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Investigating the anisotropic mechanical properties of plasma sprayed yttria-stabilised zirconia coatings

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ABSTRACT

The adhesion and cohesion bond strengths of plasma sprayed yttria-stabilised zirconia (YSZ) coatings were measured by performing the tensile adhesion test (TAT) and the tubular coating tensile test (TCTT). The TAT allowed assessment of adhesive/cohesive bond strength of a coating microstructure perpendicular to the substrate. In contrast, the TCTT quantifies the strength of a thermal spray coating parallel to the substrate without the use of any adhesive. The failure strength of the coatings from the respective tests can be approximated to a Weibull distribution and indicated the anisotropic behaviour of plasma sprayed coatings. The average coating strength parallel to the substrate is approximately 1.5 times greater than the bond strength perpendicular to substrate. The anisotropic behaviour of the plasma sprayed YSZ coatings were also probed using Knoop hardness measurements that were orientated at a well-defined geometry with respect to the lamellar microstructure. In addition, uniaxial compression tests evaluated the Poisson's ratio of these anisotropic YSZ coatings when loaded with respect to the different microstructural orientations.

1. Introduction

The use of yttria stabilised zirconia (YSZ) ceramics as thermal barrier coatings (TBCs) has been established for applications in advanced gas turbine engine components operating above 1000 °C. The low thermal conductivity of certain zirconia-based ceramics leads to benefits that include reducing the component cooling requirement while maintaining suitable metal substrate temperatures. Coupled with complex air cooling designs and the use of high temperature nickel-based superalloys, improved engine performance and durability can be attained. Commercially viable TBC applications were developed at NASA Lewis Research Center (now NASA Glenn Research Center) [1–3] in the mid-1970s with a two layer TBC consisting of a stabilised zirconia coating over a metal bond coating. Generally, the use of TBCs in gas turbine engines allows metal temperature reductions of about 190 K [4].

The partially yttria stabilised zirconia coating in the as-sprayed state [5–7] consisted of non-transformable tetragonal phase (T'). The formation of the T' phase was favoured over the monoclinic phase so that the potentially damaging $T \rightarrow M$ transformation was avoided. As well (i) phase stability when annealed at 1600 °C and (ii) excellent thermal transport behaviour of partially stabilised YSZ coatings with no hysteresis have been reported [8,9]. The thermal expansion of YSZ coatings is approximately $11 \times 10^{-6}\ C^{-1}$ and the coating thermal conductivity lies between 0.6 and 1.1 W $m^{-1}\ K^{-1}$ [9–11].

1.1. The lamellar nature of coatings

A YSZ coating may be manufactured *via* the air plasma spray process, which confers a lamellar microstructure that is formed by the rapid solidification of impinging molten droplets and cohesion among splats [12]. Formation of this lamellar microstructure is a stochastic process and is associated with inter-dependent processing variables such as the feedstock size, feedstock material, flame jet temperature, and particle velocity [13,14]. Due to the cumulative interactions of variables within the spray stream, features such as splat dimensions, pore sizes, crack density fluctuations, inter-splat coalescence, and associated artefacts can be discriminated [15–17].

It is characteristic that the lamellar splat structures give rise to the highly anisotropic mechanical properties of thermal spray coatings [17]. Thus, the coating material properties depend on the direction measured, which is quite different from the behaviour of an isotopic bulk material. The anisotropic nature of a thermal sprayed microstructure has been specifically defined as transversely isotropic because the architecture has two orthogonal planes of symmetry: *i.e.*, (i) a microstructural texture that follows the substrate, and (ii) a cross section orientation that is perpendicular to the substrate. These artefacts are reflected in the cross sections of splats, Fig. 1.

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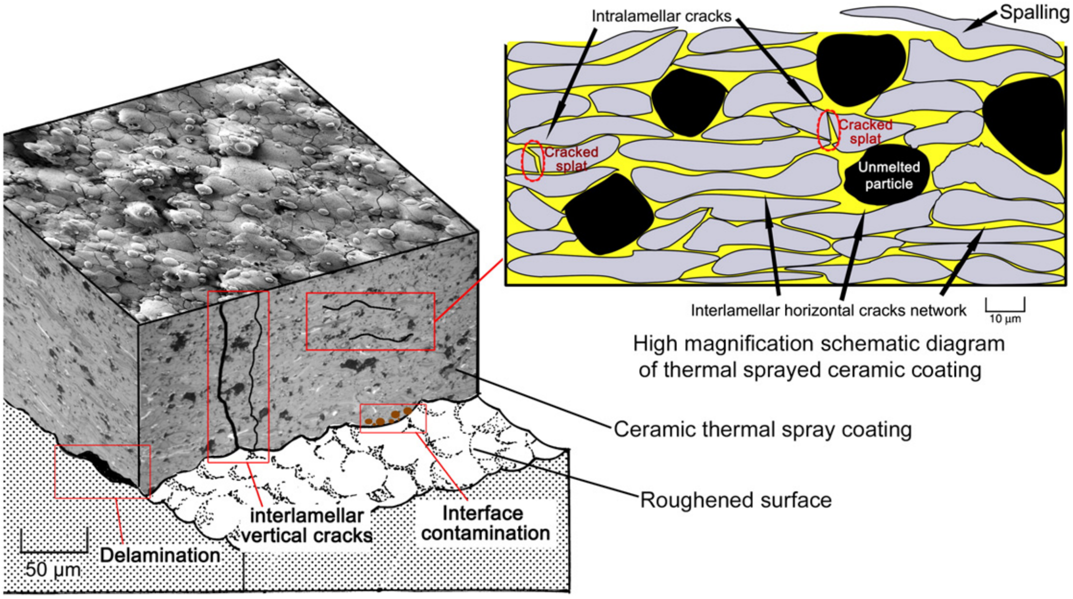

Fig. 1. Illustration of a typical ceramic thermal spray coating microstructure.

1.2. The significance of testing methods for coatings

The standard tensile adhesion test method for thermal sprayed coatings, as described in ASTM C633-08 [18], provides measurements for the coating strength perpendicular to the substrate. The load in this test is applied normal to the plane of the coating. The tensile fracture mechanism can be attributed to cumulative splat delamination occurring due to poor intersplat cohesion or splat–substrate adhesion [19]. However, the anisotropic nature of thermal sprayed coatings implies that the coating strength parallel to the substrate should differ from the coating strength measured *via* the ASTM C633 test method.

There are several references that illustrate methods to measure the strength of a thermal spray coating parallel to the substrate. Different designs have been discussed [20] for the application of a load parallel to the coating lamellae. The test design of W.E. Stanton employed a specimen configuration during coating operation to create a coating layer that bridged two substrates. Stanton's design would result in the test piece being subjected to eccentric loading due to the coating–substrate spray geometry [20]. However, the novelty was that adhesive glue was not required and the applied load would have a force component parallel to the coating surface.

The tubular coating tensile test (TCTT) [21] is an adaption of the method proposed by Stanton and has been applied to measure the ultimate tensile strength of cold sprayed coatings [21,22]. The TCTT specimen consists of two substrates that are bridged by the as-sprayed coating. Thus, upon tensile loading across the horizontal plane, the interconnected splats would fracture. The TCTT orientation indicates that the forces exerted on the test specimen will be mostly parallel to the coating surface [21]. Thus, the TCTT is a measure of the coating's intersplat cohesive strength in a direction parallel to the coating surface.

Within the current work it should be cautioned that the term “elastic” is used for convenience since thermal spray coatings deform by inelastic splat sliding. The coating modulus is affected not only by the strength of lamellae cohesion but also by the distribution of the void and crack network. The inhomogeneous architecture of a thermal spray coating is likely to cause pseudo ductility because the lamellae are able to slide over each other [23]. Therefore, the determination of the precise elastic limit, as well as estimating the linear portion of the stress–strain load curve can be difficult. In addition, the stiffness result is sensitive to the test direction due to the anisotropic lamellae coating microstructure. It was shown by Leigh et al. [24] using indentation tests, that the moduli of a thermal spray coating on the top surface is different from its cross section.

1.3. The Poisson's ratio of coatings

The Poisson's ratio of thermal spray coatings, since it is mathematically related to “elastic” properties, should also be related to the unique lamellar microstructure and be direction dependent. It has been noted that the evaluation of coating bond strength, crack growth rates, and coating stresses during in-service loading requires accurate values of the coating modulus and also Poisson's ratio [25,26]. In addition, the Poisson's ratio of a thermal spray coating would be expected to vary with spray parameters and coating material since these factors are known to alter the lamellar microstructure. There has been little experimental work to understand the unique transversely isotropic microstructure on Poisson's ratio measurements.

Choi et al. [27] determined the Poisson's ratio of as-sprayed YSZ coatings by the use of strain gauges and compared these values to a specimen annealed at 1316 °C. These values were $\nu = 0.04$ for as-sprayed YSZ and $\nu = 0.2$ for annealed YSZ. It should be noted that these tests were performed with the load normal to the substrate, and the other orientations, such as compression load on the coating cross section, were not evaluated. Rybicki et al. [28] and others have used a cantilever beam method for the *in-situ* determination of Young's modulus and Poisson's ratio for thermal spray coatings. Their analysis was based on laminate plate theory and incorporated strain gauges that were mounted parallel to the substrate. The Poisson's ratios measured were between $\nu = 0.157$ and 0.181 [28,29]. The typical bulk material value of Poisson's ratio reported for sintered YSZ is 0.23 [30]; thereby implying that errors will arise if the bulk value is assumed for YSZ coatings.

In this work, the mechanical strength of plasma sprayed YSZ coatings was determined (i) in the plane parallel to the substrate surface by TAT methods, and (ii) in the cross section orientation, perpendicular to the substrate that reflects the cross sections of splats by means of TCTT techniques. In addition, Knoop microhardness indentation tests were performed at specific orientations to establish the anisotropic behaviour of the coatings. Finally, coating removal techniques were applied to obtain free standing plasma sprayed YSZ specimens. Subsequently, the thermal spray coating modulus and Poisson's ratio were determined by uniaxial compression in different orientations. The measurements of such