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Critical Needs for Robust and Reliable Database for Design and Manufacturing of Ceramic Matrix Composites

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Abstract

Ceramic matrix composite (CMC) components are being designed, fabricated, and tested for a number of high temperature, high performance applications in aerospace and ground based systems. The critical need for and the role of reliable and robust databases for the design and manufacturing of ceramic matrix composites are presented. A number of issues related to engineering design, manufacturing technologies, joining, and attachment technologies, are also discussed. Examples of various ongoing activities in the area of composite databases, designing to codes and standards, and design for manufacturing are given.

Introduction

In recent years, there has been a surge of interest in the design, manufacturing and testing of ceramic matrix composite components for a number of aerospace and ground-based applications. The potential applications of CMCs in the aerospace industry include combustor liners, exhaust nozzles, and a number of other aircraft gas turbine and space propulsion components. The ground-based applications of these materials include radiant burners, hot gas filters, high-pressure heat exchanger tubes, and combustor liners in industrial gas turbine engines. In addition, there are a number of potential uses of CMCs for the first wall and blanket components of nuclear reactors. At present, the majority of the approaches for the manufacturing of continuous fiber-reinforced ceramic matrix composites are based on fabricating single or multiple pieces. The composite fabrication approaches are based on the gaseous or liquid infiltration of the ceramic matrix into a ceramic fiber preform. Over the last two decades, a wide variety of ceramic matrix composite components were fabricated using the "sequential" manufacturing approach. In this approach, design and performance requirements are fixed before the material selection and fabrication steps are taken. This manufacturing approach has very limited flexibility and is very expensive since all the steps have to be followed again if slight variations are made in the design, performance requirements, materials selection, or fabrication approach.

Recently, the engineering design and manufacturing of components and systems have become more interactive and interdependent as a result of computer aided design software, simulation, and computer-controlled manufacturing systems [1]. The "concurrent" manufacturing approach is being widely used in the manufacturing of metallic components. This approach is currently receiving a lot of attention for the robust manufacturing of advanced ceramics and ceramic matrix composites. The keys to robust and affordable ceramic matrix composites, with optimum strength and reliability are proper selection of materials, definition of optimal shapes, and establishment of appropriate manufacturing processes. These design and manufacturing tools are necessary to meet current demands for efficiency and reliability. The concurrent manufacturing approaches rely heavily on interactive modeling, design, rapid prototyping, and fabrication. Databases will play a key role in engineering design, modeling, and the final manufacturing of ceramic components [2-6].

The main goal of this paper is to present the current need for robust and reliable databases for the design and manufacturing of ceramic matrix composites. A number of ongoing programs on databases are described. In addition, the role of databases in the design, manufacturing, and joining of ceramic composites are presented in detail.

Database Needs for Design of Composites

Typically, there are two engineering design and manufacturing paths for ceramic matrix composites. In the 'component specific' approach, CMC properties are optimized for a particular component and application. Each CMC material is unique and the part has to be designed and manufactured individually. Since the mechanical properties of ceramic composites are highly anisotropic and non-linear, current design methodologies would require a separate design allowable database for each component. Also, the properties are dependent on the fiber architecture, which is typically component specific.

In another approach, CMCs are produced as 'billet stock' and parts are machined. These materials are not optimized for a particular application. The engineering and design of these materials are similar to that for metals, polymers, monolithic ceramics, and some polymer matrix composite components. In this case, a property database is needed for each class of composites since their thermomechanical properties depend on the constituents and manufacturing approach. Examples of the effects of the fiber/matrix interface coating thickness, matrix porosity, and fiber architecture are given below.

Traditionally, the emphasis in the optimization of mechanical properties of CMCs has been based on modifying the fiber/matrix interface to maximize in-plane tensile strength and toughness. However, as a result of the large degree of anisotropy of these materials, improvements in the in-plane properties have often been achieved at the expense of the mechanical properties in the other material directions. For example, to achieve high tensile strength and toughness it is necessary to tailor the fiber/matrix interface to reduce fiber bonding and to allow sliding of the fibers in the matrix, but this will result in poor interlaminar shear and through-the-thickness tensile properties. This is important because in most applications components will be subjected to multi-axial states of stress, which invariably will include interlaminar shear and normal tensile stresses. In 1-D and 2-D fiber reinforced CMCs, the interlaminar shear and translaminar tensile modes of failure are dominated either by the matrix or by the fiber/matrix interface. When the interlaminar matrix regions are porosity-rich, these become the weak link and the matrix controls interlaminar shear failure. On the other hand, when the interlaminar matrix regions are dense, interlaminar failure is controlled by the fiber/matrix interface. For example, the interlaminar shear strength (ILSS) of SiC fiber (CG-Nicalon™)/C interface/CVI-SiC matrix composites changes from 46.3 MPa ± 3.9 MPa for a carbon coating thickness of ~0.3 μm to 16.5 MPa ± 3.6 MPa for a coating ~1.1 μm-thick [7]. In addition, while interlaminar failure predominantly occurred between the fiber and the fiber coating for the composite with thick fiber coatings, there was evidence that the matrix porosity-rich interlaminar regions were the weakest link in the composite with the thin fiber coatings [7].

There are a number of critical issues in using the data reported in the literature for the design of ceramic composite components. Typically, most of the property data available for CMC design is collected on virgin coupon samples. There are a number of issues raised by designers in using this type of data [4]. Some typical questions asked by designers and end-users are as follows:

- Are properties in the component equivalent to coupon properties?
- To what extent is the material's behavior deterministic vs non-deterministic?
- Are the initial properties retained during the part's lifetime?
- What are the effects of thermal cycles (number and conditions) on the thermomechanical properties, and is the coefficient of thermal expansion (CTE) independent of number of thermal cycles?
- Does the material "soften" (lose modulus) even if it is only mechanically cycled below the knee on the stress-strain curve?
- Does this change the CTE? If it does lose modulus, can we use this to know when to remove the part?
- Does the damping (acoustic signature) change?
- How should we join and attach it, and does it weld to (or by contrast fret) touching surfaces?

Another issue for the designers is the reproducibility of the data, which even for plates is very poor. This issue becomes even more critical for complex shaped parts with concentrated loads. Obviously, one has to learn to control the uniformity of material/properties using simple shapes first, and to understand which materials and parameters are most important. For example, it is very important to know how to lay up fabric. However, quite often there are no specifications on that manufacturing step. These issues become very difficult to account for if the CMC component manufacturer knows of tricks to control some of these parameters, but does not want to disclose them. In this situation, manufacturing approaches that are not sensitive to small process variations are desirable. In these cases, end users still have to define the process specification very tightly. The downside is that it may limit progress, because variations cannot be made to the process.

Ultimately, the advanced ceramic composite components have to be designed to various codes and standards for wide scale application [3]. In some cases, the use of standards may be optional, but in other situations the components have to be designed using standards in order to avoid legal complications and product liability lawsuits. These codes and standards are well developed for metallic and polymeric based materials [8]. However, design codes and standards for ceramic matrix composite components are still in their infancy. One good example is the ASME Boiler and Pressure Vessel Code [9], where the material properties and design specifics must be incorporated into the code before the potential application of CMCs in power generation can be realized. The standard certification process is very time consuming and expensive. Details of various task groups involved in this design code and standard have been discussed elsewhere [3].

Design for Manufacturing

A significant effort has been made to consider manufacturing in the design process for metallic and polymeric components. Life-cycle engineering is becoming more important as industries strive to become more competitive. Composite materials are generally designed to obtain maximum performance, but quite often the manufacturing process is very labor intensive. In the polymer matrix composite (PMC) area, where different fabrication steps e.g., lay-up, vacuum bagging, surface preparation, etc. were manual and labor intensive, a number of new approaches are currently being used to save costs. In addition, composite parts are being designed for affordable and robust manufacturing. For the CMCs, a significant amount of fabrication costs could be saved if ceramic composite components or structures were designed for manufacturing.

Among the various manufacturing approaches for CMCs, chemical vapor infiltration (CVI) technology is the most mature and is used worldwide. This process is very lengthy and time consuming since the precursor gases must be transported into the interior of a fibrous preform, and the by-product gases removed from the densifying preform. Very long processing times are required to densify thick cross-sections and components with complicated fiber architectures. In addition, it becomes very expensive and extremely difficult to fabricate large size and complex shape CMC structures. Under these conditions, the small structures can be assembled into large components or structures with a reliable joining or attachment technology. It is interesting to note that high performance requirements for CMCs and their manufacturability are not considered together at the moment. However, it is very important and critical that the designers include the processing and fabrication considerations as part of the design cycle for CMC components.

Database Needs for Manufacturing of Composites

Affordable and innovative manufacturing approaches can be successfully employed if a robust database is available for design and material properties. An example of a component fabricated via the application of a simplified manufacturing approach is a variable geometry, thrust vectoring nozzle for a jet engine (Fig. 1). This nozzle can be fabricated as a one-piece, customized ceramic matrix composite unit. A simple alternative approach is to use ceramic matrix composite tiles in a metallic 'picture frame' substructure. This manufacturing methodology is called the 'building block' approach. This approach has been qualified and has been extensively used in manufacturing of polymer matrix composite components. Such PMC components are utilized on numerous aircraft, including the Northrop Grumman B-2 bomber. One of the main purposes of using the building block methodology for manufacturing is simplified design, resulting in cost savings and risk reduction.

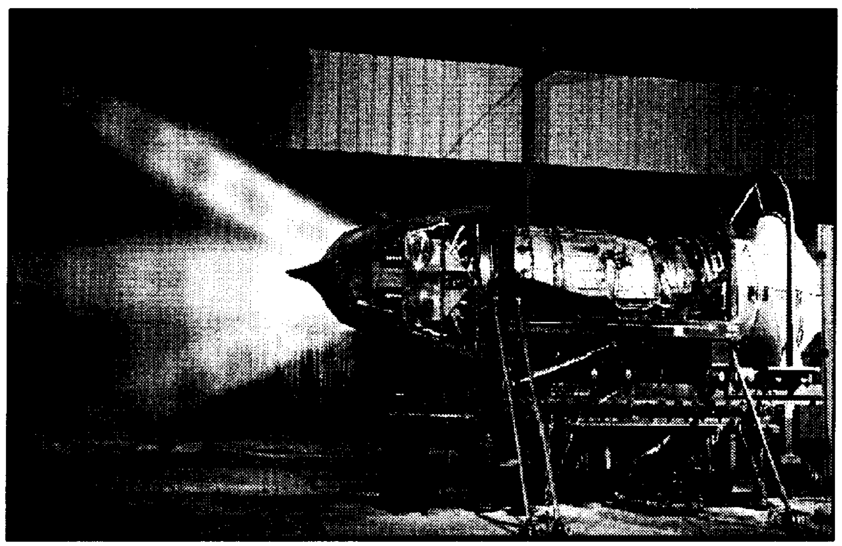

Fig. 1: Photograph showing variable geometry, thrust vectoring nozzle for jet engine [5]

Another low cost manufacturing methodology for CMCs is joining of small and simple shapes to fabricate large and complex shapes. In addition, a number of CMC parts might have to be attached or joined with metallic or monolithic ceramic materials. In both cases, joint design and property data are needed and databases play a key role. Numerous joint design and testing activities in the past have been related to metal-metal and ceramic-metal systems. For ceramic-metal systems, various joint designs and design criteria have been established [10-13]. The designs accommodate a number of factors including stresses and stress distribution in the joint regions, which are dependent upon joint configuration and chemical and thermal property mismatch between the joint and substrate materials. Determination of the mechanical properties of the joint is critical to designers. A wide variety of testing methods [10-11] have been used to determine the tensile strength, peel strength, flexural strength, shear strength, and compressive strength of ceramic-metal joints. However, unlike the joining technology for ceramic-metal systems, joint design and testing are not well developed for ceramic-ceramic systems. If the ceramic materials have to be used at high temperatures under extreme operating conditions, a number of joint design issues have to be considered, along with the high temperature thermal and environmental stability of the joint and the joint-substrate interface. One such design and testing issue is the determination of the stress-state at the joint; namely, tensile, shear, or a combination of tensile and shear stresses under operating conditions. In addition, the design of joints must take into account the response of joints to temperature changes.

An affordable, robust ceramic joining technology (ARCJoinT) has been used to join a wide variety of advanced ceramic and ceramic matrix composite parts [13-15]. Some examples of composite specimens fabricated using this technology are shown in Fig. 2.

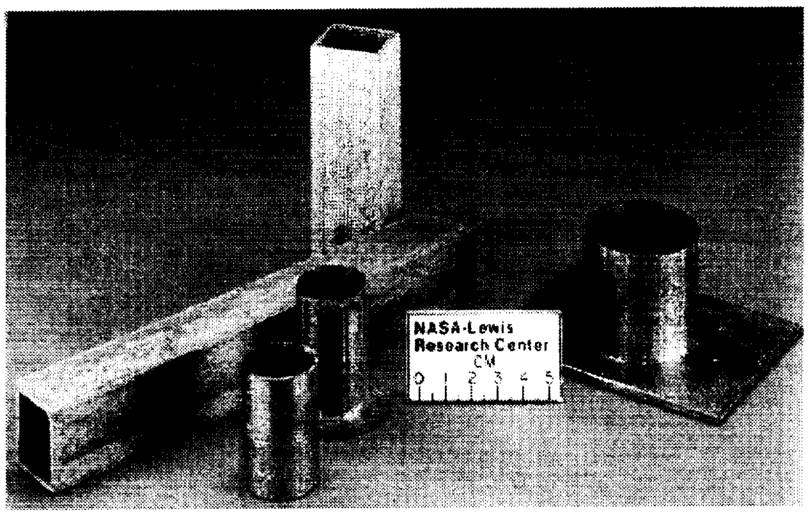

Fig. 2: Photograph showing various ceramic composite pieces manufactured using the ARCJoinT approach.

A wide variety of joints have been designed and fabricated in ceramic matrix composites using the ARCJoinT approach. The room and high temperature tensile strength, flexural strength, shear strength, and compressive strength of the joints have been obtained. An example of shear strength of ceramic joints in CVI SiC/SiC composites is given in Figs. 3-4. The shear tests were conducted in air at temperatures of 20, 1000, and 1200°C using a pneumatically-actuated mechanical testing system, a box furnace with SiC heating elements, and a SiC fixture. Fig. 3 shows a typical load versus cross head displacement curve obtained from the compression of a double-notched specimen. It is interesting to note that the joint increases in stiffness with increasing load/displacement and that failure is accompanied by a sudden load drop because the stress required for initiation of the interlaminar crack is larger than that required for propagation.

Two shear strength tests were conducted at each temperature and the results are summarized in Fig. 4. The circles represent the average of the two measurements. The apparent shear strength decreases continuously with temperature from 92 MPa at ambient temperature to 72 MPa at 1200°C. Details of the test method and results are discussed elsewhere [16].

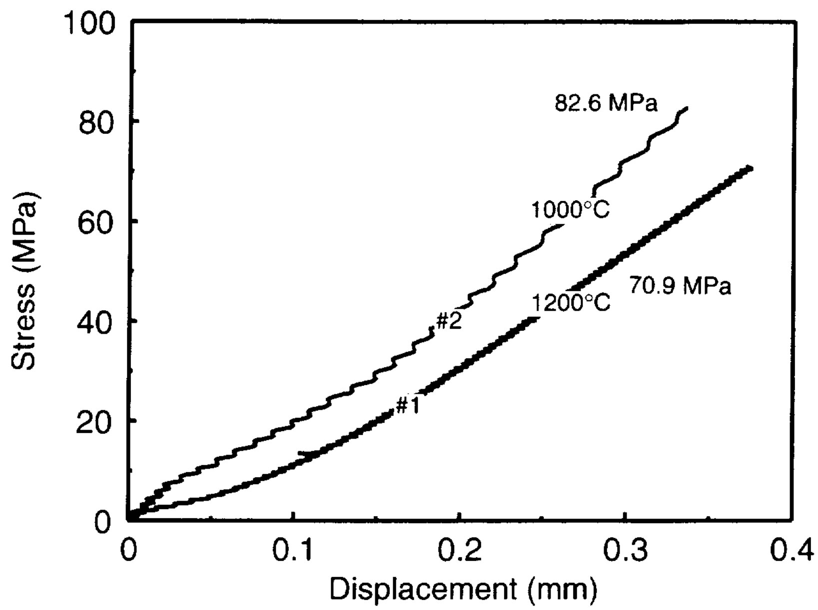

Fig. 3: Stress-displacement behavior of ceramic joints in CVI SiC/SiC composites during shear tests.

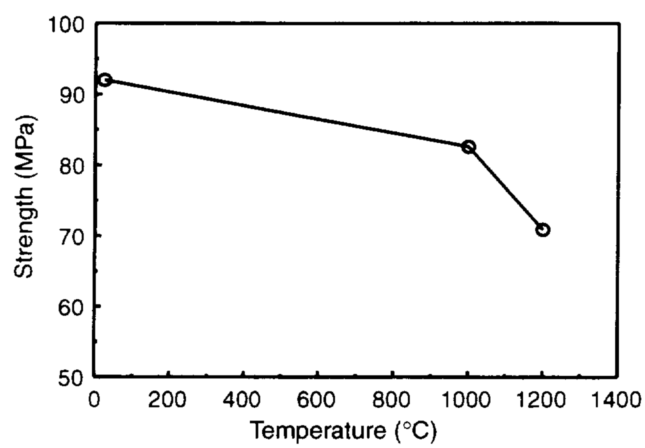

Fig. 4: Shear strength of ceramic joints in CVI SiC/SiC composites at different temperatures.

Database Activities for Composites

Although, material and property databases are readily available for metallic and polymeric materials, the design and manufacturing data for advanced ceramics and ceramic matrix composites has been very limited in scope and quite often proprietary in nature. Over the last two decades, there have been a number of major industrial and government database activities worldwide for polymer matrix composites. Most comprehensive among them is the Composite Materials Handbook (Mil Handbook 17), which provides the information and guidance necessary to design and fabricate components from composite materials [17]. The main goal of the handbook is the standardization of engineering data collection methodologies related to testing, data reduction, and reporting of property data for existing and new composite materials.

Database activities are ongoing in three composite materials areas – polymer matrix composites, metal matrix composites, and ceramic matrix composites. The work on a polymer matrix composite handbook started more than two decades ago, and three volumes have been already published. The metal matrix composites handbook work began in 1993, and the publication of the MMC volume is anticipated in 1999.

For the ceramic matrix composites, database activities started in 1996, and are slowly moving from the planning stage to implementation. For this handbook, the materials considered are current and emerging continuous and discontinuously reinforced ceramic matrix composites (including carbon-carbon). There are four working groups, which include (i) Data Review; (ii) Materials & Processes; (iii) Structural Analysis and Design Codes; and (iv) Test Methods. The handbook also relies heavily on test methods and material specifications developed through standardization organizations like ASTM and ISO. One key aspect of this activity is the willingness of various handbook committees to consider input and lessons learned from composite manufacturers and suppliers, different organizations, and end users of composite materials.

The database activities for ceramic matrix composites will be very time consuming and expensive. In order to create meaningful databases for design and manufacturing of CMCs, collaborative efforts, with sufficient resources, have to be carried out. These efforts should include various groups from academic institutions, government laboratories, various composite fabricators, and end users.

Conclusions

There is a critical need for databases for the design and manufacturing of ceramic matrix composites. The database activities described in the paper are essential to the effective interaction of design and manufacturing, from the initial concept to the finished design, including technology development, manufacturing, and field service. There are potentially significant cost savings to be realized in ceramic component manufacturing by utilizing databases, and innovative design tools and concepts including design for manufacturing.

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