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Anisotropic damage of alumina/alumina CFCCs under long term high temperature exposure: Investigations by ultrasonic stiffness measurements and quasi-static tests

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Abstract

The present work deals with the development of anisotropic damage in alumina/alumina continuous fiber ceramic composites (CFCCs). The composites were isothermally exposed to a corrosive/high temperature environment at 1100°C, which simulates the working conditions of a gas turbine. Stiffness matrix components and strength were experimentally defined as a function of exposure duration by means of ultrasonic stiffness measurements and quasi-static tensile tests.

In order to determine the stiffness matrix components, a new ultrasonic stiffness characterisation technique was employed. According to this method, the through transmission phase velocities are measured using a custom built immersion set-up. The experimental data are subsequently used in order to solve the inverse scattering problem and reconstruct the stiffness matrix of the composite at successive thermal exposure levels. The stiffness matrix of the composite was assumed to be orthotropic. Damage functions were formulated to describe the high temperature/corrosive exposure effect on the stiffness matrix of the composite.

Finally, quasi-static tensile tests were used to assess the stiffness reduction of the composite and compare the values to those acquired non-destructively. The effect of exposure time on the strength of the composite was determined in the same way.

Keywords: Ceramic-matrix composites (CMCs) (A); Ultrasonics (D); Durability (B); Anisotropic damage; Stiffness measurements

1. Introduction

Continuous fibre ceramic matrix composites (CFCCs) have been identified as the most promising class of materials for high temperature industrial applications, where high structural efficiency under mechanical and thermal loadings is required. Up to now, CFCCs have been used in applications ranging from high performance braking systems to heat shields for re-entry vehicles. One of the main disadvantages of conventional CFCC materials is their vulnerability to oxidation at high temperature environments. Although a number of oxidation protective top layer gradient coating systems have been developed together with liquid silica infiltration techniques, the problem is far from being solved.

A proposed remedy to the aforementioned problem is the use of oxide/oxide composite systems. These systems withstand high temperature oxidising environments without the need of oxidation protective layers or cooling systems. Not surprisingly, the gas turbine industry is particularly active in the research and development in the field of oxide/oxide composites. The main goal is the increase of the working temperature of the machines,

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which will reduce the cooling air supply. This will lead to the increase of the plan efficiency, the reduction of the fuel consumption and subsequently to the fulfillment of the ever more stringent emission requirements of NO_x, CO and CO_2.

In addition, the superior fracture toughness properties of oxide/oxide CFCCs ensure their strength and reliability in the presence of holes and notches. This is a result of the built-in active stress redistribution mechanisms, which minimise the possibility of catastrophic brittle failure.

For this purpose, Nextel™ type fibres have been used mainly at laboratory scale, as a candidate reinforcement material for oxide/oxide composites. Working prototypes such as gas turbine liners and exhaust pipes for aero-engines have already been produced and successfully tested at moderately high temperature level [1–5]. Different material tailoring approaches are being under development in order to increase fracture toughness and prevent brittleness.

The key problem for all alumina/alumina composites is that a phase transformation occurs at 1100 °C. Although under certain circumstances, this phase transformation has a beneficial effect on the material fracture toughness, it generates significant internal stresses. These lead to matrix microcracking and subsequently to a macroscopic degradation of stiffness and strength. The stiffness reduction is primarily attributed to degradation of the matrix properties and the formation of an extensive matrix crack network. This is attributed to changes in the matrix structure and the scale of porosity, which alter the crack propagation paths within the material structure during loading. In particular, porosity coarsening severely reduces the ability of the matrix to diffuse cracks, which results the decrease of the crack resistance of the material and the deterioration of its ultimate strength. Moreover, the observed fibre grain growth leads to lower strength and stiffness values. The performance of the fibre/matrix interface is also affected [6,7]. Cracking and burn out of the carbon fugitive coating makes way for the sintering of the fibre and matrix across the interface gaps, thus reducing fibre debonding and pullout [8].

In the present study, the material under investigation is an improved [9] mullite matrix NEXTEL 720 (3000 denier) fibre reinforced composite [9,10], with a fugitive fibre/matrix carbon interface applied by Sol/Gel technique [11]. The composite laminate was made using a symmetric 0°/90° fibre lay-up orientation, with a total fibre volume fraction of 41%. The fabrication process followed is the polymer infiltration process (PIP) [12,13]. As is believed, the matrix porosity in combination with the burn out of the carbon fugitive coating may prevent the macroscopic degradation of the mechanical performance of the oxide/oxide composite.

The aim of the present work is to investigate the mechanical performance of the material after long term isothermal exposure to a high temperature (1100 °C) corrosive environment, which simulates the working conditions of an industrial gas turbine.

Moreover, the problem of addressing damage initiation and propagation in materials possessing a certain level of symmetry incorporates the question of whether this degree of symmetry is retained after any thermomechanical loading is applied on the material. This is particularly applicable in continuous reinforcement composites, since any loading may result in damage which will alter the material symmetry. In this study, a novel technique is used, which allows for the non-destructive determination of the stiffness matrix of the material at any loading stage. The technique is based on the experimental evaluation of the velocity of the propagating modes of sound waves in controlled directions [14–16]; the velocities are subsequently used to determine the elastic properties of the material; this is performed via the numerical regression of the solution of the inverse scattering problem for an orthotropic material. As the material used in this study is transversely isotropic, changes and/or symmetry reduction of the material can be monitored using the ultrasonics technique.

In parallel, catastrophic standard tension tests were performed; for this purpose a set of high temperature exposed alumina/alumina specimens, of different exposure duration, were used. This was performed for the following reasons:

1. The comparative evaluation of the stiffness reduction trend acquired using ultrasonics and standard quasi-static tensile tests along one of the principal axes of a cross-ply composite.
2. The assessment of the effect of high temperature/oxidation exposure time of the oxide/oxide composites on their strength and strain to failure.

Finally, macroscopic damage functions which govern the damage generated in the different material directions were introduced.

2. Ultrasonic stiffness measurements

In the case of an isotropic material, only two engineering constants (for example, Young's modulus and Poisson ratio) are sufficient to fully describe its elastic behaviour. These constants can be easily determined from the results of a simple quasi-static tensile test.

When dealing with anisotropic materials, such as CFCCs, a number of independent constants are required depending upon the degree of anisotropy. These constants are the coefficients of the elasticity tensor that