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# Residual Stress in Plasma Sprayed Ceramic Turbine Tip and Gas Path Seal Specimens

R. C. Hendricks and G. McDonald
*Lewis Research Center*
*Cleveland, Ohio*

and

R. L. Mullen
*Case Western Reserve University*
*Cleveland, Ohio*

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# RESIDUAL STRESS IN PLASMA SPRAYED CERAMIC TURBINE TIP AND GAS PATH SEAL SPECIMENS

R.C. Hendricks and G. McDonald
National Aeronautics and Space Administration
Lewis Research Center
Cleveland Ohio 44135

R.L. Mullen
Case Western Reserve University
Department of Civil Engineering
Cleveland Ohio 44106

## ABSTRACT

The residual stresses in a ceramic sheet material used for turbine blade tip gas path seals, have been estimated. These stresses result from the plasma spraying process which leaves the surface of the sheet in tension. To determine the properties of plasma sprayed $ZrO_2$-$Y_2O_3$ sheet material, its load-deflection characteristics were measured. Estimates of the mechanical properties for sheet materials were found to differ from those reported for plasma sprayed bulk materials.

E-1706

## INTRODUCTION

Plasma spraying of ceramics on a suitably prepared metallic substrate is a widely used process for applying chemically, electrically or thermally insulative coatings. Such a plasma sprayed ceramic is of interest as part of a high temperature seal to increase the efficiency of operation of gas turbine engines. Since it is both nonoxidizing and refractory, refs. 1 and 2, plasma sprayed ceramics have also been extensively promoted as a means of increasing the life of highly stressed engine hot components by permitting operation at equilibrium gas temperature and thermodynamic efficiency but at lower component temperature, ref. 3–5.

However, the durability of the plasma sprayed $ZrO_2$ has not been generally adequate under the high temperature and heat transfer occuring in gas turbine engines, ref. 6-8. The successful application of such ceramics requires a better understanding of the stresses generated during fabrication and at service conditions. This report describes the stresses generated due to deposition by the plasma spraying processes.

## EXPERIMENTAL PROCEDURE

### Materials and Coating Procedure

A 304-Stainless steel strip (0.15 x 1.9 x 12.7 cm) was coated with NiCrAlY bondcoat and $ZrO_2$ ceramic by first grit blasting with $Al_2O_3$ and plasma spraying on one flat surface in air with a 0.013 cm Ni18Cr12Al0.3Y bondcoat and then with $ZrO_2$-8- or 12- wt. percent $Y_2O_3$.

After spraying, the stainless steel and bondcoat were removed by dissolution in hydrochloric acid and the $ZrO_2$-$Y_2O_3$ was washed in water and dried to leave a free form ceramic sheet.

### Curvature and Deflection Measurements

The curvature of the 0.038 cm $ZrO_2$-$Y_2O_3$ after removal from the metal substrate was measured under zero load by curve fitting. The load vs deflection of the ceramic strip was measured by clamping one end of the strip and loading the other end of the strip as a cantilever beam. Incremental loading was added to the end of the strip and deflection was measured using a grid background. The apparatus is shown schematically in figure 1. Table I shows the geometric and material properties of the ceramic sheet specimens tested.

## RESULTS AND DISCUSSION

### Experimental Results

A $ZrO_2$-8$Y_2O_3$ sheet stripped from its bondcoat and substrate is shown in figure 2. The sheet was loaded as a beam to determine the load/deflection characteristics (see table I and figure 1). The results are presented in tables II and III and plotted in figures 3 and 4. A portion of the strain is non-elastic and non-recoverable, as the $ZrO_2$-$Y_2O_3$ sheet is unloaded, but after the initial loading to any given maximum load, subsequent loading and unloading is elastic up to that load as shown in figure 3. The deflection is linear (recoverable) up to a loading of 1.9 gm added load. Above an added load of 1.9 gm, a permanent offset is produced. We speculate that microcracking of the tensile surface occurs which produces a permenant set in the specimen. Even though an offset is produced the ceramic response is elastic upto each maximum load. Despite the offset, the elastic modulus is not changed significantly (as illustrated in figure 4). This can also be seen from the three distinct steps in the initial load-deflection data of specimen 7-2 (Table III). The added load required to produce sufficient set to remove all residual bending due to the stresses generated by plasma spraying process, see figure 2, is 3.5 gm added load.

The radius of curvature of stripped sheets before loading (figure 2) averages 29.7 cm. The curvature bows away from the metal substrate. Further, the curvatures along the width and length are equal. This is characteristic of a uniformly stressed plate or sheet. For $ZrO_2$-$12Y_2O_3$ plasma sprayed at conditions similar to those described above, the curvatures of the stripped $ZrO_2$-$12Y_2O_3$ free form ceramics were the same.

Analysis

The stainless steel, after plasma spraying with NiCrAlY and 0.038 cm of $ZrO_2$-$Y_2O_3$, is straight and flat. After removal of the stainless steel and bond coat, the $ZrO_2$-$Y_2O_3$ curves to relieve the residual stresses in the $ZrO_2$-$Y_2O_3$ ceramic. These residuals are due to the fabrication process of plasma spraying onto the metal substrate. The residual strain on the outside surface of the ceramic due to plasma spraying is

$$\varepsilon = \frac{\Delta \ell}{\ell} = \frac{t}{R} = \frac{.038}{29.7} = 1.25 \times 10^{-3} \ \frac{cm}{cm}$$

The strains associated with mechanical deformation of the coated substrate are discussed in the Appendix.

The tensile stress in the $ZrO_2$-$Y_2O_3$ is due to the rapid quench of the plasma sprayed particle as it impacts the solid. The side of the impacted particle facing the atmosphere cools more slowly by convection and radiation. The plasma spraying is a non equilibrium process in that a particle heated to high temperature in the plasma is impacted onto a much colder substrate where it is rapidly solidified. The side of the impacted particle away from the substrate can flow plastically as it cools to relieve stress until it reaches approximately 1000 C, (ref. 9). Below 1000 C, plastic flow is too slow to relieve stress and the thermal contraction from 1000 C to ambient appears as a residual tensile stress.

Strain due to thermal contraction = $\varepsilon = \alpha \Delta T = 8.3 \times 10^{-6} \times 1 \times 10^{3}$ $= 8.3 \times 10^{-3}$ cm/cm.

These residual stresses are relieved by straining the free-form ceramic sheet, and to account for the bending of the ceramic sheet. The exact temperature for the end of plastic flow of the $ZrO_2$-$Y_2O_3$ is uncertain and it may be that some plastic flow occurs to some temperature somewhat below 1000 C, ref. 9.

From the beam flexure measurements, the elastic modulus ranges from 0.5 to $1.0 \times 10^{6}$ psi with a limiting bending stress of 1800 psi as determined by extrapolating the load and deflection data of table III. The elastic modulus for the plasma sprayed sheet specimens is a factor of ten less than those measured in ref. 4 for plasma sprayed coatings while the bending stresses are about half those given in ref. 4. There is little doubt that some microcracking does occur, however the sheet specimens not only remain intact when stripped from the substrate, but are sufficiently flexible to function as cantilever beams with distinct characteristics.

## SUMMARY

The residual stresses in a ceramic sheet material due to plasma spraying have been calculated from the measured bending which occurs when the sheet is removed from the metal substrate. The surface of the sheet after plasma spraying on the substrate is in tension. The tension results from the rapid cooling and solidification of the hot and plastic plasma sprayed ceramic particle as it impacts the substrate. The residual stress resulting from the plasma spraying has also been measured directly from the force required to remove the bending.

The elastic modulus of these plasma sprayed specimens is a factor of ten less than that reported for similar plasma sprayed ceramics.

### SYMBOLS

| | |
|---|---|
| <Co> | average width of cracked material |
| E | elastic modulus |
| $\ell$ | length |
| N | number of cracks |
| R | radius of curvature |
| t | thickness |
| $\omega$ | width |
| $\alpha$ | thermal expansion |
| $\sigma_t$ | stress |
| $\Delta$ | increment |
| $\epsilon$ | strain |

# APPENDIX

## Mechanical Deformation of Coated Substrates

Mechanical deformation cited in reference 10, gives a crack spacing of

$$\omega = 0.02 + 73t^2$$

and measurements of the curvature of the tensile cracked specimens, figure 5, gives,

$$R = 50t$$

or the number of 'visible' surface cracks ( e.g., figure 6) becomes

$$N = \frac{\pi(R+t)}{\omega} = \frac{102\pi}{0.02 + 73t^2}$$

For N uniformly spaced cracks, the largest the average spacing can be is when

$$\Delta\ell = 2\pi t = N\langle Co\rangle$$

Solving, for a 0.020" thick coating,

$$\langle Co\rangle = \frac{\omega}{1 + \frac{R}{t}} = .001 \text{ in.}$$

From the photograph, figure 6, spacing between cracks appear for the unaided eye to 0.004" to those which can only be seen at 50X or higher. For $\sigma_t = 10^4$ psi, $E = 5 \times 10^6$ psi and $t = 0.020$ in, the calculated <Co> becomes

$$\epsilon = \frac{\Delta\ell}{\ell} = \frac{N\langle Co\rangle}{2\pi r} = \frac{\sigma_t}{E}$$

$$\langle Co\rangle = \frac{\omega\alpha t}{E(1+\frac{t}{R})} = 10^{-4} \text{ in.}$$

or one order of magnitude less than the maximum value of <Co>. Furthermore, if the parameters, $\alpha_t = 10^3$ psi and $E = 0.5 \times 10^6$ psi, are characteristic of sheet specimens, then <Co> is the same.

The coating losses at the edges of the bar are due to double curvature which places the edges in compression and often appear to be sufficient to delaminate the ceramic.

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Table I. Geometric and Material Properties of Ceramic Sheet Specimens

| Sample | Material | Heating | Weight gmf | Density gm/cc | Width mm | Width inch | Avg. Thickness mm | Avg. Thickness inch | Length mm | Length inch | Loaded length mm | Loaded length inch | clamped length mm | clamped length inch |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2a-1 | $ZrO_2$-$8Y_2O_3$ | As sprayed | 3.7773 | 3.94 | 19 | .75 | .41 | .016 | 123.8 | 4.875 | 76.2 | 3.0 | 41.4 | 1.63 |
| 7-1 | $ZrO_2$-$8Y_2O_3$ | 1200 C (2200 F) 24 hr | 2.7862 | 3.189 | 19 | .75 | .46 | .018 | 100.3 | 3.95 | 85.1 | 3.35 | 10.2 | .4 |
| 7-2 | $ZrO_2$-$12Y_2O_3$ | 1200 C (2200 F) 24 hr | 3.6988 | 3.605 | 19 | .75 | .53 | .021 | 101. | 3.975 | 84.5 | 3.33 | 10.2 | .4 |

Table II. Load Deflection Values for Ceramic Sheet Specimens

| Sample | Ref. grid value (cm) | Load (gmf) | 0 | 0.907 | 1.907 | 2.907 | 3.907 | 4.907 |
|---|---|---|---|---|---|---|---|---|
| | load application | | | | | | | |
| 2a-1 | increasing load | | 1.8 | 2.4 | 2.8 | 3.2 | 3.8 | 4.3 |
| | decreasing load | | 2.8 | 3.2 | 3.4 | 3.9 | 4.1 | 4.3 |
| | 3-cycle Avg. | | 2.8 | 3.18 | 3.43 | 3.8 | 4.09 | 4.37 |
| 7-1 | increasing load | | 0 | .5 | .9 | 1.4 | 1.9 | 2.6 |
| | decreasing load | | .5 | 1.0 | 1.4 | 2.0 | 2.4 | 2.6 |
| | 4-cycle Avg. | | .5 | 1.0 | 1.37 | 1.84 | 2.27 | 2.65 |

| | Ref. grid value (cm) | Load (gmf) | 0 | 0.9 | 1.9 | 2.9 | 3.9 | 4.9 | 5.9 | 7.9 | 8.9 | 9.9 | 10.9 | 12.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | load application | | | | | | | | | | | | | |
| 7-2 | increasing load | | | -.3 | -.2 | -.1 | 0. | .1 | .2 | .6 | .7 | .8 | 1.1 | 1.3 |
| | decreasing load | | -.2 | -.1 | .1 | | .3 | | .6 | .8 | .8 | | 1.2 | 1.4 |
| | 3-cycle Avg. | | -.2 | | .1 | | .24 | | .56 | .76 | .84 | | 1.2 | 1.4 |

Table III. Load Deflection Values with Inelastic Behavior for Ceramic Sheet Specimens

| Specimen | Ref. grid value (cm) Load (gmf)<br>load application | 0 | Self | 0.908 | 1.908 | 2.908 | 3.908 | 4.908 | 5.908 |
|---|---|---|---|---|---|---|---|---|---|
| 2a - 2 | | 2.3 | 2.7 | | | | | | |
| same as | increasing load | 2.3 | 2.7 | 3.1 | 3.4 | | | | |
| 2a-1 | decreasing load | | | 3.1 | 3.4 | | | | |
| | increasing load | | | | 3.4 | 3.8 | | | |
| | decreasing load | | | 3.2 | 3.5 | 3.8 | | | |
| | increasing load | | | 3.4 | 3.6 | 4.0 | 4.2 | | |
| | decreasing load | | | | | 3.9 | 4.2 | 4.6 | |
| | increasing load | | | 3.5 | 3.7 | 4.1 | 4.3 | 4.6 | |
| | decreasing load | | | 3.7 | 4.0 | 4.4 | 4.7 | 5.0 | 5.3 |
| | increasing load | | | | 3.9 | 4.2 | 4.5 | 5.0 | 5.3 |
| | decreasing load | | | 3.7 | 4.0 | 4.5 | 4.7 | 5.0 | 5.3 |

Horizontal = 3.9 cm

Self-load defined as zero = 2.3 cm

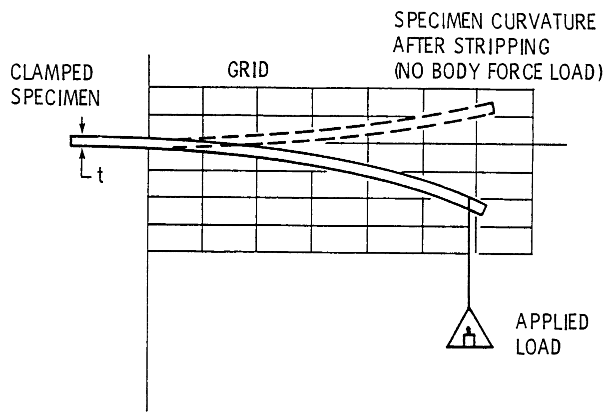


Figure 1. - Schematic of load-deflection apparatus.

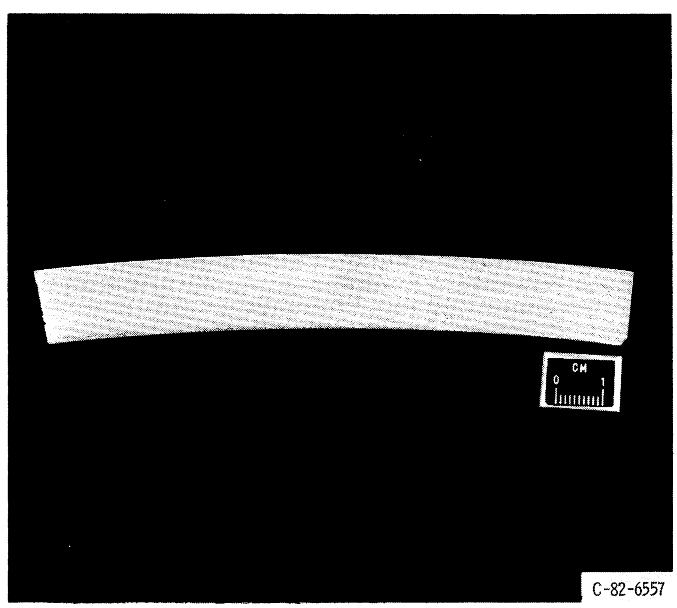


Figure 2. - Photograph of plasma sprayed sheet stripped from it's substrate.

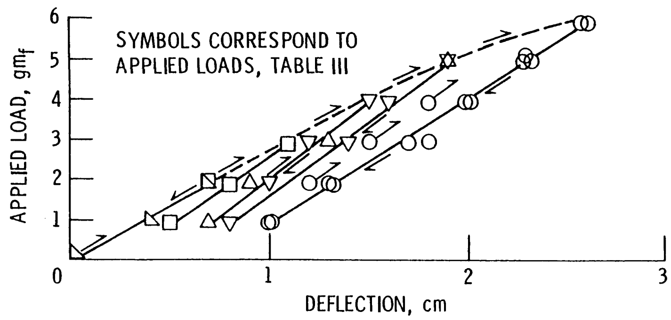


Figure 3. - Elastic and inelastic load-deflection characteristics of plasma sprayed sheet specimens.

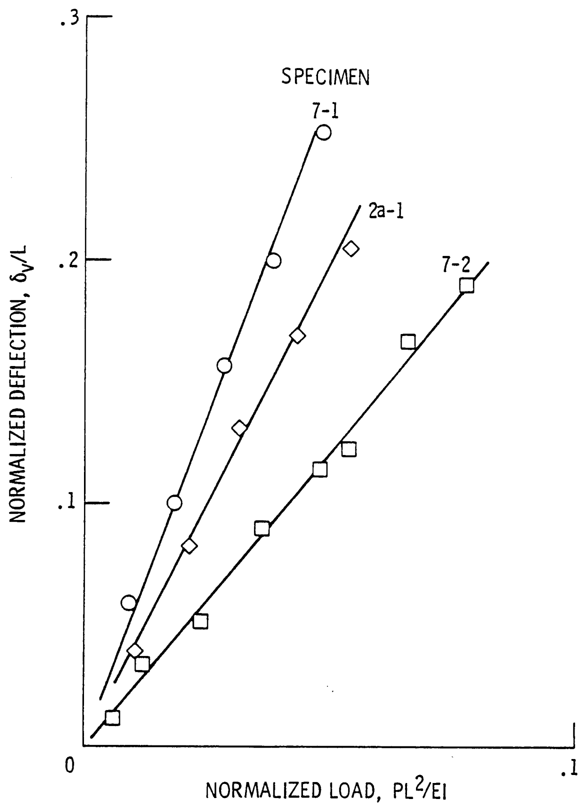


Figure 4. - Normalized load-deflection characteristics for plasma sprayed sheet specimens.

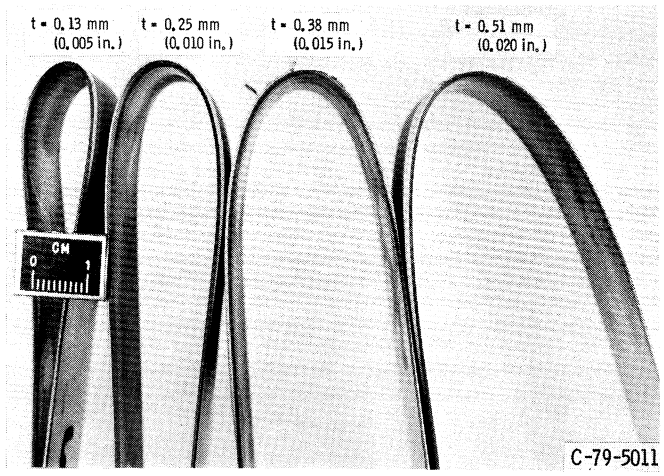

Figure 5. - Curvature due to mechanical cracking of plasma sprayed sheet attached to it's substrate.

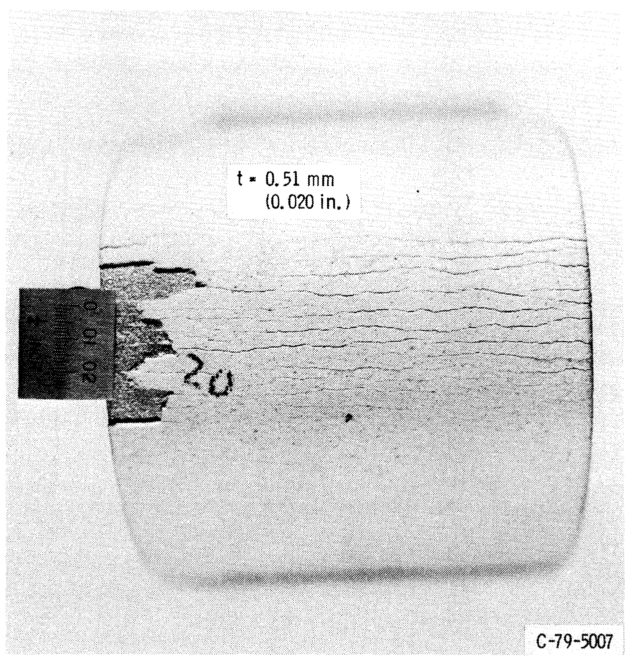

Figure 6. - Mechanical crack spacing of plasma sprayed sheet attached to it's substrate.

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16. Abstract

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