FACTORS INFLUENCING RESIDUAL STRESSES IN YTTRIA STABILIZED ZIRCONIA THERMAL BARRIER COATINGS*

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Introduction

To improve gas turbine and diesel engine performance using thermal barrier coatings (TBC's) requires an understanding of the factors that influence the in-service behavior of thermal barrier coatings. One of the many factors related to coating performance is the state of stress in the coating. The total stress state is composed of the stresses due to the in-service loading history and the residual stresses.

Residual stresses have been shown to affect TBC life [1], the bond strength of thermal spray coatings [2], and the fatigue life of tungsten carbide coatings [3]. Residual stresses are first introduced in TBC's by the spraying process due to elevated temperatures during processing and the difference in coefficients of thermal expansion of the top coat, bond coat, and substrate. Later, the residual stresses can be changed by the in-service temperature history due to a number of time and temperature dependent mechanisms, such as oxidation, creep, and sintering. Silica content has also been shown to affect sintering and the cyclic life of thermal barrier coatings [4, 5]. Thus, it is important to understand how the spraying process, the in-service thermal cycles, and the silica content can create and alter residual stresses in thermal barrier coatings.

Objectives and Approach

There are three primary objectives of this work. The first objective is to determine how residual stresses are affected by the substrate temperature as the top coat is applied. Two temperatures were selected to represent a range of possible substrate temperature conditions. The second objective is to determine the effect of post-processing thermal cycles on the build up of coating residual stresses. The third objective is to determine the effect of silica (SiO_2) content in the powder on the coating residual stresses.

The approach involves four replicates of each of the twelve test conditions to determine the reproducibility of the residual stresses. The through-thickness residual stresses in the coating were evaluated using the Modified Layer Removal Method [6]. Figure 3 is the test matrix used to reach these objectives.

Specimen Composition, Dimensions and Preparation Procedures. The specimens consisted of three materials (1) a B1900 substrate (a high strength, high temperature nickel base alloy with a chemical composition of 64%Ni, 8%Cr, 10%Co, 6%Al, 1%Ti), (2) a Ni-36Cr-6Al-1.0Y bond coat, and (3) a yttria stabilized zirconia (YSZ), ZrO_2-8%Y_2O_3 top coat. The B1900 substrate material was prepared as castings of 50.8 mm (two inch) long bars, 25.4 mm (one inch) wide and 4.8 mm (0.190 in) thick. The bars were surface ground and then stress relieved. The stress relief heat treatment was a standard superalloy solution treatment at 1090°C (1994°F) for four hours followed by an aging treatment at 870°C (1598°F) for sixteen hours. The surface oxide was lightly ground off. One side of each specimen was grit blasted and thickness measurements were made. The bond coat and top coat were applied to the specimens by air plasma spraying (APS). The thickness of each specimen was measured on a preset grid before and after the application of the bond coat. Next, the top coat was applied to the specimens. The temperature of the coating face of the specimens was monitored by a pyrometer during top coat spraying. For the specimens referred to as the "higher processing temperature specimens," the substrate was preheated to 500°C (932°F). After the first pass of the top coat application, the coated surface temperature was controlled to 500°C.

For the "lower processing temperature specimens," the substrate was initially at room temperature. Over the course of two or three top coat application passes, the coating surface temperature rose to 260°C (500°F.

Thermal Cycling. The combined effects of processing substrate temperature and post-processing thermal cycling were investigated. One thermal cycle is defined as heating the specimen in air in a resistance heated furnace to 1100°C (2012°F) for one hour, removing the specimen from the furnace while still at 1100°C, and static air cooling to room temperature. Specimens were subjected to zero, one, ten, twenty or thirty thermal cycles.

Procedure For Evaluating Residual Stresses. The "Modified Layer Removal Method" was used to determine the through-thickness residual stress distributions in the top coat [9]. The procedure involves attaching strain gauges to the uncoated side of the specimen and removing layers of the coating. Figure 4 shows the free-body diagram used to develop the method. Layers of about 0.13 mm (5 mils) were removed from the coating by polishing using a metallurgical polishing wheel. Thickness measurements of the specimen are made after each layer is removed. Changes in strain gauge readings are recorded as layers are removed. The strain and thickness changes are inputs for the residual stress analysis back-computation procedure. The analysis is applied to each layer removed and calculates the residual stress in the layer removed and the change in stress distribution for the remaining piece. The stresses are summed in the back-computation procedure, for each layer removed, to evaluate the residual stress distribution in the material removed. The material properties used in this calculation are the modulus of elasticity for the substrate and the coating, 206 GPa (3 x 10^7 psi) and 34.5 GPa (5 x 10^6 psi), respectively, and Poisson's ratios of 0.3 and 0.18 for the substrate and coating, respectively.

Results And Discussion

Through-Thickness Residual Stress Distributions. Two through-thickness residual stress distributions, that are representative of the behavior of the residual stresses, were selected for illustration. Figure 5 shows the through-thickness residual stress data for three specimens with the higher processing temperature and no thermal cycling. The second example, shown in Figure 6, illustrates the residual stress data for the specimens with a higher temperature after ten thermal cycles. Both figures are for specimens with a "standard" (STD) coating powder, i.e., a coating powder in which the silica content was not controlled.

Average Coating Residual Stress. The average residual stress through the thickness of the YSZ coating was calculated for each set of specimens listed in the test matrix. First, the average residual stress through the coating thickness for the individual specimens was calculated. Then, the average stress for each set of specimens was calculated. Figure 7 shows the average compressive stress for each combination of thermal cycling, processing substrate temperature, and silica content.

Effects Of Substrate Temperature. A comparison of the average through-thickness residual stresses for specimens with the higher processing temperature and the specimens with the lower processing temperature reveals a consistent difference. The mean residual stress through the coating thickness is shown versus substrate temperature in Figure 8. This figure shows that, for the three cases of thermal cycling involving different substrate processing temperatures (zero, one, and ten cycles), the coatings applied with the higher processing temperature have a higher average compressive residual stress than the coatings applied with the lower processing temperature. For the case of zero thermal cycles, coatings applied with the higher processing temperature had 3.8 MPa (0.6 ksi) more compressive residual stress. The residual stresses in specimens with the higher processing temperature and no thermal cycles agree with previously published findings [7, 8]. For one cycle, the difference between the higher and lower processing temperature specimens is 7.1 MPa (1.0 ksi); and, for ten thermal cycles, the difference is 8.7 MPa (1.3 ksi) difference. For zero, one, and ten thermal cycles, the higher substrate processing temperature specimens had higher average compressive residual stresses.

Effect Of Number Of Thermal Cycles. An important finding of this study is that processing can generate residual stresses to which thermal cycling "adds" further residual stresses. The residual stresses due to processing are most likely due to thermal expansion mismatch strains on cooling from the process temperature. The changes in residual stresses due to cycling may indicate a change in the TBC system by some means, such as ceramic sintering, ceramic creep, bond coat creep or bond coat oxidation. The effect of the number of thermal cycles on coating residual stress shows a pattern of increasing compressive residual stress with increasing number of thermal cycles, for cycles one through ten.. The effect of the number of thermal cycles on the average through-thickness residual stress is shown in Figure 9. This figure and Figure 7 show a marked increase of compressive residual stress

during the first cycle. The trend is then for the residual stress to reach an fairly constant level as the number of thermal cycles increases. The greatest increase in coating compressive residual stresses occurs during the first thermal cycle. As shown in Figure 7, after the first cycle, there is a 17.1 MPa (2.48 ksi) increase in compressive residual stress for the specimens with the lower processing temperature and a 20.4 MPa (2.95 ksi) increase for the specimens with the higher processing temperature [9]. In contrast, the increase in compressive residual stress in the coating due to cycles two through thirty is only 7.1 MPa (1.0 ksi) for the lower processing temperature and there is a 6.6 MPa (0.96 ksi) increase in compressive residual stress in the coating from cycles two through ten for the higher processing temperature.

Effect of Silica Content during Thermal Cycling. The effect of the difference of the silica content in the spray powder is shown in Figure 10. In the as-sprayed condition (0 cycles), the compressive residual stress of the 1.0% silica coating is 27 MPa (3.9 ksi) while the residual stress for the 0.1% silica content is practically zero. Interestingly, after ten cycles the residual stresses begin to approach each other: the compressive residual stress in the coating applied using the lower silica content powder increases to 11.4 MPa (1.65 ksi) while the compressive residual stress in the coating applied using the higher silica content powder decreases to 15.1 MPa (2.19 ksi).

Trends of Residual Stresses. The results demonstrate six features of residual stresses in these TBC's:
(1) Compressive residual stresses in the YSZ coating can be controlled by controlling the processing temperature of the specimen.
(2) Top coat residual stresses were more compressive for the higher processing temperature of 500°C than for the lower processing temperature of 260°C.
(3) The effect of the post-processing thermal cycle history considered here was to increase the compressive residual stresses in the STD top coats for both the higher and lower processing temperatures.
(4) For the STD coating powder, the first thermal cycle produced a larger change in top coat residual stress than cycles two through ten combined for both processing temperatures, but with a greater change in the residual stresses (6.6 MPa) occurring during cycles two through ten for the higher processing temperature than the change in residual stress (5.0 MPa) for the lower processing temperature.
(5) The effect of silica in the as-sprayed condition was to dramatically increase the coating compressive residual stress.
(6) The residual stress in the coating applied using the higher silica content powder became less compressive with thermal cycling while the compressive residual stress for the lower silica case became more compressive.

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Paper 2

OUTLINE

- Background
- Objectives and Approach
- Experimental Procedure
- Residual Stress Results
- Summary and Conclusions

Fig. 1

OBJECTIVES

Evaluate Residual Stress Changes Due to

- Controlling Substrate Temperature During Spraying (260°C and 500°C)
- Thermal Cycles (Zero, One, Ten, Twenty, Thirty)
- Silica Content (0.1% and 1.0%)

Fig. 2

TEST MATRIX

Thermal Cycles	Number of Samples Tested			
	Lower Temp. (260°C)			Higher Temp. (500°C)
	STD	0.1% SiO$_2$	1.0% SiO$_2$	STD
Zero (As-sprayed)	4	4	4	4
One	4			4
Ten	4	4	4	4
Twenty	4			
Thirty	4			

Fig. 3

Modified Layer Removal Method
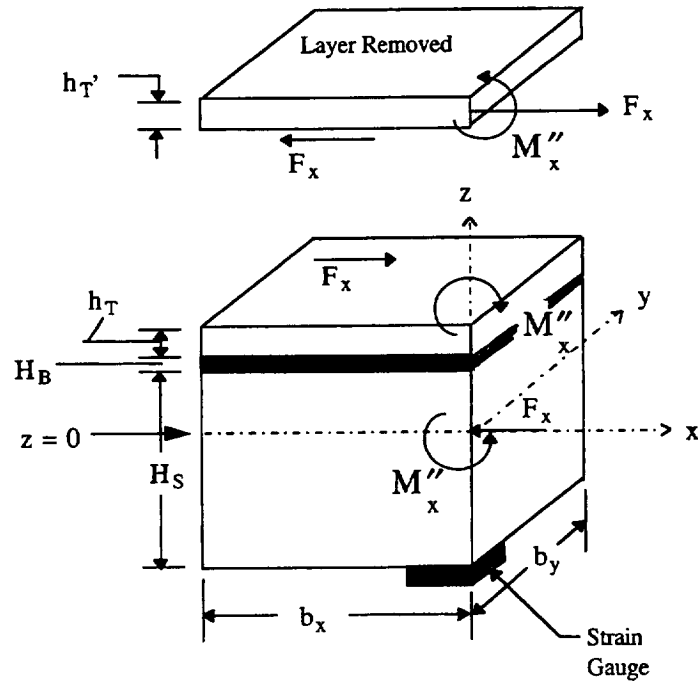
Fig. 4

Through-Thickness Residual Stress Distribution
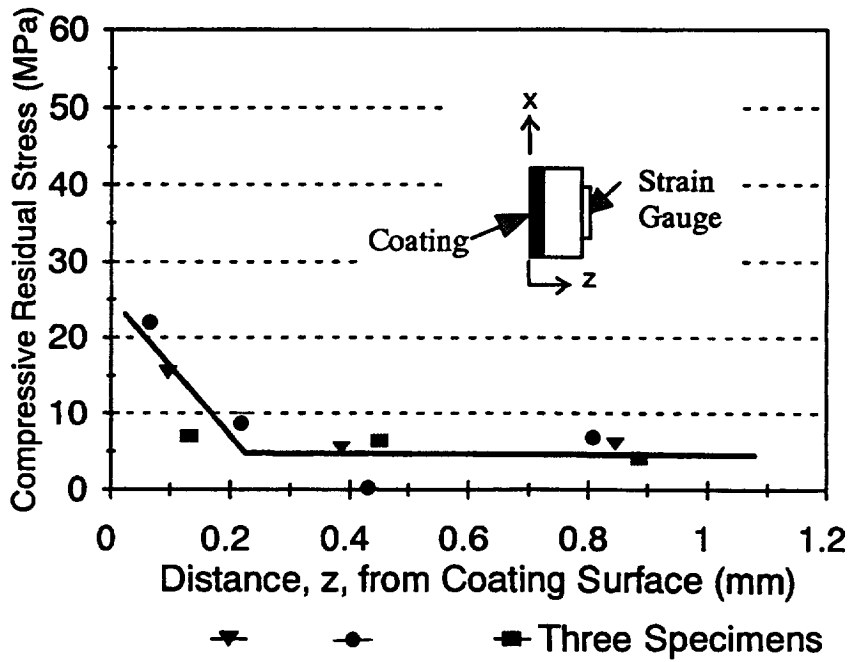## Higher Substrate Temperature, Zero Thermal Cycle

Fig. 5

Through-Thickness Residual Stress Distribution
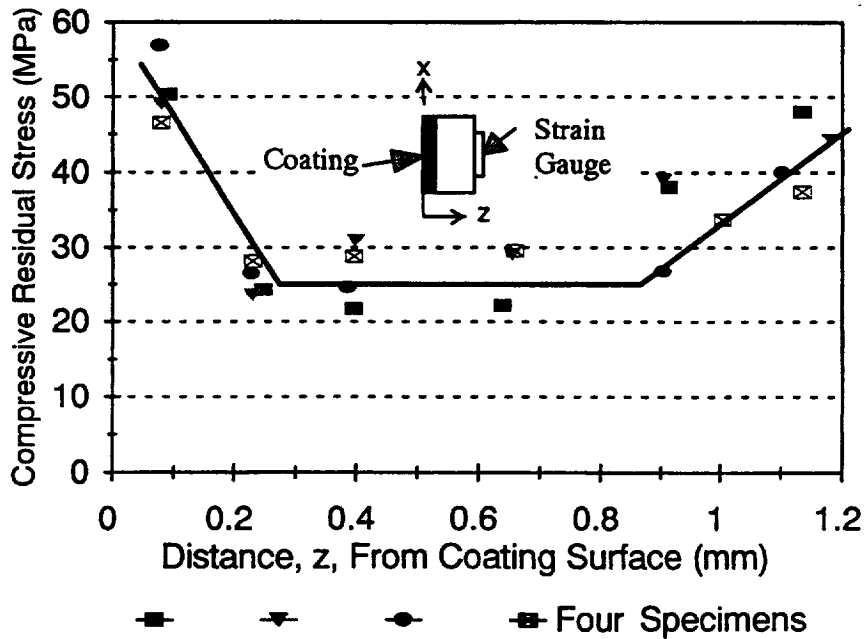## Higher Substrate Temperature, Ten Thermal Cycles

Fig. 6

Average Compressive Residual Stress (MPa)				
	Lower Temp. (260°C)			Higher Temp. (500°C)
Cycles	STD	0.1% SiO$_2$	1.0% SiO$_2$	STD
Zero	3.0	0	27.6	6.8
One	20.1			27.2
Ten	25.1	11.4	15.1	33.8
Twenty	19.8			
Thirty	27.0			

Fig. 7

Effect of Substrate Processing Temperature
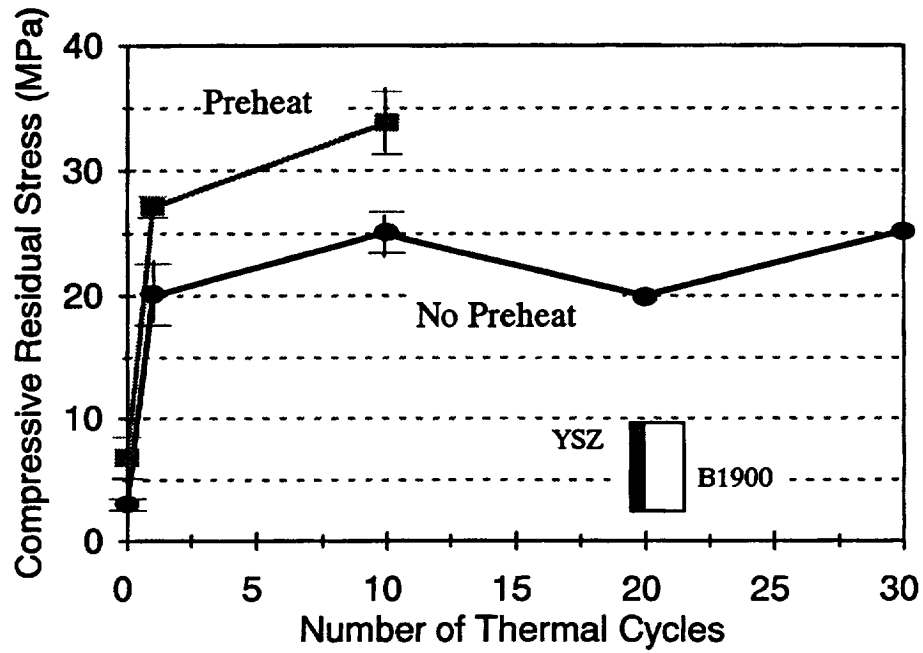

Fig. 8

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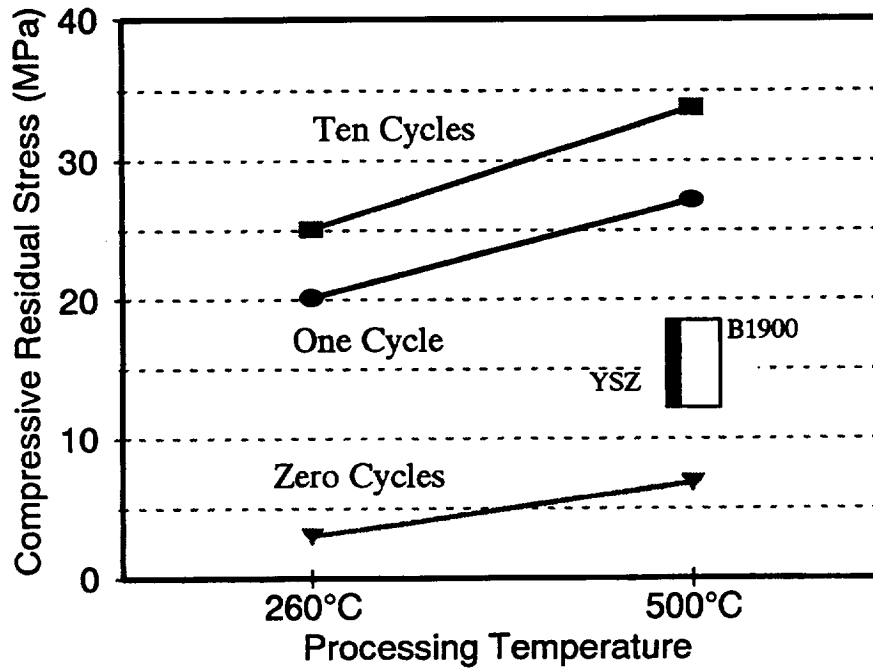
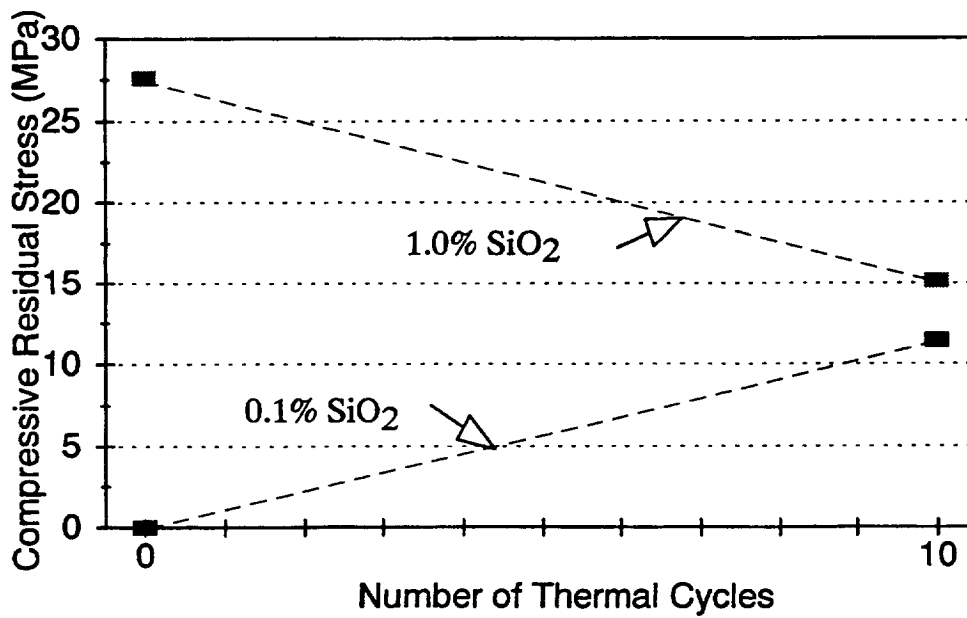# Effect of Thermal Cycles

Fig. 9

Effect of Silica

Fig. 10

CONCLUSIONS: Substrate Temperature

◆ The higher substrate processing temperature (500°C) produced higher compressive residual stresses in the YSZ top coat.

◆ Compressive residual stresses in the YSZ top coat increased for both processing temperatures as a result of one and ten thermal cycles.

Fig. 11

CONCLUSIONS: Thermal Cycles

◆ The residual stress change in the YSZ top coat due to the first cycle was greater than the change due to cycles two through ten by a factor of three.

◆ The residual stress level in the YSZ top coat after thirty cycles was equal to the residual stress level after ten cycles.

Fig. 12

CONCLUSIONS: Silica Content

◆ The residual stress for the lower (0.1%) SiO_2 content coating is close to zero in the as-sprayed condition and became _more_ compressive after ten thermal cycles.

◆ The residual stress for the higher (1.0%) SiO_2 content coating is very compressive in the as-sprayed condition and became _less_ compressive after ten thermal cycles.

Fig. 13

Suggestions for Further Work

◆ Residual Stresses and Oxidation and Sintering

◆ Material Property Determination Methods

◆ Residual Stresses and Other Application Processes

Fig. 14