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DESIGN NOTE

A novel method for the measurement of Young's modulus for thick-film resistor material by flexural testing of coated beams

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Abstract. A method for measuring the Young's modulus of thick-film resistor material is presented. 96% alumina beams were coated with Heraeus 8241 resistor material and flexural tested in the three-point bend mode using a DMA 2980 Thermal Mechanical Analyser. Young's modulus was found to decrease linearly over the 173 K to 573 K temperature range. There was no evidence of non-elastic behaviour. Modulus results for the alumina substrate relate closely to published data. This method could be used to measure the modulus of a wide variety of thick-film coatings on substrates.

Keywords: elastic modulus, Young's modulus, thick-film coating, flexural testing, 3-point-bend testing, mechanical testing

1. Introduction

Thick-film resistors have found wide application as strain sensors [1]. They are usually applied as a coating to a substrate whereby resistor strain follows that of the usually much thicker substrate. However, where a thick-film resistor is loaded in the z axis, for example in the accelerometer proposed by Sion [2], it is necessary to know the Young's modulus of the resistor material.

Sion obtained a value of 103 GN m^{-2} ± 20% at room temperature for DuPont HS8039, 10 k$\Omega/\Box$, using a resonant cantilever beam method. This method, however, may be subject to error caused at the clamped end, for example variation in clamp load. Knowledge of the temperature dependence of Young's modulus would also be useful for the modelling of stress and strain in devices which have to operate over a range of temperatures.

It was decided to flexural test simply supported beams in the three-point bend mode. Thin alumina beams, length 50.8 mm, width 10 mm, depth 0.27 mm, some coated with thick-film material and some uncoated, were tested using a DMA 2980, manufactured by TA Instruments. Then, using composite beam stress analysis [3], the Young's modulus of the thick-film coating was calculated. This paper reports on test results for Heraeus 8241 ink (10 k$\Omega/\Box$) and Coors 96% alumina ceramic ADS96R, across the temperature range 173 K to 573 K. Heraeus 8241 is a proprietary material, but is thought likely to consist of ruthenium dioxide semiconductor in a borosilicate glass matrix.

2. Experimental details

2.1. Fabrication of test pieces

The substrates, 50.8 mm (2 in) square, were laser scribed to delineate four beams, 10 mm wide, on each sheet. Two beams per substrate were coated on both sides with Heraeus 8241. The coating width was 9.5 mm, so as not to allow the ink to flow over the scribed lines. In order to build up a reasonable thickness of resistor material, a PPDPPDF process was applied to each side, where P = print, 13 μm emulsion thickness, using a 230 stainless steel mesh screen, D = dry, 10 min at 150 °C and F = fire, 1 h cycle, 850 °C peak temperature for 10 min.

The beams were numbered and the thickness of each beam was measured at five locations to an accuracy of 0.001 mm with a micrometer. It was therefore possible to obtain substrate thickness for a coated beam by using the mean thickness for the two adjacent uncoated beams. Coating and beam widths were measured after separation with a shadowgraph, to an accuracy of 0.01 mm. Four coated and four uncoated beams were tested.

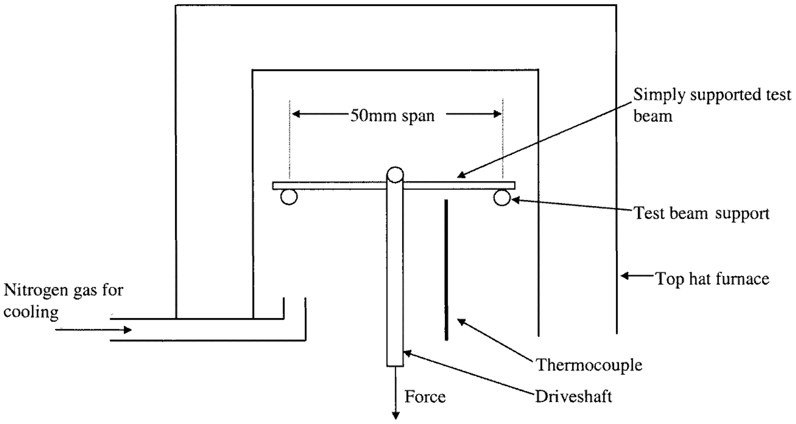

Figure 1. Diagrammatic representation of the test set-up.

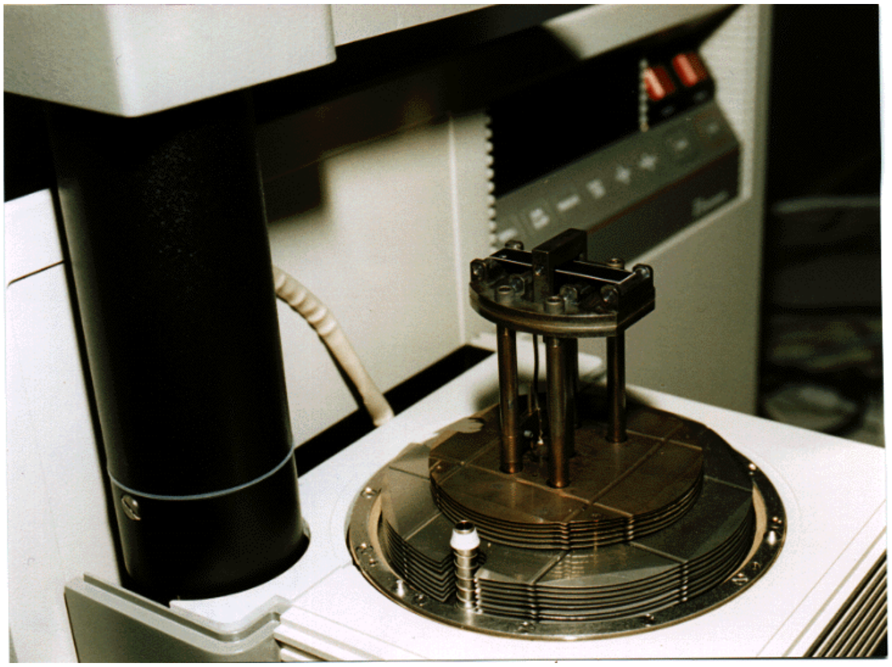

Figure 2. A test beam on the DMA 2980, with furnace lifted.

2.2. Test details

Figure 1 shows the test set-up. Figure 2 shows a test sample on the DMA 2980. The furnace and test beam were stabilized at the test temperature. Force was ramped up at 0.500 N min^{-1} to 1.500 N, to cause a deflection of approximately 0.9 mm on an uncoated beam and approximately 410 $\mu\varepsilon$ at the surface. The force was ramped down at 0.500 N min^{-1} to 0.100 N (samples kept loaded at 0.100 N between tests). The DMA provided two outputs—driveshaft displacement, measured with an optical encoder, and driveshaft load. These results were plotted on a graph, checked for hysteresis, which would be indicative of creep of the thick-film material, and the gradients were measured.

The presence of porosity is known to reduce Young's modulus. A porosity comparison was therefore made between a beam sample and a Heraeus 8241 resistor sample. Mounted and polished sections were prepared and examined using Quantimet 520 image analysis equipment. Coating thickness on both sides of a beam was also checked.

3. Theory

It was assumed that the beams were subject to pure bending with no shear. The beams were simply supported, and loaded with a concentrated load, applied in the middle of the span.

The second moment of area of a beam, I, is defined as:

$$I = \int_A y^2 \, \mathrm{d}A \tag{1}$$

where each element of area of a beam, $\mathrm{d}A$, is multiplied

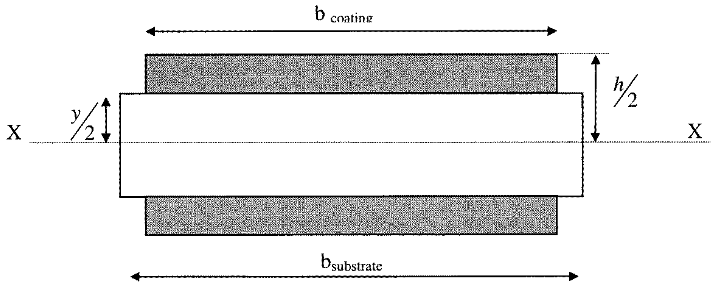

Figure 3. Transverse section of a coated beam. XX represents the position of the neutral axis for the composite beam.

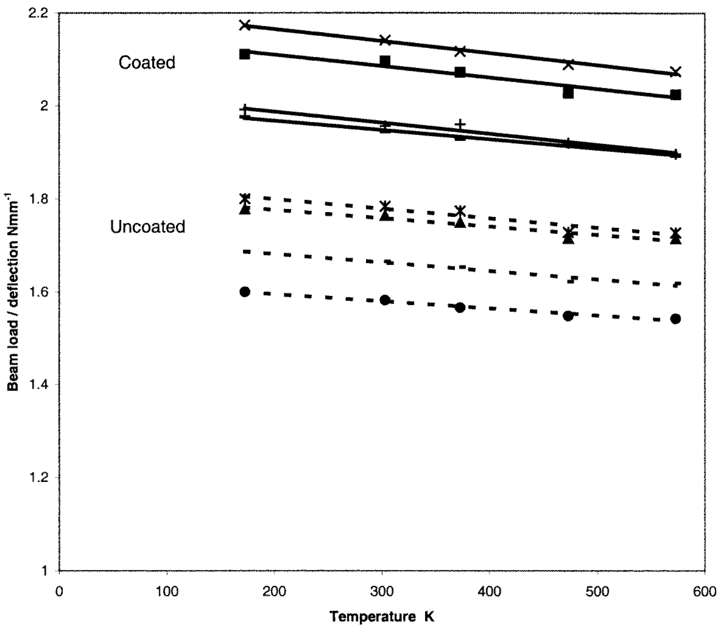

Figure 4. Beam load deflection versus temperature

by the square of its distance, y, from the neutral axis.

$$I = 2\int_0^{h/2} y^2 b\,\mathrm{d}y = bh^3/12 \qquad (2)$$

where b is the beam width and h is the beam thickness.

The second moment of area for a coating on a beam (figure 3) can be found by changing the limits of integration:

$$I_{XX} = \int_{y/2}^{h/2} y^2 b\,\mathrm{d}y = b(h^3 - y^3)/24 \qquad (3)$$

where y is the substrate thickness.

Young's modulus, E, for the uncoated beams can be calculated from the widely published formula:

$$E = Pl^3/48dI \qquad (4)$$

where P is the applied force, l the length of beam between supports and d the deflection of the beam.

The modulus for the coating on the beam can then be calculated. From equation (4):

$$S = Pl^3/48d \qquad (5)$$

where

$$S = [E \times I_{XX}]_{\mathrm{topcoat}} + [E \times I_{XX}]_{\mathrm{substrate}} + [E \times I_{XX}]_{\mathrm{bottomcoat}}. \qquad (6)$$

Using equation (6), it is possible to account for differences in thick-film width and thickness. The average of the top and bottom coating thickness was used for the modulus calculation.

4. Results

The mean substrate thickness ranged from 0.2580 to 0.2686 mm, a 4% variation. The mean coating thickness for the four beams tested was 32.5, 34.1, 35.0 and 32.2 μm. The sectioned beam had a mean coating thickness of 33.7 and 37.5 μm on each side, a 3.8 μm difference.

Image analysis showed that the thick-film material contained closed porosity, 6.9% in the beam sample, and 6.5% in a resistor sample.

The DMA 2980 load/deflection plots showed that all beams tested obeyed Hooke's Law. The data are plotted in figure 4. Young's modulus for the substrate, the coating and

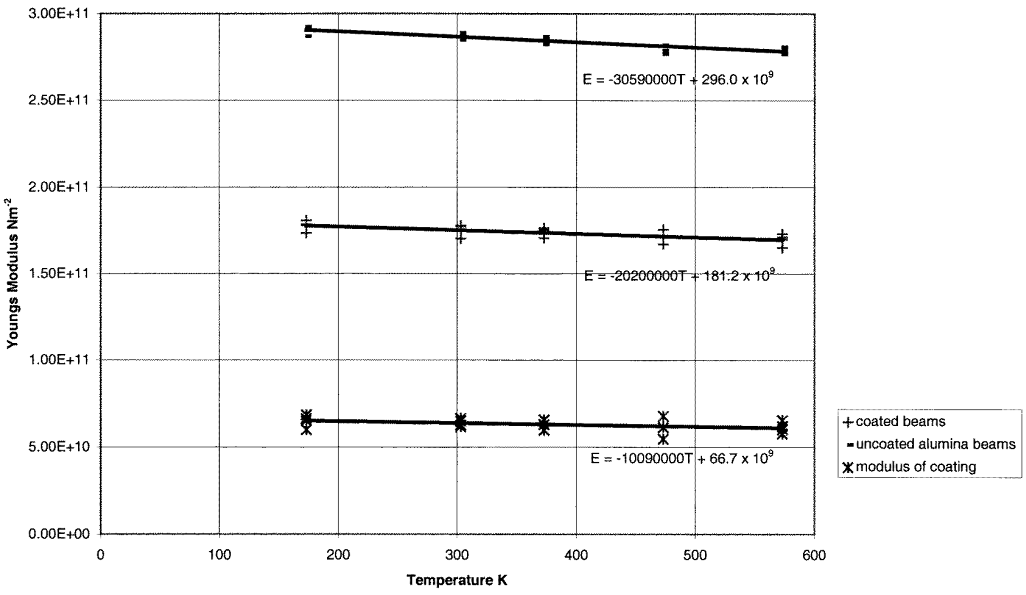

Figure 5. Young's modulus versus temperature for coated and uncoated alumina beams.

composite beam were calculated and are plotted in figure 5. The standard deviation of the data points from the line of best fit was also calculated.

5. Discussion

The mean thick-film coating thickness varied between 32.2 and 35.0 μm, which indicates good process consistency, as did the coating thickness measurement on the sectioned beam. Porosity results indicate that the test beam coatings are representative of resistor material. The absence of hysteresis in the load/deflection plots indicates that creep of the thick-film coating was not apparent, and therefore that dynamic testing was not necessary.

Young's modulus for the alumina beam at 25 °C, from figure 5, is 287 GN m^{-2} with a standard deviation $\sigma_{n-1} = 2.0$ GN m^{-2}. This is close to the manufacturer's specification of 303 GN m^{-2} [4].

Young's modulus for Heraeus 8241 at 25 °C is 64 GN m^{-2} with a standard deviation $\sigma_{n-1} = 3.2$ GN m^{-2}. This value is as expected since a major constituent of this material is borosilicate glass.

Young's modulus for alumina was found to decrease linearly with temperature by -31 MN m^{-2} K^{-1}. This compares with a published value of -34 MN m^{-2} K^{-1} [5]. Heraeus 8241 was found to decrease by -10 MN m^{-2} K^{-1}.

The effect of different top and bottom coating thicknesses was investigated. The results from a tested beam were taken, and it was supposed that the top coat was 10 μm thicker than the bottom coat. The new position of the neutral axis was calculated and the elastic modulus recalculated. The value changed from 61.2 to 61.0 GN m^{-2}, which is not a significant error.

6. Conclusion

Young's modulus for Heraeus 8241 thick-film material has been derived over a broad temperature range by the three-point bend test on coated and uncoated alumina beams on a DMA 2980. Results obtained for the Young's modulus of alumina are close to published data [4, 5]. The derived modulus for Heraeus 8241 is 64 GN m^{-2}, with a negative temperature coefficient of -10 MN m^{-2} K^{-1}. This result will prove useful for stress/strain analysis.

Acknowledgments

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