

Measurement of the Creep Performance of Coatings used in Gas Turbines

Thermal barrier coatings (TBCs) are vital to the performance of modern gas turbines. During service stresses develop in the coating system due to thermal expansion mismatch between the substrate, bondcoat, ceramic and the thermally-grown oxide, leading to eventual failure of the system. However, these stresses may be relaxed due to creep processes in one or more of the individual layers in the coating system. It is therefore necessary to measure the creep performance of these individual layers.

This measurement note reviews possible techniques for determining the creep properties of the various components of the TBC system.

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INTRODUCTION

Thermal barrier coating systems are multi-layered with an outer ceramic layer, a metallic or intermetallic bondcoat and a metallic substrate. During service a thermally-grown oxide (TGO) forms at the interface between the ceramic and the bondcoat (Figure 1).



Figure 1 Schematic Representation of TBC System

Each of these layers has a representative thermal expansion coefficient such that, during temperature changes, stresses develop which eventually lead to failure of the system. However, these stresses may be relaxed due to creep processes. It is therefore vital to measure the creep strength of each layer in order to predict the evolution of stress, and hence potential failure of the system, during service.

TRADITIONAL CREEP TESTING

Creep testing of monolithic materials is well established and standardised [1]. This method is obviously suitable to determine the creep performance of the substrate and also can be used on bondcoat materials if the coating can be produced in thickness suitable to manufacture specimens.

Figure 2 shows results from a commercial MCrAlY coating, tested in this manner. The coating behaves in a ductile, almost superplastic, manner and follows an Arrhenius relationship for creep rate viz:

$$\dot{\epsilon} = 1 \times 10^{10} s^{-2.28} \exp\left(\frac{-300000}{RT}\right)$$

where $\dot{\epsilon}$ is the creep rate measured in hours

σ is the stress measured in MPa

R is the gas constant = $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$

T is the absolute temperature

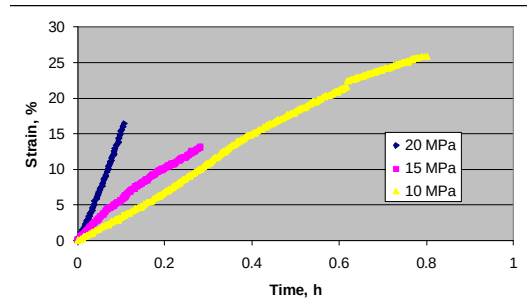


Figure 2 Creep performance of a commercial MCrAlY coating at 950 °C

The main concern regarding this method of generating creep data on the bondcoat is whether the microstructure produced in the thick coating is representative of that in the service component.

CREEP TESTING OF THIN COMPOSITE SPECIMENS

Taylor *et al* (2) demonstrated that the creep properties of MCrAlY bondcoats can be derived from the creep behaviour of a 'composite' specimen of a coating on a thin substrate. The specimen is a coated plate with the thickness of the core (substrate), h , and coating thickness, z .

Taylor's approach is to consider the load redistribution between coating and substrate during creep. Both primary and steady state creep are considered and the creep strain, ϵ , in the specimen is described by the expression:

$$\epsilon = \epsilon_T \left(1 - \exp\left(-b A s_h^n \exp\left(\frac{-Q_h}{RT}\right) t\right) \right) + A s_h^n \exp\left(\frac{-Q_h}{RT}\right) t$$

where ϵ_T , β , A , Q and n are materials constants
the subscript h refers to the core of the specimen

The stress in the coating can be derived from the creep rate, $\dot{\epsilon}$, and applied stress of the

composite specimen, σ_g , as the behaviour of the core approaches steady state, i.e. after considerable time. In this situation the coating stress, σ_c , can be expressed as:

$$s_c = \frac{1}{2z} \left(s_g (h + 2z) - h \left(\frac{\dot{\epsilon}}{A \exp\left(\frac{-Q_h}{RT}\right)} \right) \right)^{\frac{1}{n}}$$

Thus a series of datapoints correlating $\dot{\epsilon}$ with s_c are obtained from a single test under constant s_g at a given temperature. Additional tests at different temperatures can then generate sufficient data to develop a creep law for the coating of the form:

$$\dot{\epsilon} = A_c s_c^{n_c} \exp\left(\frac{-Q_c}{RT}\right)$$

where the subscript c refers to values for the coating.

Using this approach Taylor *et al* derived the creep properties of APS Ni25Cr6AlY coating on a 20Cr25Ni austenitic steel substrate.

The main criticisms of this approach are that representative substrates cannot always be used and that some coating processes, e.g. High Velocity Oxy-Fuel (HVOF), may cause excessive distortion of the thin substrate.

SHEAR LOADING

Majerus *et al* [3] have developed a technique to measure the creep properties of a bondcoat under shear loading. A schematic representation of the test is shown in Figure 3.

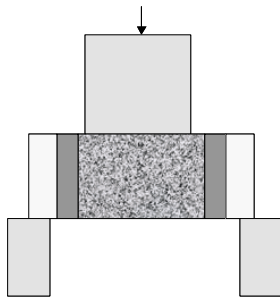


Figure 3 Schematic Representation of Shear Creep Test

A cylindrical specimen is prepared with the bondcoat to be investigated and a thick ceramic overlayer. The specimen is supported by the ceramic over a circular recess. Load is then applied via a rigid punch to the substrate thereby subjecting the bondcoat to shear stresses. Strain is monitored through the relative displacement of the top and bottom rig components.

A creep law is obtained that relates the applied shear stress, τ , to the resultant shear strain rate, $\dot{\gamma}$. This has a similar form to the uniaxial creep law, thus:

$$\dot{\gamma} = A'_c \tau^{n'} \exp\left(\frac{-Q_c}{RT}\right)$$

where A'_c and n' are material constants relating to the behaviour in shear.

Using this technique Majerus *et al* has measured the shear creep properties of a Low Pressure Plasma Sprayed (LPPS) bondcoat on a CMSX-4 substrate.

One criticism of this technique is that the results can be distorted if the shear deformation is localised at a weak region in the bondcoat, leading to data that are not representative of the bondcoat as a whole.

COMPRESSIVE LOADING

The ceramic layer has usually been assumed to deform elastically but recent studies by Heckmann *et al* [4] have demonstrated that this is not necessarily the case.

Heckmann *et al* developed a technique to measure the creep properties of this layer in compression: specimens were prepared using APS to deposit a zirconia layer onto a cylindrical low carbon steel substrate. This substrate was then dissolved by etching to leave a ring of ceramic that was loaded in compression to determine the creep properties. Creep of the zirconia was observed at temperatures as low as 850 °C.

SUMMARY

Four approaches to measure the creep properties of coatings for use in gas turbines have been reviewed. Each approach has some limitations but if used in combination the approaches can give valuable data.

ACKNOWLEDGEMENTS

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