (HIPing), which is required for the most refractory compositions. The in situ toughened silicon nitrides can be quite creep resistant up to 1200°C, but tend to creep rapidly at higher temperatures, due to the less refractory grain boundary phase, which is present in significant volumes.

Fig. 3. Apparent fracture toughness as a function of crack length for an in situ toughened Si$_3$N$_4$ showing R-curve behavior. After Yeh, et al.\textsuperscript{15}

DEVELOPMENT OF HIGH RELIABILITY MONOLITHIC SILICON NITRIDE

The second approach to improved reliability has been the development of improved processes for manufacturing structural ceramics, which result in fewer and smaller flaws in the microstructure. Primary approaches have been the use of in-process inspections to identify the sources for the introduction of the flaws, and the use of SPC to bring the manufacturing process under control and systematically improve it.

The work has been carried out in a cost-shared contract with Saint Gobain/Norton Industrial Ceramics, Inc.\textsuperscript{16} The objectives of the program, which began in 1989, are a uniaxial tensile strength (see discussion below of tensile testing) of 900 MPa with Weibull modulus of 20; 1370°C tensile strength of 500 MPa, and 1230°C/350 MPa tensile strength of 100 hr. for a silicon nitride-4% yttria material. The component made during the program was a button-head uniaxial tensile specimen.

A parallel program was also carried out at GTE Laboratories,\textsuperscript{17} but was not completed due to a decision by GTE to divest their Si$_3$N$_4$ business.

In the course of the Norton program, a class 10,000 clean room facility was completed, an aqueous process for powder preparation developed, and powder processing scaled up to 35 kg capacity. Two major forming techniques, injection molding and colloidal consolidation, were fully evaluated, including use of finite element modeling and Taguchi\textsuperscript{18} based experimental designs. Colloidal consolidation was selected for the remainder of the program. SPC procedures were established and implemented throughout the process. Examples of SPC procedures include particle size distribution, surface area, pH, conductivity and isoelectric point of powders, and in-situ, real-time ultrasonic inspection of mold filling during colloidal consolidation. Casting rate was directly controlled to minimize nonuniformity of green density. Computed tomography was used to optimize mold design. Various unit operations were optimized by statistically designed experiments.

The results of the 3-year program are shown in Fig. 4. The baseline process, at the beginning of the program resulted in a mean strength of 692 MPa and a Weibull modulus of 4.4. Figure 4 shows the frequency distributions for the baseline process and the distribution representing the program goal (mean of 900 MPa and Weibull modulus of 20). At the conclusion of the program a set of 320 tensile bars were made by the optimum process developed in the program and was tested at ambient temperature. The fracture origin for each specimen was identified and the fracture strength data analyzed by competing risk analysis. It was concluded that the data fall into 3 distinct groups: (1) a set of specimens that failed from an intrinsic set of flaws, and which may be described by a 3-parameter Weibull distribution with threshold strength of 665 MPa ($\sigma_0=444$, $\sigma_a=665$, $m=3.9$), (2) a group of specimens with fracture origins traceable to a ruptured filter in the pressure slip casting system, and (3) a set of specimens that failed from surface flaws introduced by diamond grinding. The filter that was associated with one group of fracture origins has been removed from the processing system with no adverse effects, thus, removing that source of flaws. The total set of 320 specimens has a mean of 997 MPa and a Weibull modulus of 10; however, a single 2-parameter distribution may not be the best representation of the data for use in design and life prediction calculations. Pujari and Tracey\textsuperscript{16} discuss these data in more detail.

This data set is unique in its completeness. The 320 bars represent all sources of deviation in the manufacturing process. The mean strength of the set of specimens representing the intrinsic flaws is 1067 MPa. Whereas the 2-parameter distribution, as shown in the baseline case and the program goal, predicts a finite number of failures down to very low stresses, the 3-parameter distribution predicts that no specimens will fail below 665 MPa. The improvement in reliability over the baseline is unprecedented, and represents a degree of reliability acceptable for many heat engine applications.
Specimens have been tested at constant loads at high temperature and the time to failure determined, called stress rupture testing. A variation of the stress rupture test, that is controllable in terms of testing time, is to expose the specimen for a fixed length of time at a constant temperature and stress, and then rapidly load the specimen to failure and determine the failure stress. Another variation is to periodically increase the stress or temperature of the stress rupture test until a failure occurs, called stepped stress rupture testing. Creep tests have been performed, in which the high temperature specimens are exposed to a constant stress and temperature, and the deformation rate measured as a function of time. The creep tests may be carried to rupture of the specimens, and the rupture time measured. The effects of cyclic stress, cyclic fatigue, have been characterized for several structural ceramics.

In all of the mechanical characterization, the mechanical tests have been followed by fractography analysis, with the objective of identifying the critical flaw that precipitated the failure. In addition, many test specimens have been subjected to examination by scanning electron microscopy to determine the effects of the testing atmosphere on the microstructure of the specimens. Often, the microstructure of high temperature specimens is changing as a function of the temperature, stress, and chemical atmosphere of the test. The changes in the microstructure result in changes in the strength of the specimens, which can be either higher or lower than before, depending on the nature of the microstructural change. We have attempted to model these time dependent processes to predict the behavior of the materials, and to serve as a guide to microstructural improvements that might be made to improve the behavior of the ceramics.

Post fracture analysis has identified basically two types of high temperature failures: those that result from growth of preexisting flaws, and those that result from an accumulation of damage during the test, eventually resulting in the formation of a critical flaw. The envelope of conditions under which each failure type may occur can be identified and quantified. For example, Fig. 5 shows dynamic fatigue results for a silicon nitride ceramic, in which the failure mechanism was shown to change from slow crack growth to creep rupture depending on the temperature and stressing rate.

Figure 6 shows a convenient way to present creep rupture life data, called a Monkman-Grant plot. The specimen lifetime is plotted against the creep rate, regardless of the stress and temperature. On a log-log scale the data typically fit a straight line. This particular plot shows data representing the state of development of silicon nitride over the last 10 years. The stresses and temperatures are approximately the same for each datum. These results indicate that the creep rupture resistance of silicon nitride has improved by 4 orders of magnitude over the past ten years. Creep rupture lives of 10,000 hours at 1370°C and 125 MPa are a recent breakthrough, applicable for many high temperature heat engine applications.

**CHARACTERIZATION OF TIME DEPENDENT HIGH TEMPERATURE STRENGTH**

An important aspect of our effort in mechanical characterization has been the development of practical means of tensile testing of ceramics. This effort is important in that the uniaxial button head tensile specimens employed have a stressed tensile volume approximately 100 times larger than that of a typical (ASTM C 1161-90, size B) flexure specimen. The larger stressed volume is important due to the volume dependence of strength as discussed earlier. An additional advantage of the tensile test is for creep testing, as the stress configuration in the uniaxial tensile specimen remains constant (nominally pure tension), whereas the stress distribution in the flexure bar, which varies from tension on one face to compression on the opposite face, changes as the bar is deformed during testing.

The Ceramic Technology Program has investigated ambient and high temperature fast fracture, in bending and in tension. Time dependence has been characterized by several types of testing. Specimens have been tested at stressing rates varying over several orders of magnitude, called dynamic fatigue testing.

![Graph showing frequency distributions for tensile strength of silicon nitride. The "baseline" shows the results for 22 specimens of pressure slip cast and hipped material at the beginning of a program to achieve the goal illustrated by the "program target" distribution. The curve labeled "intrinsic" represents the underlying strength distribution for the process and exceeds the program target. The improved strength and strength distribution resulted from a systematic program to eliminate the sources of microstructural flaws.](http://electrochemical.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1993/78927/V03CT17A078/2403853/v03ct17a078-93-gt-417.pdf)
Fig. 5. Tensile dynamic fatigue of a 6%-yttria silicon nitride. The results suggest a transition from slow crack growth to creep rupture at a stress rate of $10^{-2}$ MPa/sec at temperatures of 1260°C and 1370°C, and illustrate the complex time dependent high temperature behavior of silicon nitride.

The significant improvement in creep resistance has resulted from a continuing improvement in the microstructure of silicon nitride ceramics over the past decade. Figure 7 shows a transmission electron micrograph of a state-of-the-art 4% Y$_2$O$_3$ silicon nitride which has virtually no grain boundary phase at the 2-grain junctions, and only limited material at the triple points between grains.\(^2^7\)

### CERAMIC LIFE PREDICTION

The ultimate aim of the above mechanical characterization efforts is to develop a methodology that will allow the designer of a heat engine component to accurately predict the lifetime of the component under a given set of conditions, and to calculate a numerical confidence in the prediction. Programs are currently underway to accomplish those goals.\(^2^8\)-\(^2^9\) The programs consider the effects of uniaxial and multiaxial stresses, time and atmosphere dependent effects, and statistical (i.e., Weibull) representations of strength and lifetime.

The strategy of these programs is to generate a database of mechanical property and NDE data which will contribute to the development of material behavior models. The mechanical and thermal stresses in the component are estimated by finite element modeling. The finite element stresses, along with the material behavior models, feed into a program that integrates the risk of failure over the volume and surface of the component. This methodology leads to the prediction of the lifetime of a component, e.g., a high temperature spin disk. The predictions of component life will be tested against the observed lifetimes of static and dynamic silicon nitride specimens tested to failure at high temperatures.

### FUTURE WORK

The anticipated improvements in mechanical reliability of structural ceramics have been accomplished over the past ten years. However, the expected corresponding applications in heat engines have not kept pace with these improvements. The reason for the slow development of heat engine applications has been the high cost of ceramic components relative to present metal components. A new thrust in the Ceramic Technology Project, *Cost Effective Ceramics For Heat Engines* has been initiated, with the objective of developing the technology required to make ceramic components more competitive with metal components. An extensive assessment has been performed, and a program plan for the five year period beginning in 1993 published.\(^3^0\) Major cost drivers for ceramic engine components include diamond grinding, expensive ceramic powders, expensive forming and densification processes, and low process yields. A comprehensive program has been planned to systematically develop the required technology for cost effective ceramics. The elements of Cost Effective Ceramics For Heat Engines include economic cost modeling, ceramic machining, powder synthesis, alternative forming and densification processes, yield improvement, component design studies, testing and performance standards, and testing and data base.
Fig. 7. Transmission electron micrograph of a high performance silicon nitride (NT-164, Norton-TRW Ceramics, Northboro, MA.) Showing virtually no grain boundary phase at 2-grain junctions. The lattice images of two adjacent beta silicon nitride grains are separated by a disordered boundary less than 0.5 nm thick. No discrete grain boundary phase was seen. A small quantity of grain boundary phase is present at 3-grain intersections. After Nolan.

SUMMARY AND CONCLUSIONS

The Ceramic Technology Project was initiated in 1983 for the purpose of developing highly reliable structural ceramics for applications in advanced heat engines, such as the automotive gas turbine and advanced heavy duty diesel engines. The reliability problem was determined to be a result of uncontrolled populations of processing flaws in the brittle, flaw-sensitive materials, along with microstructural features, such as grain boundary phases, that contribute to time dependent strength reduction in service at high temperatures. The approach taken to development of high reliability ceramics included the development of tougher materials with greater tolerance to microstructural flaws, the development of advanced processing technology to minimize the size and number of flaws, and the development of mechanical testing methodology and the characterization of time dependent mechanical behavior, leading to a life prediction methodology for structural ceramics.

The development of silicon carbide whisker toughened alumina and silicon nitride ceramics led to the understanding of toughening mechanisms by crack deflection and whisker pull out, the influence of the bond strength between the whisker and the matrix, and the influence of the strength, diameter, and surface quality of the whiskers. It was also found that processing of the whisker composites was critical, and that whisker debris or even clumps of whiskers could become strength limiting flaws. Impurities in the whiskers were found to contribute to loss of high temperature mechanical properties. The substantial improvement in strength and toughness (≈2x) of alumina was not achieved in silicon nitride, and the creep damage was found to accumulate along the whisker-matrix interface in some cases, leading to development of incipient cracks. The silicon carbide whiskers were found to be potential carcinogens, similar to asbestos. Nevertheless, a significant market developed in cutting and wear applications for the toughened alumina.

The knowledge gained in the development of the silicon carbide toughened ceramics was transferred to silicon nitride ceramics toughened by the deliberate growth of silicon nitride grains into acicular, whisker-like shapes. These in situ toughened materials have greater toughness than was realized by incorporation of silicon carbide whiskers, are free of the handling concerns for the potentially hazardous whiskers, and are lower in cost, due to the absence of the relatively expensive whiskers and the lower cost densification process. The primary limitation of the in situ toughened silicon nitride at present is high temperature behavior above 1200°C.

Improved processes which result in fewer and smaller flaws have been developed. The approach to developing these processes has included the use of in-process NDE to identify the sources of flaws. The objective is to then modify the process and eliminate the sources of the flaws, rather than reject the parts. Statistical process control has been used to bring the manufacturing process under control and then to systematically improve the process. A large program was carried out: large enough to deal with all the sources of variation in the manufacturing process. Aqueous processing and colloidal consolidation of silicon nitride were developed, which resulted in an ambient uniaxial mean tensile strength of 997 MPa, an improvement over the beginning baseline of 692 MPa. The strength distribution for 320 button head tensile bars was found to fall into three distinct groups, one of which represents an intrinsic flaw population and which is described by a 3-parameter Weibull distribution, with a failure threshold of 665 MPa.

A self aligning grip system was invented, which made tensile testing practical for characterization of the mechanical behavior of structural ceramics. Tensile specimens have a stressed volume =100 times greater than the most commonly used B-size flexure test bar, and have a constant, virtually pure tension, stress distribution during high temperature deformation. Candidate heat engine materials have been tested at high temperatures as a function of time via a number of tests: static fatigue, stress rupture, stepped stress rupture, interrupted stress rupture, creep, cyclic fatigue, and dynamic fatigue. Most testing has been performed in air atmospheres, representative of the oxidizing atmospheres incurred in service.
These mechanical testing programs have been accompanied by rigorous pre- and post-test microscopy (optical, scanning and transmission electron) to determine the effects of microstructure on the mechanical behavior, and the changes that occur in microstructure as time-dependent testing progresses. Models have been developed which allow prediction of the behavior of the materials and which help in understanding how the behavior is related to the initial processing and resulting microstructure of the material.

A significant data base of mechanical property data for candidate heat engine materials has been developed. An effort is currently in progress to develop and demonstrate an integrated life prediction methodology for heat engine components. The component chosen for the demonstration is a gas turbine rotor, which is a highly stressed, high temperature component, and which is subject to virtually all the failure modes identified for heat engine components. The methodology, however, is relatively generic, and will be useful for many components, including those in other engine types.

Future work will concentrate on developing the technology to systematically reduce the cost of high performance ceramic components. A five year plan for Cost Effective Ceramics For Heat Engines has been published and the new thrust in the Ceramic Technology Project is underway.

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