Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Engineering Fracture Mechanics 72 (2005) 2144–2158
Engineering Fracture Mechanics
www.elsevier.com/locate/engfracmech

Fracture behavior under mixed-mode loading of ceramic plasma-sprayed thermal barrier coatings at ambient and elevated temperatures

S.R. Choi *, D. Zhu, R.A. Miller

National Aeronautics & Space Administration, Glenn Research Center, Cleveland, OH 44135, USA

Received 6 January 2004; received in revised form 3 January 2005; accepted 17 January 2005
Available online 1 April 2005

Abstract

The fracture behavior under modes I and II loading of ceramic plasma-sprayed thermal barrier coatings was determined in air at 25 and 1316 °C in asymmetric four-point flexure. The mode I fracture toughness was found to be $K_{Ic} = 1.15 \pm 0.07$ and 0.98 ± 0.13 MPa $\sqrt{m}$, respectively, at 25 and 1316 °C. The respective '*nominal*' mode II fracture toughness values were $K_{IIc} = 0.73 \pm 0.10$ and 0.65 ± 0.04 MPa $\sqrt{m}$. The empirical mixed-mode fracture criterion best described the coatings' fracture behavior under mixed-mode loading. The angle of crack propagation was in reasonable agreement with the minimum strain energy density criterion.

Keywords: Ceramic thermal barrier coatings; Mixed modes I and II loading; Asymmetric four-point flexure; Fracture toughness testing; Plasma-sprayed ZrO_2–8wt%Y_2O_3

1. Introduction

Thermal barrier coatings (TBCs) have attracted increasing attention for advanced gas turbine and diesel engine applications due to their ability to provide thermal insulation to engine components [1–3]. The merits of using the ceramic TBCs are well recognized and include the potential increase in engine operating temperature with reduced cooling requirements, resulting in significant improvement in thermal efficiency, performance, and reliability. Plasma-sprayed zirconia-based ceramics are one of the most important coating materials in light of their low thermal conductivity, relatively high thermal expansivity, and unique microstructure as a result of the plasma spraying process.

* Corresponding author. Tel.: +1 216 433 8366; fax: +1 216 433 8300.
E-mail address: sung.r.choi@grc.nasa.gov (S.R. Choi).

0013-7944/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engfracmech.2005.01.010

It has been suggested that the important limiting factor encountered in thin plasma-sprayed TBCs is the relatively low fracture energy of the coatings in planes close to and parallel to the interface. Various efforts have been made to determine mode I 'interfacial' fracture toughness of the coatings in the vicinity of the interface using techniques such as the indentation method, debonding technique, three- or four-point flexure delamination technique, and compact tension test method [4–6]. Failure of the thick TBCs has been observed within the bulk of the coating material, independent of any delamination that typically occurs at the interface of a thin coating and a substrate [7].

The majority of data on fracture toughness of both thin and thick coatings have been determined under mode I loading. However, rarely are structural components or coatings subject to pure mode I loading. This is particularly true for TBCs that encounter complex thermal and mechanical loading in engine operations. Recently, Callus and Berndt [8] used a pure-shear technique to determine the interfacial critical mode II strain energy release rate of some thin coatings. Their data, however, were only for *ambient* temperature. Mixed-mode data on either thin or thick coatings are rarely available in the literature at *elevated* temperatures, despite an important fact that mechanical behavior of coatings should not be based solely on ambient-temperature properties.

The objective of this work was to determine mixed-mode fracture behavior of free-standing TBCs of ceramic plasma-sprayed ZrO_2–8wt%Y_2O_3 at an *elevated* temperature of 1316 °C in air. The choice of this temperature was based on a typical target temperature of aerospace gas turbine applications. These same properties were also determined at ambient temperature (25 °C). An asymmetric four-point flexure test technique was used at both temperatures in conjunction with single-edge-v-notched beam (SEVNB) test specimens, which yielded simplicity in both specimen and crack preparation and in test procedure.

2. Experimental procedures

2.1. Material and test specimens

The ZrO_2–8wt%Y_2O_3 powder with an average particle size of 60 μm, was first plasma-sprayed on a graphite substrate measuring 150 by 100 by 6.5 mm to a thickness of about 6 mm, using a Sulzer-Metco ATC-1 plasma coating system with an industrial robot. The plasma-spray conditions can be found elsewhere [9]. A free standing, plasma-sprayed ceramic billet was then obtained by burning away the graphite substrate at 680 °C in air for 24 h. The billet was machined into the final, rectangular flexure test specimen with nominal dimensions of 3 by 4 by 50 mm, respectively, in width, depth, and length. The 3-mm-wide face of flexure test specimens corresponded to the plane perpendicular to the plasma spraying direction. Major physical and mechanical properties of as-sprayed coating material at ambient temperature [10,11] are shown in Table 1. Fig. 1 shows a typical fracture surface and a polished surface showing the microstructure of as-processed coatings, in which large amounts of microcracks and pores are characterized in conjunction with a platelet (or splat) structure.

2.2. Mixed-mode testing

2.2.1. Preparation of sharp precracks

Sharp v notches were introduced in flexure test specimens, using the single-edge-v-notched-beam method [12]. This method utilizes a razor blade with diamond paste to introduce a sharp root radius by tapering a saw cut. Sharp v-notch radii ranging from 4 to 6 μm have been successfully obtained for alumina, glass ceramic, silicon nitride, zirconia, and silicon carbide ceramics [12]. A starter straight-through notch 0.6 mm deep and 0.026 mm wide was made on the 3-mm-wide face of the test specimens. A steel razor blade was put into the starter notch sprinkled with diamond paste with a particle size of 9 μm. Typically, a load of