EAN '97

35th International Conference on
Experimental Stress Analysis
June 4 - 6, 1997, Olomouc, Czech Republic

DETERMINATION OF YOUNG'S MODULUS AND POISSON'S RATIO OF COATINGS USING A CANTILEVER BEAM SPECIMEN

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Young's modulus and Poisson's ratio of thermal spray coatings are necessary to evaluate coating properties and characteristics such as residual stresses, bond strength etc. A cantilever beam method to determine the Young s modulus and Poisson s ratio of coatings requires only a simple loading rig and makes use of laminated plate theory to compute these values from strain gauge data of the cantilever beam under static loads.

1. Introduction

Two important properties of thermal spray coatings, that are not easily determined, are Young's modulus and Poisson's ratio. Accurate values of the Young's modulus E_C and Poisson's ratio ν_C of the coating are needed to evaluate residual stresses by the hole drilling strain gauge method.

The main problem is that the coating is usually thin and therefore it is very difficult to obtain a specimen made entirely of coating material to perform a modulus test. Another problem is that as-sprayed properties are desired. Therefore, it is necessary to use a coated substrate specimen and determine these properties from the composite material behaviour.

2. Experimental Equipment and Procedure

Fig. 1 shows a scheme of the experimental equipment used for determining Young's modulus and Poisson's ratio of the coating. A thermal spray coating is applied to a beam from one side by the same spraying parameters and conditions as the real product or component. One biaxial HBM 3/120 XY11 strain gauge is bonded on the coated surface, one is placed directly opposite on the substrate side. Fig. 1 shows the location of the two strain gauges. The instrumented beam is then clamped in a testing rig and the strain gauges are connected to the four channel strain indicator. A simple loading is applied by hanging weights in steps to the end of the cantilever beam.

The known moment and measured strain gauge data are recorded and are used as input for numerical or graphical solution of the Young's modulus E_C and Poisson's ratio ν_C of the coating.

3. Analysis of Strain Gauge Data

The laminated plate theory is used in this cantilever beam method to relate the unknown Young's modulus and Poisson's ratio of the coating to the loading at the gauged section. The above mentioned laminated plate theory assumes a linear strain distribution through the thickness of the coated cantilever beam and plane stress conditions. Fig. 1 and 2 show a schematic of the strain and stress distribution respectively in the X- and Y-direction for the coated cantilever beam with the applied loading. The difference in mechanical properties between the coating and substrate introduces the stress discontinuity at the interface.

The stresses are related to the forces and moments in the equilibrium equations (1) to (4) by

$$0=F_x=\iint\sigma_x dzdy \qquad M_x=M_x=\iint\sigma_x zdzdy$$

$$0=F_y=\iint\sigma_y dzdy \qquad 0=M_y\iint\sigma_y zdzdy$$

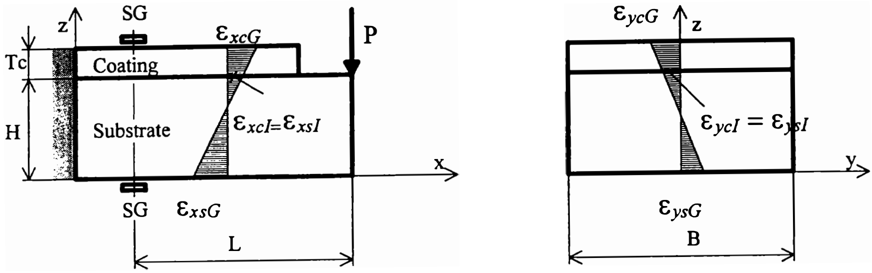

Fig. 1. Strain distribution for coated cantilever beam (one coating)

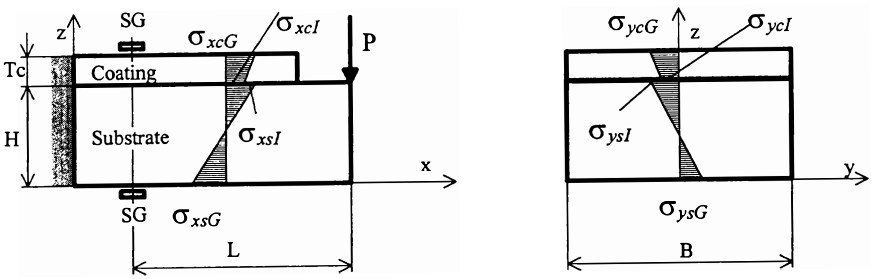

Fig. 2. Corresponding stress distribution

The equilibrium equations for coated beam:

$$0 = \Sigma Fx = B(\sigma_{xsI} + \sigma_{xsG}) \cdot \tfrac{H}{2} + B(\sigma_{xcI} + \sigma_{xcG}) \cdot \tfrac{Tc}{2} \tag{1}$$

$$0 = \Sigma Fy = B(\sigma_{ysI} + \sigma_{ysG}) \cdot \tfrac{H}{2} + B(\sigma_{ycI} + \sigma_{ycG}) \cdot \tfrac{Tc}{2} \tag{2}$$

$$P \cdot L = \Sigma Mx = B\left[\sigma_{xsG} \cdot \tfrac{H^2}{2} + (\sigma_{xsI} - \sigma_{xsG}) \cdot \tfrac{H^2}{3}\right] + B\left[\sigma_{xcI} \cdot T_c\left(\tfrac{Tc}{6} + \tfrac{H}{2}\right) + \sigma_{xcG} \cdot T_c\left(\tfrac{Tc}{3} + \tfrac{H}{2}\right)\right] \tag{3}$$

$$0 = \Sigma My = B\left[\sigma_{ysG} \cdot \tfrac{H^2}{2} + (\sigma_{ysI} - \sigma_{ysG}) \cdot \tfrac{H^2}{3}\right] + B\left[\sigma_{ycI} \cdot T_c\left(\tfrac{Tc}{6} + \tfrac{H}{2}\right) + \sigma_{ycG} \cdot T_c\left(\tfrac{Tc}{3} + \tfrac{H}{2}\right)\right] \tag{4}$$

The surface stresses σ_{cG} and σ_{sG} are related to the strains and to the mechanical properties of the coating and substrate from the following

$$\sigma_{xcG} = \frac{E_c}{1-\nu_c^2}(\varepsilon_{xcG} + \nu_c \cdot \varepsilon_{ycG}) \tag{5}$$

$$\sigma_{xsG} = \frac{E_s}{1-\nu_s^2}(\varepsilon_{xsG} + \nu_s \cdot \varepsilon_{ysG}) \tag{6}$$

where E_c and ν_c are the Young's modulus and Poisson's ratio for the coating, and E_s and ν_s are the substrate properties, which are known. The surface strains ε_{xcG} , ε_{ycG} , ε_{xsG} and ε_{ysG} are measured with strain gauges.

The interface stresses can be calculated from

$$\sigma_{xcI} = \frac{E_c}{1-\nu_c^2}(\varepsilon_{xcI} + \nu_c \cdot \varepsilon_{ycI}) \tag{7}$$

$$\sigma_{xsI} = \frac{E_s}{1-\nu_s^2}(\varepsilon_{xsI} + \nu_s \cdot \varepsilon_{ysI}) \tag{8}$$

where the interface strains ε_{xcI} , ε_{ycI} , ε_{xsI} and ε_{ysI} can be found from the assumption of a linear strain distribution from the surface strains.

All dimensions, forces and properties are known exactly, therefore the four equilibrium equations (1) to (4) can be used to solve the Young's modulus and Poisson's ratio of the coating.

The evaluation of Young's modulus and Poisson's ratio using a cantilever beam specimen with two coatings can be solved on the analogy of the mentioned solution for one coating.

4. Experimental Results

The cantilever beam method was used to determine the Young's modulus and Poisson's ratio of four thermal spray coatings. A coating of plasma sprayed 7 % yittria stabilised zirconia with interlayer of NiCoCrAlY was applied to an aluminium substrate. A plasma sprayed coating of Cr_3C_2 + 25 NiCr and/or ZrO_2 + 7wt% Y_2O were applied to a CSN 11 523 carbon steel substrate. Also a coating of NiAl and Metcoloy 2 were applied by Wire Arc Spray System to a CSN 11 523 carbon steel substrate.

Dimensions of the beam specimens, thickness of the coatings, measured strains and evaluated values of stresses, Young's modulus and Poisson's ratio calculated by the cantilever beam method for these four coatings are given in Table 1.

Table 1. Results determined by the cantilever beam method

BEAM WITH COATING		$NiCoCrALY + ZrO_2+7wt\%Y_2O_3$	NiAl	METCOLOY 2	$Cr_3C_2+25NiCr$
Substrate material		Al-Alloy	Carbon steel CSN 11 523	Carbon steel CSN 11 523	Carbon steel CSN 11 523
Substrate cross section	[mm]	5.0 x 20.0	3.03 x 30.2	3.02 x 30.2	3.05 x 30.2
Layer thickness	[mm]	0.7	0.77	0.42	0.2
Bending moment	[N.mm]	1 569.6	4 414.5	4 708.8	2 943
Strain ε_{xCG}	[μm/m]	118.1	491.5	536.38	298.75
Strain ε_{yCG}	[μm/m]	-31.7	-110.25	-124.81	-76.08
Strain ε_{xSG}	[μm/m]	-112.3	-384.25	-462.76	-288.5
Strain ε_{ySG}	[μm/m]	33.2	93.38	113.13	71.83
Strain $\varepsilon_{xCI}=\varepsilon_{xSI}$	[μm/m]	90.2	314.05	414.39	262.61
Strain $\varepsilon_{yCI}=\varepsilon_{ySI}$	[μm/m]	-23.8	-68.99	-95.76	-66.98
Stress σ_{xSG}	[MPa]	-8.196213478	-80.64243514	-97.0737648	-60.43066591
Stress σ_{ySG}	[MPa]	0.0057102402	-4.956450548	-5.817349449	-3.332219779
Stress σ_{xSI}	[MPa]	6.620053944	66.4073824	87.30370547	54.89922636
Stress σ_{ySI}	[MPa]	0.2191659136	5.710274723	6.464551646	2.671887911
E_s substrate	[MPa]	70 576	206 000	206 000	206 000
μ_s substrate	[1]	0.295	0.26	0.26	0.26
E_c coating	[MPa]	49 970	66 850	68 500	135 000
μ_c coating	[1]	0.15	0.13	0.1	0.31

5. Conclusions

Two important characteristics of thermal spray coatings, that are not easily evaluated and that are needed to evaluate residual stresses, are Young's modulus and Poisson's ratio.

The cantilever beam method was developed and verified experimentally to determine " in situ" values of Young's modulus and Poisson's ratio of thermal spray coatings. This method has several advantages that make it very useful. It is easy to use and inexpensive. The equipment needed is a coated substrate beam, clamping rig, strain gauges, a strain indicator, a micrometer, a slide ruler, a hanger and a set of weights.

Errors in the measurements of dimensions, strain gauge readings and substrate properties needed for input to the method can influence the values Young's modulus less than ± 5 % for a steel substrate and ± 3 % for the aluminium substrate. The values of Poisson's ratio are more sensitive to errors in the measurements used for input to this method but are accurate enough for practical applications.

References

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