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Influence of Glass Content on Damping Properties of Plasma-Sprayed Mixtures of Zirconia and Glass

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The addition by vacuum infiltration of small quantities of a polymer has been found to increase significantly the ability of a plasma-sprayed coating to dissipate vibratory energy at temperatures in the glassy-rubbery transition range of the polymer. As vitreous enamels and glasses undergo a glassy transition, but at much higher temperatures, the addition of a small amount of glass to a ceramic has the potential of providing high damping at such temperatures. Mixtures of yttria-stabilized zirconia (YSZ) and a glass frit were plasma sprayed on specimens with bond coats. Measures of system response (resonant frequencies and loss factors) were extracted from frequency responses to excitations of cantilever beam specimens over a range of excitation amplitudes. Comparisons of values determined before and after coating were used to determine the damping properties of the coatings alone as functions of strain, at temperatures of special interest. Emphasis was given to identifying the lowest level of glass giving significantly more damping than that of the plasma-sprayed ceramic alone. Coatings with weight fractions of 5, 2, 1, ½, and 0% glass were tested. The inclusion of glass at all weight fractions considered was found to yield significant increases in both the stiffness and dissipation of the coatings.

Keywords ceramic-glass mixtures, coatings, damping, mechanical testing

1. Introduction

Components of gas turbine engines, especially blades, are vulnerable to fatigue failures resulting from resonant vibrations excited by periodic pulses arising as rotating components pass vanes, and from other sources. As the maximum value of the response at resonance is determined by the energy dissipation (damping) of the system, response amplitudes may be reduced by incorporating dissipative components during engine design. The alteration of plasma-sprayed ceramic coatings, as are applied for other purposes, to enhance their dissipative ability is an attractive means for reducing the amplitudes of vibratory stress.

The addition of a polymeric material to a plasma-sprayed ceramic has been found (Ref 1-4) to provide significant increases in the ability to dissipate energy at temperatures in the range of the glassy-rubbery transition, an inherent characteristic of each viscoelastic material. In the case of polymeric materials, this temperature is less than a few hundred degrees C. At much higher temperatures, however, the mechanical properties of glasses and vitreous enamels display the dependence on frequency and temperature characteristic of viscoelastic materials (Ref 5). Thus, the addition of glass to a ceramic may lead to multifunctional coatings, capable of reducing the amplitude of resonant vibrations while acting as thermal barrier coatings and providing protection against erosion, corrosion, and wear.

A preliminary study conducted at low strains (Ref 6) had shown that a mixture of 5% glass in 8% yttria-stabilized zirconia (YSZ) provided exceptionally high damping, only about 20% less than a mixture with 10% glass. Concern about the possibility of the glass particles being subject to creep at high temperatures led to consideration in this work of further reductions in the glass fraction. For comparison, results for a plasma-sprayed YSZ coating without glass were also obtained.

The standard tests for the damping properties of free layer coatings as described in the ASTM standard (Ref 7) are based on the presumption that the materials are linear, i.e., that the storage modulus and loss modulus (or loss factor) are independent of the amplitude of cyclic strain. It has been found (Ref 1-4, 8, 9), however, that the damping properties of plasma-sprayed ceramics, both with and without polymeric viscoelastic infiltrates, have a significant dependence on amplitude. As it is therefore of interest to ascertain the degree to which the properties of coatings of a plasma-sprayed ceramic-glass mixture depend on the amplitude of cyclic strain, testing was extended to higher levels of strain than previously employed.

The objectives of this study were to determine the damping properties (storage and loss moduli) of a ceramic-glass coating, with the constituents mixed and applied simultaneously by the air plasma spray technique. These mechanical properties of the coating materials were extracted from comparisons of the resonant frequencies and system loss factors of test specimens before and application of the

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coatings, using procedures described elsewhere (Ref 2, 4) and only summarized here.

2. Experimental Methods and Materials

2.1 Test Procedure

System level tests were conducted by mounting specimens as cantilever beams on a large (27,000 N) shaker, and exciting through resonance with constant amplitude of base acceleration and, because of the observed strain softening, with excitation frequencies swept downward from above resonance. Testing was restricted to cantilever modes 2 and 4. Frequency response functions (Bode plots) were developed from response velocities measured with a laser vibrometer at 47% of span, near an antinode for both modes. Each specimen was retested at numerous levels of excitation amplitude as regulated by a control accelerometer near the base of the specimen. Successive tests were conducted with decreasing levels of excitation. Aside from modification of specimens to permit testing at high temperatures, and the use of a different heating chamber, the facilities and procedures are the same as those employed in previous work (Ref 2-4, 9).

The resonant frequency (maximum response amplitude) provides a measure of system stiffness. The system loss factors (η_S for coated and η_B for bare specimens) provide measures of the total damping for that level of excitation. The repeated tests at different levels of excitation (and response) then provide a means of evaluating the dependence of system response on the amplitude of strain in the coating.

Resonant frequencies given here are as determined from the identification of the frequency of maximum response to sine sweeps at constant levels of exciting acceleration with frequencies swept from high to low. Values of system loss factor are as determined by controller software (VibrationVIEW) from the half-power bandwidths of the response. Care was taken to assure the validity of test data with special attention given to insuring that the response was not significantly influenced by an interaction with a mode of the support structure or with a torsional mode of the beam, that the sweep rates were sufficiently slow as to enable accurate capture of the response, and that a system nonlinearity did not preclude accurate capture of the response. Results are given as functions of the maximum strain at the beam root, as obtained from the mode shapes of Bernoulli-Euler beams vibrating at the observed frequency and peak velocity at the measurement point.

2.2 Test Specimens

Test specimens were designed with a thickened root section to enable insertion of the 216 mm test section sufficiently far into a heating chamber as to assure a nearly uniform temperature distribution, while separating sensitive shaker components from high temperature air. Clamping the root over 51 mm enabled excitation as a cantilever beam. Each of six test specimens was constructed of Hastelloy X with a nominal test section thickness of 1.6 mm and width of 19 mm. See Fig. 1.

Properties of Hastelloy X as provided (Ref 10) by the manufacturer are a density of 8220 kg/m^3 and a room temperature (20 °C) Young's modulus of 205 GPa. The dynamic moduli at various temperatures as given are in tabular form, but can be represented (for E in GPa and temperature, T, in °C) by:

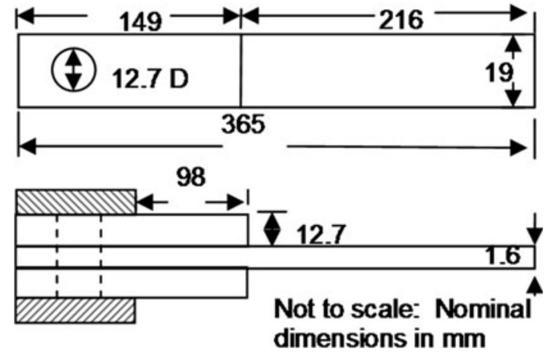

Fig. 1 Specimen for testing at high temperatures

$$E(T) = 206.0 - 0.03665T - 0.0000293T^2 \quad \text{(Eq 1)}$$

2.3 Bond Coat Material

NiCrAlY bond coats, nominally of 0.076 mm or 3 mil thickness as measured by micrometer, were applied by air plasma spray to both sides of all specimens. By comparing the weight and thickness differences between small coupons coated first with a measured thicknesses of 0.076 mm (3 mils) and then with 0.76 mm (30 mils) of the bond coat material, the true density of a plasma-sprayed NiCrAlY bond coat was estimated to be about 6020 kg/m^3. Using this density with the average of measured weights of nominally identical bond coats applied to 12 samples, the true average value of the bond coat thickness was determined to be only about 0.04 mm (1.6 mil), much less than the apparent thicknesses of about 0.076 mm (3 mil) obtained by micrometer measurements because of the high, and deliberate, surface roughness of the bond coat.

2.4 Top Coat Materials

After application of bond coats, mixtures of 8% YSZ and glass were applied by air plasma spray to both sides of specimens. The glass, designated as Frit 4, used in this study was chosen after testing beams coated with mixtures of YSZ and several different frits at low strains using the ASTM standard methodology (Ref 7). Frit 4 has an initial softening point below 500 °C, with partial melt over 700 °C. This glass was selected as being appropriate for applications at about 650 °C.

Five specimens were prepared with various quantities of Frit 4 mixed into the spray stock and co-sprayed with the stabilized zirconia. One specimen was coated with YSZ without the glass frit. Specimens with the YSZ-glass top coats were cured by cycling three times through the temperature range from room temperature to 816 °C. Determinations of material properties at low strain yielded the same results after the second and third cycles, indicating stable properties.

By weighing and measuring specimens 11 and 12 before and after coating, the average densities of the complete coating systems (YSZ, glass, and bond coat) were determined to be as shown in Table 1. The average value and the estimates of true bond coat thickness and density were used to determine the density of plasma-sprayed YSZ with 5% glass alone as 3864 kg/m^3. Because of the low glass fractions, and the similarity of YSZ and glass densities, it was assumed that densities of mixtures with lower glass fractions and of YSZ alone could be approximated by this value. Average densities of the complete coating system for other specimens were computed using this value, the measured total thickness, and the bond coat thickness and density. Values are shown in Table 1, together with measured thicknesses before and after adding both bond and top coats. As the thicknesses of two of the specimens (16-6 and 16-7) before coating were not available, the average thickness of the other four specimens was assumed. The ratio of total coating thickness (each side) to substrate thickness for each specimen is also shown.

3. Results from Tests

3.1 Bare Beams

Resonant frequencies and system loss factors of four bare beams were obtained at room temperature for values of maximum (root) strain up to about 600 ppm. Two of the bare specimens were also tested at 650 °C. For use in the extraction of material properties from changes in response after adding the coatings, the mode n resonant frequencies of the bare beams, $f_{0\text{-}n}$, were found to be adequately represented for strains up to 600 ppm by linear relationships of the form

$$f_{0\text{-}n} = a_{0\text{-}n} + a_{1\text{-}n}(\varepsilon/1000) \quad \text{(Eq 2)}$$

Values of the necessary coefficients for mode n frequencies in Hz with strains expressed in ppm, i.e., microstrain, are shown in Table 2.

Resonant frequencies at 650 °C for specimens 15 and 16 were estimated by multiplying the room temperature parameters in Table 2 by a factor of $\sqrt{0.83}$ as determined with Eq 1 to account for thermal softening of the specimen material.

Loss factors for the bare beams, η_B, were also obtained. Values in the range of 0.0004-0.0009 indicated that losses to the support structure and the environment were satisfactorily low in both modes and at both temperatures. Loss factors for the two modes, n_{B-n}, and two temperatures were found to be adequately represented by polynomials of the form

$$1000\,\eta_{B\text{-}n} = b_{0\text{-}n} + b_{1\text{-}n}(\varepsilon/1000) + b_{2\text{-}n}(\varepsilon/1000)^2 \quad \text{(Eq 3)}$$

with necessary coefficients as shown in Table 3, for strains in units of ppm.

The adequacy (rigidity) of the shaker-mounted cantilever support was evaluated by determining the effective modulus, E_0, of the bare beams at low strain from the observed resonant frequencies by inverting the frequency equation for a homogeneous isotropic (Bernoulli-Euler) beam, assuming a perfect cantilever mounting, i.e.,

Table 1 Parameters of coated specimens

Specimen	Glass (w.f.), %	Thickness, mm Bare	Total	Coating	t/h	Density Total, kg/m^3
11	5	1.589	2.071	0.241	0.152	4200
12	5	1.585	2.047	0.231	0.146	4270
15	2	1.628	2.309	0.341	0.209	4130
13-6	1	1.607(a)	2.349	0.371	0.231	4110
13-7	0.5	1.607(a)	2.285	0.339	0.211	4130
16	0	1.625	2.285	0.330	0.203	4140

(a) Assumed values

Table 2 Linear representations of resonant frequencies of bare beams

Beam	Temp.	$a_{0\text{-}2}$	$a_{1\text{-}2}$	$a_{0\text{-}4}$	$a_{1\text{-}4}$
11	RT	167.49	−0.160	914.02	−1.33
12	RT	167.36	−0.120	912.56	−0.98
15	RT	169.78	−0.159	925.50	−1.66
16	RT	169.97	−0.196	927.22	−1.45
11	650 °C	151.54	−0.11	828.27	−1.23
12	650 °C	151.51	−0.48	826.85	−1.48

Table 3 Polynomial representations of loss factors of bare beams

Beam	Temp.	$b_{0\text{-}2}$	$b_{1\text{-}2}$	$b_{2\text{-}2}$	$b_{0\text{-}4}$	$b_{1\text{-}4}$	$b_{2\text{-}4}$
11	RT	0.466	0.776	0.082	0.279	0.519	0.317
12	RT	0.465	−0.075	0.408	0.199	0.4374	0.956
15	RT	0.366	−0.011	1.035	0.408	0.345	0.837
16	RT	0.478	−0.061	0.944	0.489	−0.196	0.870
11	650 °C	0.692	0.197	0.000	0.314	−0.210	0.966
12	650 °C	0.680	0.017	0.369	0.308	−0.221	0.956

$$E_{0\text{-}n} = \frac{12\rho_B}{h^2}\left(\frac{L}{K_n L}\right)^4 (2\pi f_{0\text{-}n})^2 \quad \text{(Eq 4)}$$

Observed frequencies, together with the eigenvalues for the second and fourth modes ($K_2L = 4.6941$ and $K_4L = 10.9955$), a beam density of 8220 kg/m^3, and measured values of thickness and length gave an apparent or effective modulus for each beam in the two modes at room temperature and 650 °C. As expected, because of some flexibility of the long unsupported section at the root and of the mount, the average value of the apparent modulus for the eight room temperature determinations (191.3 GPa) was slightly lower than the published value of the dynamic modulus. The average of the four determinations at elevated temperature (158.9 GPa) was 82% of the average room temperature value, in satisfactory agreement with the expected value (83%) from Eq 1. As the agreement between values obtained in the two modes ($E_{0\text{-}2}$ and $E_{0\text{-}4}$) is within about 1%, these comparisons indicate that the specimen support system is adequate for tests in both modes at both room and elevated temperatures and that the observed responses are not significantly influenced by interaction with another mode of the specimen or the support structure.

3.2 Beams with Bond Coat Alone

After application of the bond coats, specimens 11 and 12 were tested over a range of excitation amplitudes at the two temperatures. Room temperature resonant frequencies were found to be slightly above, and frequencies at 650 °C slightly below, values obtained with the bare beams. System loss factors at room temperature differed little from bare beam values and loss factors at 650 °C were only about twice the values at room temperature, with no values observed to be >0.002. Thus, a bond coat can be expected to add little to the stiffness or damping of a complete coating system.

Using the same facilities and procedures as in the testing of bare beams, the amplitude-dependent resonant frequencies and system loss factors were determined for each specimen with top coat at room temperature and at one or more elevated temperatures. In most cases, one or more repeat tests at room temperature were conducted after cool-down to determine the extent, if any, that exposure to the elevated temperature changed the properties of the material. These results are denoted by line codes b and c in figures.

3.3 Beams with Top Coat of YSZ Alone

To provide a baseline for the evaluation of the effectiveness of the added glass in enhancing the dissipation, tests were conducted with coatings of plasma-sprayed 8% YSZ on the bond coat, but without the added glass component. Specimen 16 was tested in the second and fourth cantilever bending modes at room temperature and at elevated temperature. The observed resonant frequencies and loss factors are represented in Fig. 2.

The increase in temperature is seen to lead to lower frequencies due to thermal softening of the glass component. Characteristic slopes of the system loss factor versus strain (log-log) are about $m = 0.32$.

A second specimen, nominally identical to the first, was tested at room temperature and three higher values. The results (not shown) indicated the damping to be insensitive to temperature for the range of 593-704 °C. Values of the storage modulus and loss modulus at room temperature and 650 °C were in satisfactory agreement with values obtained with the first specimen.

3.4 Beams with Top Coat of YSZ and 5% Glass Frit 4

Specimens 11 and 12 were prepared and tested in mode 4 at several temperatures. The observed resonant frequencies and loss factors are represented in Fig. 3.

These data suggest that this coating provides maximum damping about 650 °C and that the material is nearly linear, i.e., the damping is nearly independent of strain. Irregularities in data are a consequence of degradation of the laser vibrometer target at high temperatures. Characteristic slopes of the system loss factor versus strain (log-log) are about $m = 0.33$ at room temperature and 0.032 at the high temperature.

3.5 Beams with Top Coat of YSZ and 2% Glass Frit 4

Specimen 15 was prepared and tested in two modes (frequencies) at room temperature and 650 °C. The observed resonant frequencies and loss factors are represented in Fig. 4.

For this and other specimens with glass fractions of 2% and less, the coating thickness was increased. As higher than

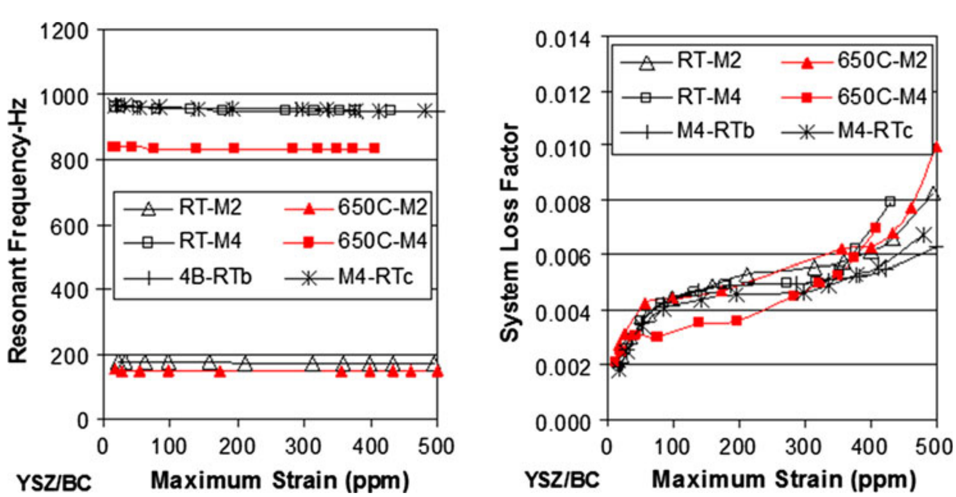

Fig. 2 System response of beam with coatings of YSZ, two modes

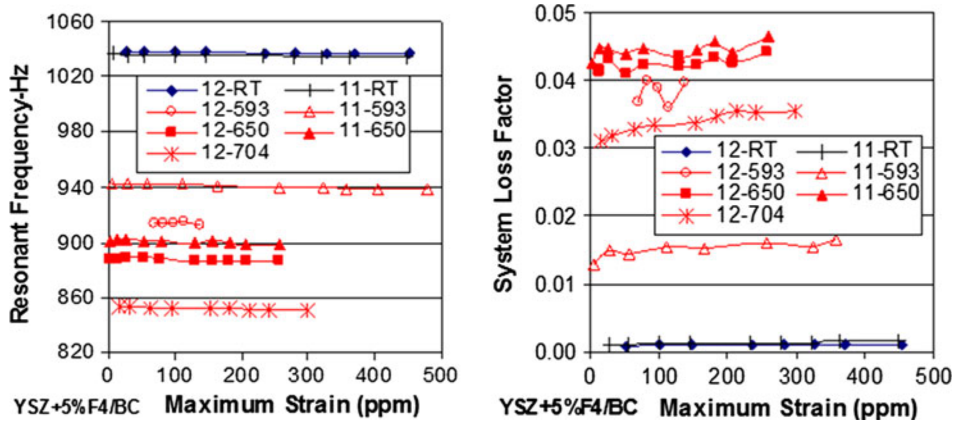

Fig. 3 System response of beams with coatings of YSZ and 5% glass

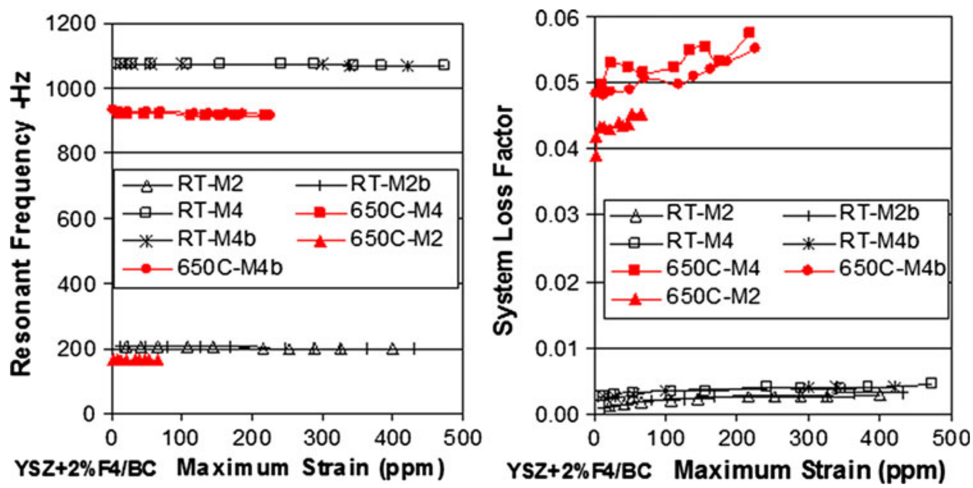

Fig. 4 System response of beam with coatings of 2% glass in YSZ, two modes

anticipated damping led to lower levels of response than expected, only modest levels of strain were achieved with this specimen. Characteristic slopes of the system loss factor versus strain (log-log) are about $m = 0.32$ at room temperature and 0.032 at high temperature.

3.6 Beams with Top Coat of YSZ and 1% Glass Frit 4

Specimen 13-6 was prepared and tested in the two modes at room temperature and 650 °C. The observed resonant frequencies and loss factors are represented in Fig. 5.

Characteristic slopes of the system loss factor versus strain (log-log) are about $m = 0.33$ at room temperature and 0.025 at high temperature.

3.7 Beams with Top Coat of YSZ and 0.5% Glass Frit 4

Specimen 13-7 was prepared and tested in two modes at room temperature and 650 °C. The observed resonant frequencies and loss factors are represented in Fig. 6.

At this low concentration of glass, the amplitude dependence of the loss factor at 650 °C becomes much more significant. Characteristic slopes of the system loss factor versus strain (log-log) are about $m = 0.36$ at room temperature and 0.19 at high temperature.

4. Extraction of Coating Properties

The desired material properties of the coating materials are the storage modulus, E'_C, and the loss modulus, E''_C. These are defined in terms of the maximum energy stored, U, and dissipated per cycle, D, per unit volume at maximum cyclic strain ε by

$$U = E'_C \varepsilon^2/2 \quad \text{(Eq 5)}$$

$$D = \pi E''_C \varepsilon^2 \quad \text{(Eq 6)}$$

For a linear material, i.e., properties independent of the amplitude of strain, these constitute the real and imaginary parts, respectively, of a complex Young's modulus.

These material properties of the coatings were determined from the observed values of resonant frequency and system loss factor of coated and uncoated specimens at various amplitudes of excitation (and response) by using a methodology (Ref 2, 4), developed from a more general approach (Ref 9). Since both the storage and the loss modulus are obtained through comparisons of responses before and after coating, it is essential that the same facilities and procedures be used for both determinations, and that these values are obtained to a rather high degree of accuracy.

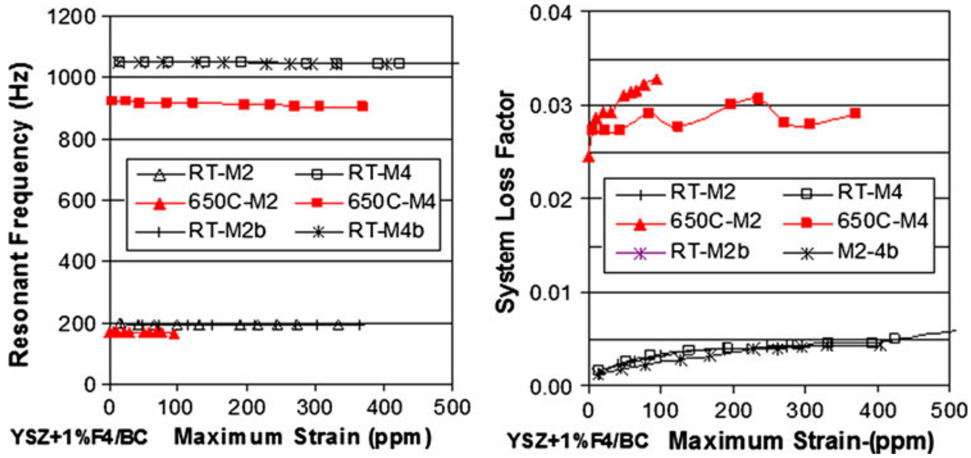

Fig. 5 System response of beam with coatings of 1% glass in YSZ, two modes

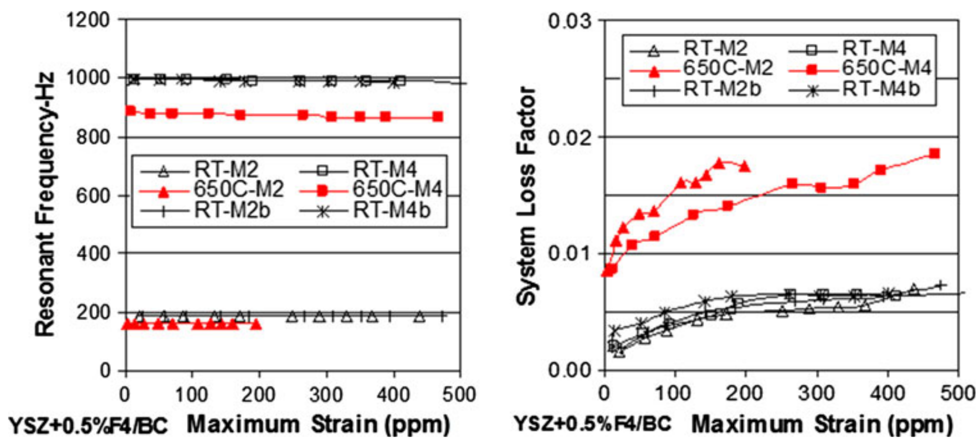

Fig. 6 System response of beam with coatings of ½% glass in YSZ, two modes

The ratio of maximum strain energy stored in the coating to that in the substrate for each specimen is first found from the ratio of resonant frequencies for the same mode and temperature before (f_0) and after (f) coating and the ratio of the mass per unit area of the coating to that of the substrate. The densities (ρ_C and ρ_B) are presumed to be known. The result, for coatings of thickness t on both sides of a substrate beam of thickness h, follows from a consideration of the Rayleigh quotients and is that

$$R_{SE} = \frac{f^2}{f_0^2}\left(1 + \frac{2t\rho_C}{h\rho_B}\right) - 1 \qquad \text{(Eq 7)}$$

Some tests were conducted at temperatures near, but differing, from the nominal high temperature value of 650 °C. In these cases, the bare beam frequency at temperature T was estimated from the value at 650 °C with Eq 1 and

$$f_0(T) \cong f_0(650)\sqrt{\frac{E(T)}{E(650)}} \qquad \text{(Eq 8)}$$

As it is not practical to achieve in experiments precisely the same values of response strain for both coated and uncoated specimens, representations of the bare beam data as given in Eq 2 and Table 2 were used to determine the bare beam frequencies and to evaluate with Eq 4 the effective modulus, E_0, of the substrate beam at the specific values of strain achieved in the tests with the coated specimens. Once the ratio of strain energies is determined, the ratio of the storage modulus, $\bar{E}'_C$, of the coating to that of the substrate beam follows. The Young's storage modulus of the coating is

$$\bar{E}'_C = \frac{R_{SE}E_0}{6t/h + 12(t/h)^2 + 8(t/h)^3} \qquad \text{(Eq 9)}$$

While Eq 7 and 9 give the same result as the standard methodology (Ref 7), a value of the storage modulus, $\bar{E}'_C$, found in this manner is not the true value for an amplitude-dependent material. It is rather a strain-weighted average or effective modulus for the entire volume of coating on a beam vibrating in a specific mode at a specified value of maximum strain. It is related to the true value of the amplitude-dependent storage modulus, E'_C, by

$$\bar{E}'_C \equiv \int_V E'_C \varepsilon^2 dv \Big/ \int_V \varepsilon^2 dv \qquad \text{(Eq 10)}$$

It has been found (Ref 9) however, that the true or local modulus is readily extracted from this quantity.

The value of the Young's loss modulus, E''_C, may then be found from the strain energy ratio, the storage modulus of the coating, and the system loss factor, η_S, after coating. The loss factor of the bare beam at the coated beam strain, η_B, is estimated using Eq 3 and Table 3. The result is a local or material property, given by

$$E''_C = \left[\frac{E'_C}{\bar{E}'_C}\right]\bar{E}'_C \frac{[\eta_S(1+R_{SE}) - \eta_B]}{R_{SE}}[M(2+m, t/h, n)] \quad \text{(Eq 11)}$$

The first factor in Eq 11 is a measure of the influence of the nonlinearity due to strain-dependent stiffness. The last factor in Eq 11 is a measure (Ref 2) of the influence of strain-dependent damping, expressed as an exponential dependence of system loss factor on strain of the form $\eta_S \sim \varepsilon^m$. As will be demonstrated in later sections, however, taking both factors to be unity leads to relatively minor underestimates of the loss modulus of these coatings. If the bare beam losses, η_B, are also neglected, a loss modulus evaluated with Eq 10 becomes equivalent to the use of the standard methodology (Ref 7).

Values of the storage modulus given below are the average or effective values, $\bar{E}'_C$, given as functions of the maximum strain at the beam-coating interface. Values of the loss modulus were evaluated with the first and last factors of Eq 11 taken as unity, and are given as functions of the true, or local, strain in the coating. In cases where a complete characterization of the bare beam was not accomplished before coating, bare beam frequencies for Eq 7 and loss factors for Eq 11 were estimated as being the average values of all specimens tested, as shown in Table 2 and 3. As these properties were obtained from comparisons of the bare beam response with that for the entire coating system (bond coat and top coat), the resulting values are effective values for the entire coating system, and may not be appropriate for use if the ratio of bond coat to top coat thickness differs significantly from the 6-11% used here.

4.1 Plasma-Sprayed Yttria Stabilized Zirconia on NiCrAlY Bond Coat

The test data of Fig. 2 were used in Eq 7, 9, and 11 to obtain the material properties represented in Fig. 7.

These results indicate that the material properties as determined from data taken at two modes (frequencies) are in satisfactory agreement, and that values obtained from data taken before and after exposure to high temperatures are also in satisfactory agreement.

At a strain of 250 ppm, the storage modulus obtained here is somewhat (20%) higher, and the loss modulus at a strain of 250 ppm is lower (30%) than the room temperature values obtained by Tassini et al. with a different test methodology (Ref 8). The increasing values of loss modulus at the highest strains are not characteristic of plasma-sprayed ceramics without a viscoelastic component, for which declining values at higher strain are typical (Ref 8, 9). The higher values at high strain are possibly due to the emergence of a strong history effect or a different damping mechanism.

4.2 Plasma-Sprayed YSZ with 5% Glass on NiCrAlY Bond Coat

The test data of Fig. 3 were used in Eq 7, 9, and 11 to obtain the results shown in Fig. 8.

Addition of the glass increased the storage modulus by nearly a factor of three at both room and elevated temperatures. Addition of the glass reduced the room temperature loss modulus by well over a factor of two, but increased the values at elevated temperatures by more than an order of magnitude. Agreement in both storage and loss modulus as determined from data for the two specimens are in satisfactory agreement at both 650 °C and room temperature, but the differences seen in properties at 593 °C may indicate some difference in the curing process for the two specimens.

4.3 Plasma-Sprayed YSZ with 2% Glass on NiCrAlY Bond Coat

The test data of Fig. 4 were used in Eq 7, 9, and 11 to obtain the material properties shown in Fig. 9.

While values of the loss modulus are somewhat lower than values obtained with 5% glass (Fig. 8), the values at the design temperature of 650 °C remain at about 80% of those obtained with the higher concentration. Retests in mode 4 (line codes b) at room temperature and 650 °C after tests at 650 °C showed excellent replication of the original results, indicating stability of material properties.

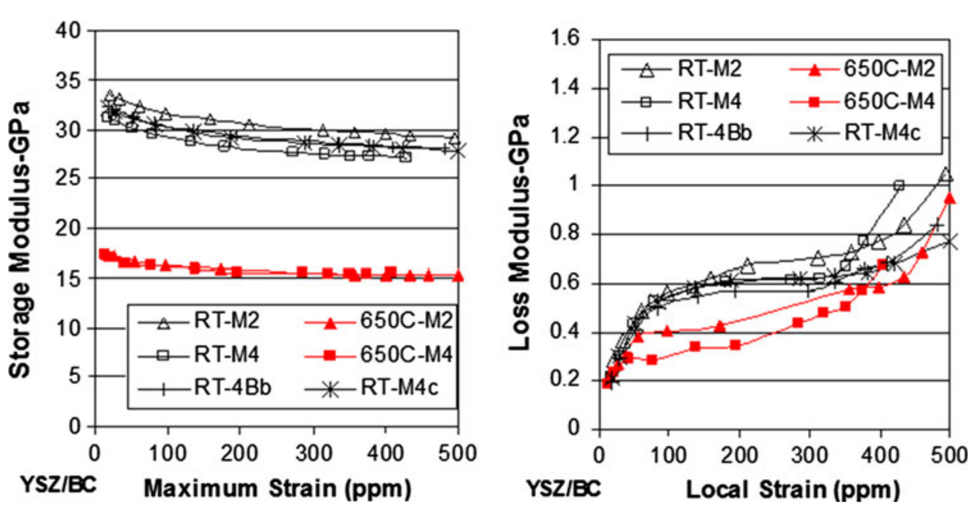

Fig. 7 Material properties of 8% yttria-stabilized zirconia on bond coat

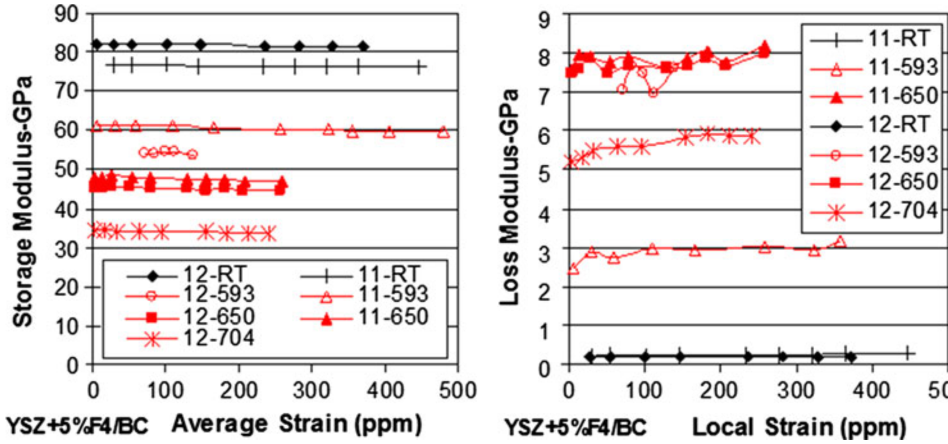

Fig. 8 Material properties of YSZ with 5% glass on bond coat

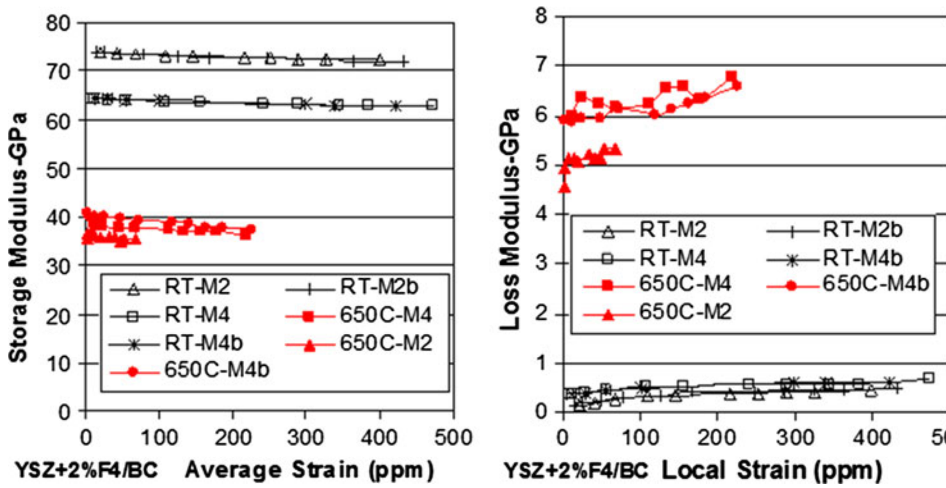

Fig. 9 Material properties of YSZ with 2% glass on bond coat

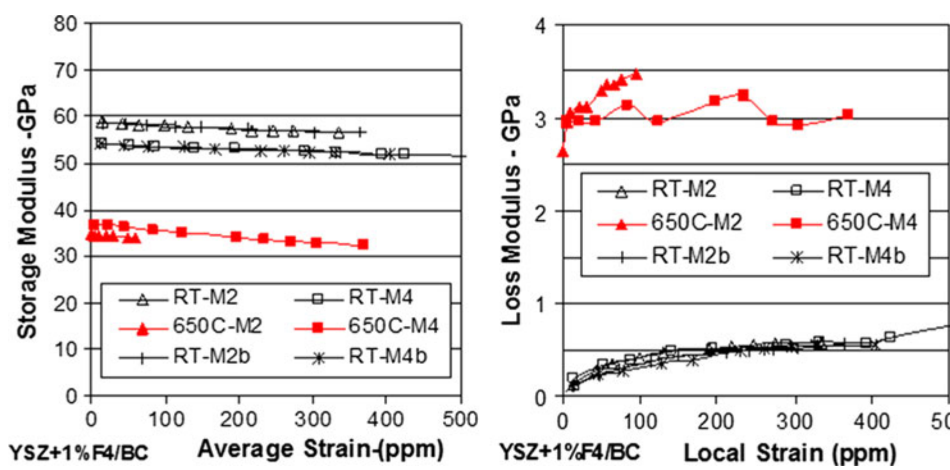

Fig. 10 Material properties of YSZ with 1% glass on bond coat

4.4 Plasma-Sprayed YSZ with 1% Glass on NiCrAlY Bond Coat

Test data of Fig. 5 were used in Eq 7, 9, and 11 to obtain the material properties shown in Fig. 10.

The reduction in glass content from 2 to 1% appears to have reduced the loss modulus at 650 °C by about a factor of two, but to have reduced the storage modulus only slightly.

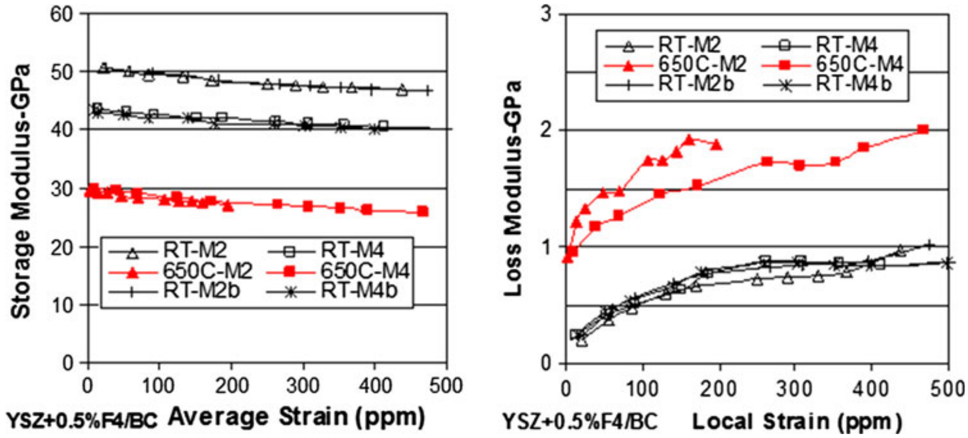

Fig. 11 Material properties of YSZ with 0.5% glass on bond coat

4.5 Plasma-Sprayed YSZ with 0.5% Glass on NiCrAlY Bond Coat

The test data of Fig. 6 were used in Eq 7, 9, and 11 to obtain the material properties shown in Fig. 11.

With only 0.5% glass, the loss modulus at 650 °C shows a notably stronger dependence on amplitude of strain than was seen with in the results obtained for the same ceramic and bond coat but with a higher glass content. Replication of values obtained using data from retests at room temperature (line codes b) after testing at the elevated temperature is satisfactory.

5. Discussion of Results

5.1 Stiffness Nonlinearity: Average versus True or Local Modulus

The values of the storage modulus, $\bar{E}'_C$, as found in Eq 9 and shown in Fig. 7-11 are the strain-weighted average or effective modulus over the entire coating volume on a beam vibrating at the specified maximum strain. However, it has been shown (Ref 9) that, for coatings on cantilever beams vibrating in the lower modes, the true local coating storage modulus, E'_C, at strain ε is quite satisfactorily approximated by

$$E'_C(\varepsilon) = \bar{E}'_C(3\varepsilon/2) \quad \text{(Eq 12)}$$

Values obtained using mode 4 data for specimen 16 (YSZ alone on bond coat, Fig. 7) and specimen 11 (YSZ + 5% glass on bond coat, Fig. 8) were compared with the values of the true modulus as determined by adjustment with Eq 12. Results shown in Fig. 12 demonstrate that the ratio $E'_C/\bar{E}'_C$ is essentially unity for these materials. Thus, the neglect of the first factor of Eq 11 for the evaluation of the loss modulus is justified at both temperatures and at all values of strain. In the case of coatings displaying a greater dependence of the storage modulus on strain, such as the ceramics infiltrated with a viscoelastic material (Ref 2-4), this ratio is typically somewhat greater.

5.2 Damping Nonlinearity (Amplitude Dependence)

In the determination of the values of loss modulus as shown in Fig. 7-11, the last factor, M, of Eq 11 was taken as unity. This is strictly appropriate only for a material without amplitude dependence. Characteristic values of the parameter m (slope of log η_S vs. log ε) quantifying the damping nonlinearity are given in text above. For the coatings tested here, the typical values for the room temperature data and for YSZ alone at 650 °C are m = 0.32-0.36. For the YSZ-glass at high temperatures, however, the characteristic value is about 0.19 for YSZ with ½% glass, and <0.06 with the higher concentrations. Using these to evaluate the parameter M shows that taking $M = 1$ leads to underestimates of as much as 10% for the loss modulus of the YSZ-glass at room temperature, and about 8% for the loss modulus of the YSZ alone at all temperatures. For the YSZ-glass mixtures at the high temperatures, the underestimates are only about 5% for the mixture with ½% glass and $<2\%$ for the mixture with 1-5% glass. However, the use of half-power bandwidths to determine the system loss factors when the loss factors are amplitude dependent leads to overestimates of system loss factors (Ref 11) of 11, 6, and 2%, respectively, for values of m = 0.36, 0.19, and 0.6. Thus, the underestimates in the evaluation of Eq 11 are very nearly offset by the overestimates inherent in the determination of the system loss factors, η_S.

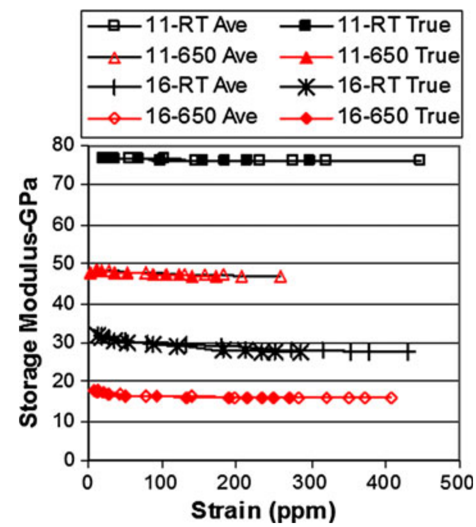

Fig. 12 Comparison of strain-weighted and true values of storage moduli

5.3 Influence of Frequency

Emphasis was given to testing in the fourth bending mode as the resulting frequency (~1 kHz) is of special interest for a potential application. As some frequency dependence is to be expected, especially at elevated temperatures, tests in the second mode were included. Values of the room temperature storage modulus extracted from mode 2 data (~200 Hz) were found to differ somewhat from values obtained with mode 4 data (~1000 Hz). However, the two values at 650 °C were found to be in quite good agreement, suggesting a minimal dependence on frequency.

5.4 Influence of Glass Fraction

The inclusion of glass in the plasma-sprayed YSZ was found to increase the room temperature storage modulus significantly, with only 2% glass being necessary to more than double the stiffness at room temperature. Such large increases in storage modulus, E'_C, as were found to result from the addition of glass are consistent with the hypothesis that the presence of the co-sprayed glass either bonds the splats of zirconia together or blocks the "splats" from sliding against each other. This restricts the dissipation due to friction that has been identified as the source of dissipation in plasma-sprayed materials (Ref 12). In consequence, the loss modulus, E''_C, of the ceramic-glass mixture at room temperature, where the dissipation due to deformation of the glass is negligible, is reduced significantly from that of plasma-sprayed YSZ alone. As a result, these coatings do not provide useful damping at low temperatures. The results in Fig. 7-11 show that the loss modulus at room temperature decreases monotonically with increasing glass content.

At temperatures within the transition range, however, the glass deforms as a viscoelastic material, softening with temperature. At 650 °C, the storage modulus of the ceramic with glass drops 50-60% of the value at room temperature, but the loss modulus increases dramatically.

Typical values of the storage and loss moduli at room temperature and 650 °C as extracted from Fig. 7-11 for each of the concentrations of Frit 4 glass investigated are compared in Fig. 13. Representative values of each are shown (when available) at two values of local strain, 100 and 300 ppm. At these strains, the amplitude dependence at 650 °C is seen to be negligible.

At 650 °C, the addition of only 1% glass increases the storage modulus by nearly a factor of two, and the increase to 5% results in a coating almost three times the stiffness of plasma-sprayed zirconia alone. The loss modulus at 650 °C is seen to increase nearly linearly with glass content up to about 2%, but less rapidly with further increases. This is consistent with the findings in preliminary work (Ref 6) that the dissipation with 5% glass was about 80% of that with the inclusion of 10% glass.

While the loss modulus for coatings of YSZ alone and with low glass fractions all show some dependence on amplitude of strain, especially at strains below 100 ppm, the loss modulus with 5% glass at 650 °C (Fig. 8) becomes nearly independent of amplitude. As the variation in storage modulus with strain is also nearly independent of amplitude, this material may be treated as being linear. Even with concentrations as low as 1%, the ceramic-glass coating exhibits significantly less amplitude dependence than was found to result from the addition of a viscoelastic material to a ceramic by vacuum infiltration (Ref 1-4). This is believed to be a consequence of the more uniform distribution of the dissipative component throughout the thickness that is achieved through co-spraying.

6. Summary and Conclusions

Although measures of system level response, such as loss factors or quality factors ($Q = 1/\eta_S$) of coated beams, are often used to compare the damping properties of coatings, the prediction of the vibratory response of a structure requires that the relevant damping properties of the coating material be known. Accordingly, in this study, emphasis was given to the determination of the storage and loss modulus of the coating materials, and to their dependence on temperature and amplitude of strain.

Tests were conducted for the purpose of determining these material properties for hard coatings formed by air plasma spraying 8% YSZ mixed with various weight fractions of a glass, identified as Frit 4, functioning as a high temperature viscoelastic material (HTVEM). Specimens were prepared of Hastelloy X sheet stock, sprayed with a NiCrAlY bond coat, and then co-sprayed with mixtures of YSZ and glass. Resonant

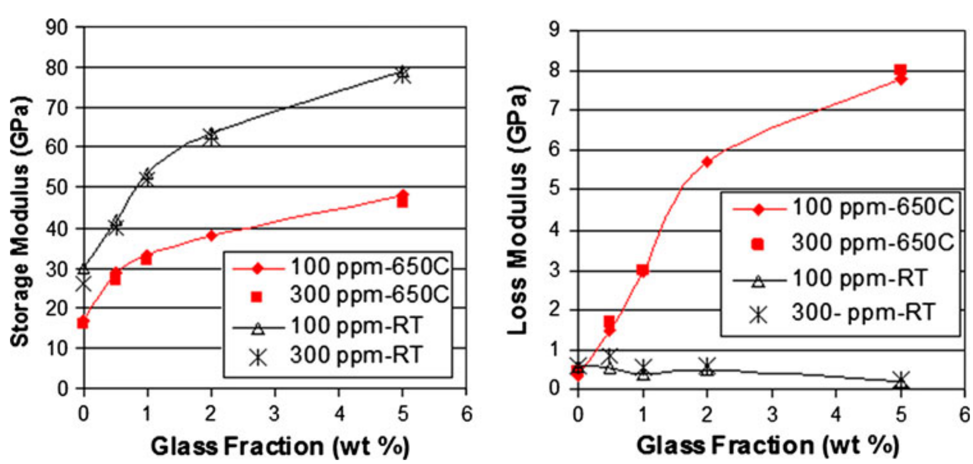

Fig. 13 Influence of glass content on properties of YSZ on NiCrAlY

frequencies and system loss factors were determined at room and elevated temperatures from frequency response functions for each beam before and after coating.

An established methodology for the extraction of the critical material properties from such data was applied to determine effective values for the tensile storage and tensile loss moduli of the entire coating system (bond and top coat) as functions of the amplitude of cyclic strain. The YSZ with 5% glass was found to have extremely high damping at 650 °C, with a loss modulus, E''_C, higher by factors of about 14-40 (depending on strain) than that of YSZ alone. The nearly amplitude independent loss modulus of about 7.5 GPa is higher than those of any other known hard coating (Ref 13). As the storage modulus is about 46 GPa, the loss factor, $\eta = E''_C/E'_C$, at strains of several hundred ppm is about 0.16.

The degree to which the glass content could be reduced while still retaining significant damping was explored because of the possibility that a lower glass fraction would reduce creep migration due to the high centrifugal loading of a rotating engine component at high temperatures. At the design temperature of 650 °C, coatings with 2 and 1% glass retained about 80 and 40%, respectively, of the loss modulus with 5% glass. The coating with only 1% glass still increased the loss modulus to about seven times that of the zirconia without glass.

To summarize, increasing the fraction of glass functioning as a HTVEM in a plasma-sprayed ceramic coating:

– creates a more linear (less amplitude dependent) material,
– increases the storage modulus significantly at all temperatures,
– reduces the loss modulus at room temperature, and
– increases the loss modulus at high temperatures.

The addition of low weight fractions of Frit 4 glass by co-spraying with 8% YSZ creates a multifunctional material with significant potential as a damping coating for temperatures near 650 °C. As such, it offers promise as a means of reducing the amplitude of resonant vibrations in such severe environments as the high temperatures and high rotational rates experienced by the components of gas turbines while protecting the substrate from erosion, corrosion, and wear.

As the loss modulus was found to be somewhat lower at 593 and 704 °C, the design objective of a maximum damping near 650 °C for frequencies about 1 kHz was achieved. This, together with the successful development (Ref 3, 4) of a material optimized for a lower temperature 93 °C, offers promise for the development of coatings optimized for high damping in other applications by the inclusion of a viscoelastic constituents with transition near the temperatures of interest.

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