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MODELING THE MECHANICAL BEHAVIOR OF CERAMIC MATRIX COMPOSITE MATERIALS

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Introduction to Project

Ceramic matrix composites are ceramic materials, such as SiC, that have been reinforced by high strength fibers, such as carbon. Designers are interested in using ceramic matrix composites because they have the capability of withstanding significant loads while at relatively high temperatures (in excess of 1000 °C). Ceramic matrix composites retain the ceramic materials ability to withstand high temperatures, but also possess a much greater ductility and toughness. Their high strength and medium toughness is what makes them of so much interest to the aerospace community.

This work concentrated on two different tasks. The first task was to do an extensive literature search into the mechanical behavior of ceramic matrix composite materials. This report contains the results of this task. The second task was to use this understanding to help interpret the ceramic matrix composite mechanical test results that had already been obtained by NASA. Since the specific details of these test results are subject to the International Traffic in Arms Regulations (ITAR), they are reported in a separate document (Jordan, 1997).

Three excellent sources of general information about ceramic matrix composites are Evans' paper (Evans, 1997), Solti's Ph.D. dissertation (Solti, 1996a), and Nair and Jakus' book (Nair and Jakus, 1995). Evans paper examines a number of design issues for high temperature applications of ceramic matrix composites. He discusses fiber pull out, the effect of pin–loaded holes, notch sensitivity, fiber bridging, and inelastic strains caused by fiber/matrix microcracking.

The book edited by Nair and Jakus provides an excellent introduction to the high temperature behavior of ceramic matrix composite materials. There are sections in the book dealing with both short term behavior (impact) as well as long term behavior (creep and fatigue).

The first two chapters of Solti's dissertation provide an excellent introduction to ceramic matrix composite materials. An engineer unfamiliar with high temperature ceramic matrix composite behavior should probably start with the beginning of Solti's dissertation (if available), then Nair and Jakus book, and finally proceed to Evans article.

Modeling Mechanical Behavior of Ceramic Matrix Composites

There are two very broad approaches to modeling material behavior. A macroscopic approach attempts to predict future performance based on prior macroscopic tests. Examples of such macroscopic tests are tensile tests, impact tests, creep tests, and fatigue tests. A second basic approach is to model on a microscopic level. This approach looks at such issues as fiber properties, matrix properties, fiber/matrix bonding, etc. These properties are then used to predict composite material behavior. This approach is frequently combined with a finite element analysis of the structure in question. Using either approach, modeling the behavior of ceramic matrix composite materials is intrinsically a difficult task (Solti, 1996a).

For any failure theory to there needs to be good mechanical test data. Any theory is no more precise than the basic mechanical property measurements that are used within it. Testing of brittle materials is much more difficult than ductile materials, since very small flaws can promote premature failure. Testing at the high temperatures of interest is also more difficult than at room temperature. One research group (Curtin, et al., 1994) has developed techniques to perform tensile and fatigue tests on composites up to 1500 °C.

NASA is interested in how ceramic matrix composites respond to high velocity impact loads. Such tests can be performed at NASA's facility at White Sands, NM. Stoltzfus describes their capability in a 1988 paper (Stoltzfus, et al., 1988). They exposed a cup shaped sample to high velocity particle impact at temperatures over 400 °C.

Estimating Toughness from Mechanical Tests

Impact toughness results can be estimated from particle impact tests. It was assumed that all of the impact energy went into creating a hole in the base of the cup. G_{IC} is the energy released per unit area of crack growth. By dividing the impact input energy by the area of the newly cracked surface, we can estimate the G_{IC} of a material that just failed by the impact. The more commonly used critical stress intensity (K_{IC}) can be calculated from G_{IC} .

The approach described above is the maximum toughness material that can be broken by the impact tests. The next step was to estimate the toughness from room temperature tensile tests. The deformation energy in the material is the energy under the stress–strain curve in each test. The total energy absorbed by the cup would be the strain energy per unit time the volume of the cup base. This energy term was divided by the newly cracked area to get a value for G_{IC}.

The toughness of these materials when exposed to oxygen at elevated temperatures can be approximated. This can be done using the stressed in oxygen data and calculating the strain energy that was input into these samples. The energy per unit volume that the material could withstand was then used as the input energy into the cup shaped samples that were used in the particle impact test.

Modeling Tensile and Creep Behavior

There are several macroscopic failure theories available. Use of tensile strength or the creep based Larson Miller Parameter to predict strength are both macroscopic models. A number of researchers have proposed various micromechanical models. Several (Curtin, et el., 1994) have proposed a micromechanical model for high temperature tensile and fatigue behavior. They amplified this approach in a 1996 conference paper (Materials Science Corporation, 1996). While this method looks promising, it is not possible to verify without getting a copy of their computer code and running it with some of the data generated by NASA.

One interesting approach to mechanical behavior is a mixed macroscopic / microscopic approach that has been taken by a group of researchers at NASA's Lewis Research Center (Murthy, et al., 1996, and Mital, et al., 1996). They have created a software called CEMCAN, which stands for Ceramic Matrix Composite Analyzer. This software uses both macroscopic and microscopic tensile type data. The user inputs the laminate structure which includes such things as fiber type, matrix type, loading, and stacking sequence. The software then calculates what is occurring on an individual fiber level. It then rebuilds itself back up to the laminate level and produces macroscopic results (such as moduli for the laminate). Their model incorporates the stress redistribution that occurs when the material progressively fails. It can be used to monitor the damage initiation and progression as the load increases. It has the capability of dealing with the non–linear stress strain behavior that is characteristic of many of these CMC materials. This software was not designed for analyzing fatigue loading. One of the benefits of this is that it produces engineering properties that can directly be used by design engineers. While this method looks promising, it is not possible to verify without getting a copy of the computer code they have created and running it with some of the data generated by NASA.

Modeling Fatigue Behavior

There are a number of models that have been used to represent fatigue data. The most common macroscopic method uses what is called the S–N curve, where the maximum applied stress is plotted as a function of lifetime. For many materials there is a stress level below which an infinite lifetime is expected. This value is called the endurance limit.

The S–N curve approach is limited because it does not distinguish between issues such as varying the amplitude stress while keeping the maximum applied stress the same. These issues are frequently dealt with using variations of the Goodman plot (which is another macroscopic model). In the Goodman plot the amplitude stress is plotted as a function of the mean stress. The safe region is below a line that connects the endurance limit for a pure tension/fatigue test (on the amplitude scale) and the tensile strength (on the mean stress scale). This approach is based on the idea that fatigue crack growth is dependent on the size of the maximum applied stress. A part that is experiencing a high mean stress does not have to have a very high amplitude stress before the stress required to grow the crack is reached. Conversely, a material with a low mean stress, will require a higher amplitude stress before it will fail.

The Goodman approach is commonly used along with a fracture mechanics approach. The Goodman approach is used to estimate the maximum allowable stress (and therefore the maximum crack size) before final failure occurs. Fracture mechanics is then used to estimate the subcritical crack growth. This is illustrated in Hertzberg's book (Hertzberg, 1996).

One important parameter used in describing fatigue behavior is the value of R. R represents the ratio of the minimum applied stress to the maximum applied stress. At high values of R, there have been cases of premature failure in what otherwise would be seen as the safe region (Nicholas and Zuiker, 1996).

There have been several micromechanical based approaches to modeling fatigue behavior. Curtin's approach (Curtin, et al., 1994 and Materials Science Corporation, 1996) looks promising, it is not possible to verify without getting a copy of the computer code they have created and running it with some of the data generated by NASA.

Another micromechanical approach to fatigue has been described by Solti (Solti, 1996a and Solti, 1996b). Solti's approach has the advantage that it can be tried out without using a complicated computer code. He refers to this as a "simplified approach". One disadvantage of his approach is that it is for unidirectional systems. It will need to be expanded to the more complicated layups that need to be used in actual aerospace applications.

Conclusions

Many of the equations that are used to model fiber reinforced polymers can be used for fiber reinforced ceramic matrix composites as well. However, the very different property values of ceramic matrix composites compared to polymeric based ones indicate that something different is occurring on a microscopic level.

Toughness can be estimated from tensile tests, particle impact tests, and elevated temperature stress tests. These yield values that are consistent with more direct measurements of toughness.

The Goodman approach to modeling fatigue failure appears to work well as long as the R value is not too large. Large R values tend to promote premature failure. A number of micromechanical approaches to fatigue failure have been developed. Their precision cannot be estimated until the specific software has been tested using results already obtained by NASA.

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