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Measurements and FEM calculations

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Summary

The first part of this paper concerns measurements of through-thickness residual stresses in Thermal Barrier Coating (TBC) by the hole-drilling method. The influences of top coat thickness and different thermal histories (furnace and burner rig) were determined. Low tensile stresses prevailed in the as-sprayed state, and low compressive stresses after annealing in a furnace. In both cases the stresses tended to decrease with increasing coating thickness. The specimens tested in the burner rig showed a stress state between those of as-sprayed and annealed specimens. Moreover, the stress sign depended on top coat thickness. Finally, some experimental problems are discussed. The second part describes model predictions of residual stresses in a TBC after cooling from an initial stress-free state at high temperature. Compressive in-plane stresses were predicted, and these decreased with coating thickness. However, the calculated stresses were much higher than the measured stresses in an annealed specimen. This discrepancy between experiment and model is attributed to stress relaxation in the real TBC system. Also, calculated shear stresses along the top coat / bond coat interface at the free edge of the specimen explain the delamination often observed during furnace cycling.

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1 Introduction

Thermal Barrier Coatings (TBCs) are insulating ceramic layers plasma sprayed onto gas turbine hot section components. After deposition, residual stresses are present in the top coat owing to quenching and secondary cooling effects [1-3]. When TBCs are heat treated (isothermally or cyclically) the as-sprayed stress state can be completely altered owing to stress relaxation at high temperature and successive stress build-up during cooling owing to differences in coefficients of thermal expansion (CTE) between substrate and ceramic [4-6]. Hence residual stress measurements can assist in understanding the evolution of the coating build-up or the thermal history of a TBC. Also, it is often reported that the residual stress state after spraying is an important parameter for the life and adhesion of a TBC [3,7].

Coating thickness can have a large effect on residual stresses. It is well known that during coating deposition spontaneous delamination can occur when the coating thickness increases, and in furnace cycling tests thick (1.0 mm) TBCs show shorter lives than the more modern 0.3 mm top coats [8].

Many techniques are available to measure residual stresses. They can be divided in three main types of method: 1) diffraction methods using an X-ray beam or neutrons, 2) material removal methods, in which changes in in-plane strain due to nearby material removal are measured, and 3) curvature methods, in which specimen bending is monitored [3]. In previous work [9] the X-ray diffraction, hole-drilling and layer-removal methods were compared. The hole-drilling method was found to be the most suitable for measuring a through-thickness stress profile.

In the current research the stresses in as-sprayed and heat treated TBCs are measured with the hole-drilling method. The objective is to investigate whether a correlation exists between residual stresses and the earlier reported [8] lives during thermal testing (furnace and burner rig). The effects of coating thickness and type of thermal loading are determined. During the measurements some experimental problems were encountered which will be discussed. Next, the residual stresses after furnace annealing are calculated numerically to verify whether the measured stresses agree with theory. Also, it is often stated that high normal and shear stresses at the free edge of laminated composite materials [10] and coated specimens [11] are responsible for delamination and the modelling predicts these stresses too.

2 Experiments

2.1 Materials and Thermal Loading

The materials are listed in Table 1. The spraying conditions for the bond coat and top coat are given elsewhere [8]. The spraying parameters for the top coat combined with a water cooled substrate resulted in high deposition efficiency (about 60%), and a coating with low porosity (<5%), a dense network of micro-cracks, and high thermal shock and erosion resistance [8,12].

Residual stresses were determined in as-sprayed specimens, annealed specimens (1050°C/5hr and 1250°C/5hr) and thermal shock specimens (200 cycles). The latter were tested in a burner rig where the top coat surface was locally heated by an oxygen/acetylene flame to 1300°C. One cycle consisted of a 30 sec. heating period followed by a 30 sec. cooling period. Further details of the burner rig are given elsewhere [12].

2.2 Hole-Drilling Method

The hole-drilling method [13] evaluates residual stresses near the surface of a specimen by drilling a small hole and measuring the relieved strains in the surrounding material. The strains are measured with a three-element strain gauge rosette as shown in Fig. 1. The rosette design incorporates marks for aligning the drill (diameter D_0) precisely at the centre of the gauge circle. To measure a possibly non-uniform stress profile, the hole is incrementally drilled, and for each increment the strains are measured and converted to the principal stresses σ_{max} and σ_{min} within that hole depth increment [13,14].

The holes were drilled with a high-speed air turbine diamond cutter, using an RS-200 Milling Guide. The first increment was 0.06 mm, followed by steps of 0.04 mm up to a depth corresponding to the total coating thickness. The size of the strain gauge rosette (D), and hence the diameter of the drill (D_0), depended on the thickness of the top coat. For the 0.3 mm TBCs the strain gauge rosette EA-06-031RE-120 (D=2.56 mm) was used and for the TBCs with thickness 1.0 mm the strain gauge rosette EA-06-062RE-120 (D=5.13 mm) was used (both types of rosettes were from Measurements Group). The hole diameter was measured after the entire drilling process with an Amsler binocular. Data reduction was done using a top coat Young's modulus and Poisson's ratio of 25 GPa and 0.2 respectively [8].

The specimens for the measurements on as-sprayed and furnace annealed TBCs were 30×30 mm^2. The strain gauge rosettes were positioned in the centres of the specimens. The thermal shock tested specimens were 30×80 mm^2 with two strain gauge rosettes on it (centre flame area and 15 mm off-centre). As an example, Fig. 2 shows a thermal shock tested specimen (top coat thickness: 1 mm) with strain gauge rosettes EA-06-062RE-120 connected to contact wires via a terminal. The holes are already drilled.

2.3 Results

Fig. 3 gives the average stresses, (σ_{max}+σ_{min})/2, for the 0.3 and 1.0 mm TBCs. These results show:

1. Significant differences in residual stresses depending on the coating condition. In general, the as-sprayed residual stresses were changed to less tensile or compressive stresses by heat treatment. Annealing was especially effective in this respect.
2. The as-sprayed residual stresses were low, varying from 0-40 MPa in the tensile regime, and apparently independent of depth within the coating.
3. After annealing the residual stresses were entirely compressive, increasingly so towards the top coat/bond coat interface. There was no apparent dependency on annealing temperature (Fig 3a).
4. Thermal shock resulted in low residual stresses both in the tensile and compressive regimes. The sign of the residual stresses in the top coat depended on coating thickness. At the centre of the area covered by the flame these stresses were compressive in the 0.3 mm coatings, but less so than in the annealed state, and tensile in the 1.0 mm top coat, but lower than in the as-sprayed state. The residual stresses in the top coat 15 mm off-centre were close to zero. The sign was tensile in the 0.3 mm coating and compressive in the 1.0 mm TBC.

2.4 Experimental Problems

The results can be affected by several experimental errors. This is because residual stress measurements by the hole-drilling method involve many variations in technique and parameters (material removal, depth and diameter determination and strain measurement). The five main sources of errors are 1) strain measurement errors, 2) hole eccentricity, 3) elastic property errors, 4) hole depth measurement errors and 5) hole diameter measurement and shape errors. The first four sources of error are commonly known and their effect on the calculated stresses is discussed in the literature [13,15,16]. However, hole diameter measurement and shape errors appeared to be particular problems for the brittle TBCs.

Fig. 4 shows a blind hole in a 0.3 mm TBC. The hole diameter in the top coat is larger than the drill diameter (D_0). This is caused by deflection of the drill owing to the porous structure of the coating and by abrasion during material removal. This means that the diameters of the first increments are probably smaller than those of the final increments. From the theory of the hole-drilling method it can be deduced that an overestimate in hole diameter of 10% results in predicted stresses 20% lower than the real stresses. Another problem is the rounded hole bottom, which deviates from the required flat-bottomed and square-cornered hole shape. This means that for the last increment the effective diameter is *less* than the drill diameter. This too can be regarded as a hole diameter measurement error and the stress error involved can hence be deduced likewise.

3 Theoretical

3.1 Finite Element Model

The model predicts the stresses after cooling down from annealing temperature of a 30 mm in diameter disc-shaped flat Hastelloy X plate, coated with a 0.1 mm NiCrAlY bond coat and a 0.3 or 1.0 mm thick ZrO_2-8wt%Y_2O_3 top coat. It was assumed that the coating was stress free at high temperature owing to creep. Fig. 5 illustrates the model specimen geometry. The substrate, bond coat and top coat are assumed to be isotropic, homogeneous and elastic. The simulation was performed as an uncoupled thermo-mechanical analysis, using the MARC code. Cooling was modelled by radiation and forced convection at the coating surface, and radiation and free convection at the substrate rear side. Further details and material properties required for the model are given elsewhere [8].

3.2 Modelling Results

Fig. 6 shows the in-plane (yy), normal (xx) and shear (xy) stresses just above the bond coat / top coat interface for the outer 5 mm of the specimen in radial (y) direction. Since the predictions of stresses in the two elements closest to the singularity at the intersection of the interface and the free edge can be very inaccurate [17] they are omitted (from 14.6 mm to 15.0 mm). Along most of the radial direction, out to y~11 mm, the normal and shear stresses were (nearly) zero and only in-plane stresses were present (plane stress situation). This situation was disturbed close to the free edge, where the shear stresses were high. The normal stresses became first tensile but were compressive near the singularity. When the coating thickness was increased from 0.3 to 1.0 mm (+330%), the in-plane stresses decreased 11%. However, the normal and shear stresses at the free edge and close to it increased considerably (about 50%), and the distance from the edge over which these stresses apply increased with increasing thickness. An increase in initial temperature from 1050°C to 1250°C (about 20%) resulted in an increase of 20% for all stress components.

4 Discussion

Owing to experimental errors the scatter in residual stress data can be considerable, making it difficult to discuss the results. However, since the stresses in the TBCs were almost uniform over the thickness, the equivalent uniform stress for the last increment equals the average stress for the entire coating thickness. This provides a good overall picture of the effects of coating thickness and thermal load, Fig. 7. These effects will be discussed next, along with the results of the FEM calculations.

As-sprayed.

The magnitude of the measured residual stresses agrees well with predictions for (water) cooled specimens [2,3]. Hence in the as-sprayed condition the residual stresses can be attributed to primary cooling effects. The stresses in the 1.0 mm top coat were lower than those in the 0.3 mm coating. On the other hand, it is well known that very thick TBCs (>2 mm) can delaminate spontaneously just after deposition. This can be explained as follows. Owing to the relatively large thickness, the heat from the plasma and melting particles is poorly removed and the specimen temperature increases during spraying. On subsequent cooling, high shear stresses develop at the intersection of the bond coat / top coat interface and the free edge of the specimen. As shown in Fig. 6, these stresses increase with coating thickness and can cause delamination.

Furnace annealed.

Residual compressive stresses were present after furnace annealing for all values of coating thickness. This agrees with literature results [4-6] and can be easily understood. From the top coat creep data [18] it can be deduced that the coating stresses after heating relax completely at high temperatures. Hence, since $CTE_{tc} < CTE_{sub}$, compressive stresses develop in the top coat, and these increase towards the interface due to specimen bending.

The measured stresses are much lower than the theoretical stresses after a heat treatment. Apparently, some stress relaxation mechanisms operate during cooling. Micro-cracking is not likely to occur under compressive conditions, and by performing one calculation allowing the materials to creep (not shown here) it was shown that creep could also be excluded. The most plausible mechanism left is plastic deformation of the top coat. Owing to tensile stresses during heating the top coat is plastically stretched. At high temperatures the stretched microstructure is retained, whilst the stresses relax by creep. When the specimen is cooled the top coat is pushed together again and the consequent compressive stresses are partially dissipated by this. This explanation implies that TBCs have a relatively open microstructure at high temperatures, for which no evidence can be found in the literature. This hypothesis should be investigated in future research.

Though magnitudes differed, both the measurements and calculations showed decreasing in-plane stresses with increasing coating thickness, which agrees with the theory of (thermal) stresses in composite bars. However, the model also predicted about the same difference in residual stresses when decreasing the annealing temperature from 1250ºC to 1050ºC, while the measurements showed a minor effect of annealing temperature on residual stresses. Apparently, the change in stress due to a change in heat treatment temperature is annulled by the stress relaxation mechanism discussed earlier, while the change in stress due to a change in thickness is still present after stress relaxation.

Thermal shock.
Fig. 7 shows that in the centre of the flame covered area and in the heat affected zone the residual stresses underwent a remarkable reversal in sign as the coating thickness increased. An explanation for this phenomenon must be sought (a) in the combination of changes in stress at high temperatures and cooling stresses and (b) differences in temperature between substrate and top coat. This will be further investigated with the model developed.

Failure mechanism
An explanation for early failing of the 1.0 mm TBCs in comparison with the 0.3 mm TBCs [8] can be given from the FEM results at the free edge. Large shear stresses occur, which increase considerably with increasing thickness. The maximum tensile normal stress, just away from the free edge, increases also with increasing thickness. The following possible failure mechanism for delamination with or without (thermal) fatigue is proposed. When the shear stress exceeds a critical value, cracks initiate at the intersection of the interface and the free edge. Crack propagation is driven by the normal tensile stresses. The region of singularity travels with the crack along the interface, so shear stresses and tensile normal stresses remain present at the crack tip. This results in crack propagation until complete delamination has occurred. It was indeed observed that failure after furnace testing appeared as complete delamination or partial delamination from one edge to the opposite edge [8]. The influence of an increased heat treatment temperature on the failure mechanism is twofold. Firstly, the oxidation rate and hence the oxide layer thickness is increased, which enhances delamination [19]. Secondly, the shear stress at the free end is increased.

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Table 1 Specimen materials

Material		Thickness [mm]
substrate	Hastelloy X	3.2
bond coat	Ni 22Cr 10Al 1Y	0.1
top coat	ZrO_2-8wt%Y_2O_3	0.3 & 1.0

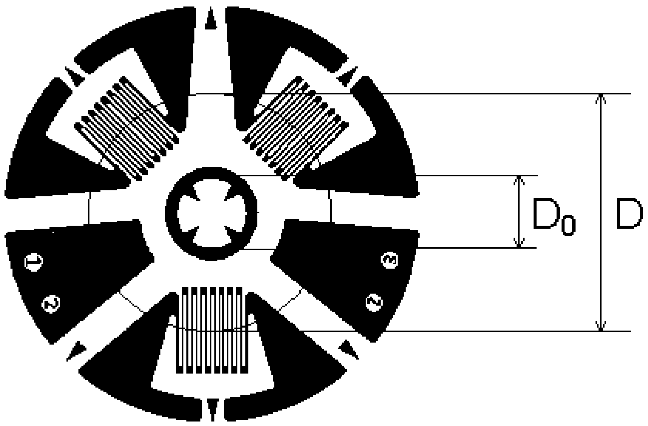

Figure 1 *Strain gauge rosette for the hole drilling method*

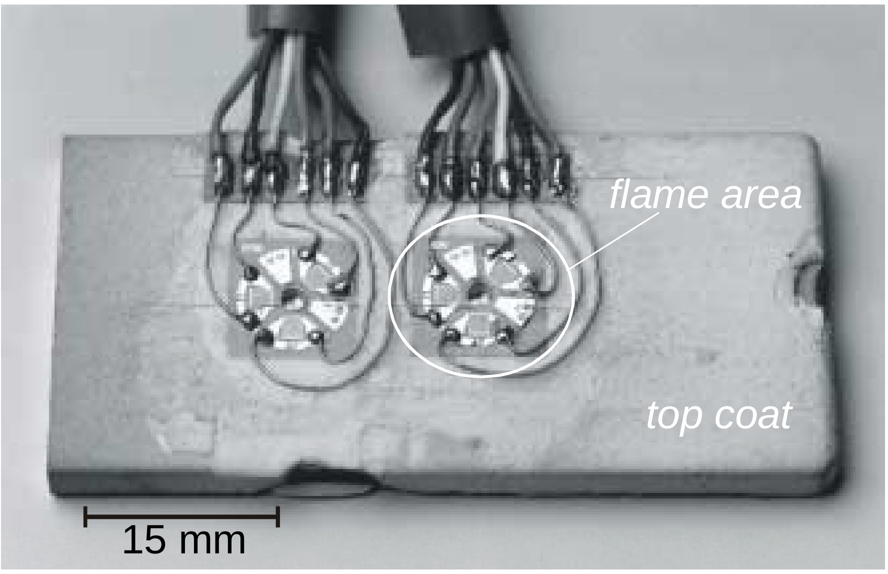

Figure 2 *Strain gauge configuration on thermal shock specimen*

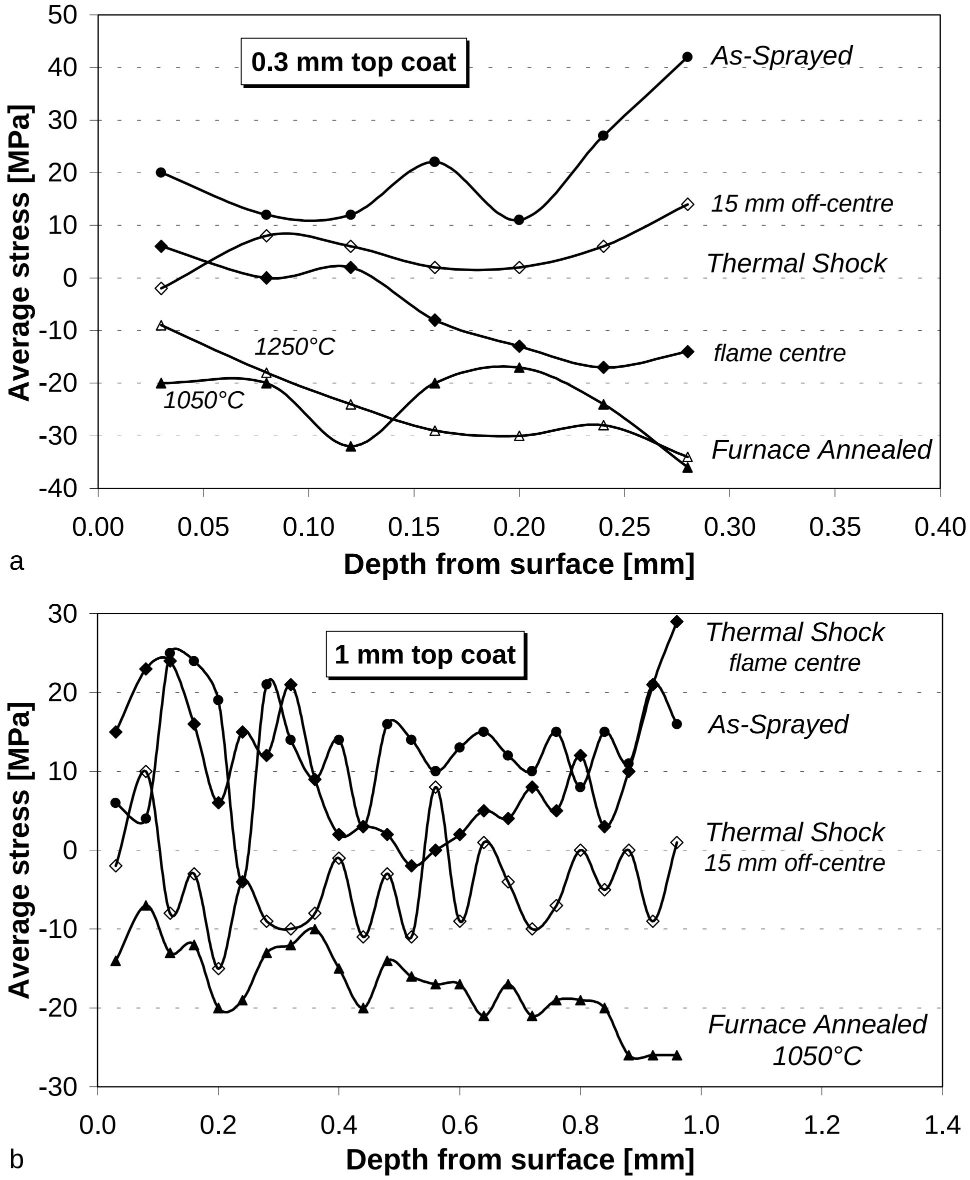

Figure 3 *Average through-thickness stress profile for a 0.3 mm (a) and 1.0 mm (b) top coat*

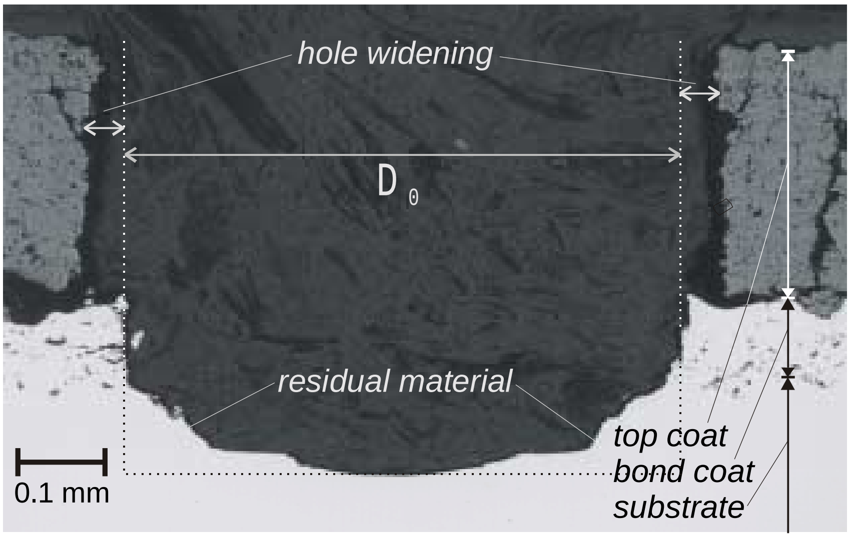

Figure 4 *Cross-section of drilled specimen*

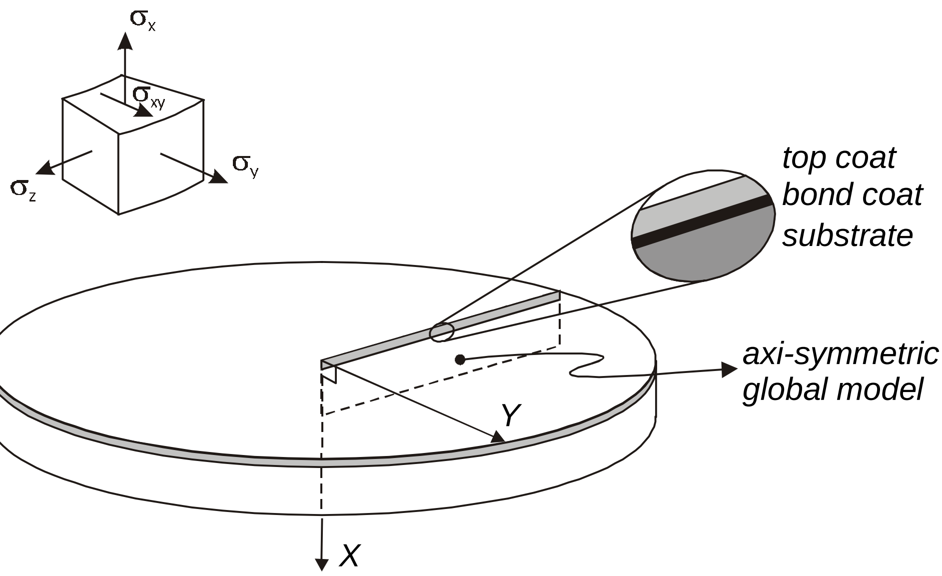

Figure 5 *Geometry of FE-model. The radial direction is indicated by 'y', the normal direction by 'x'*

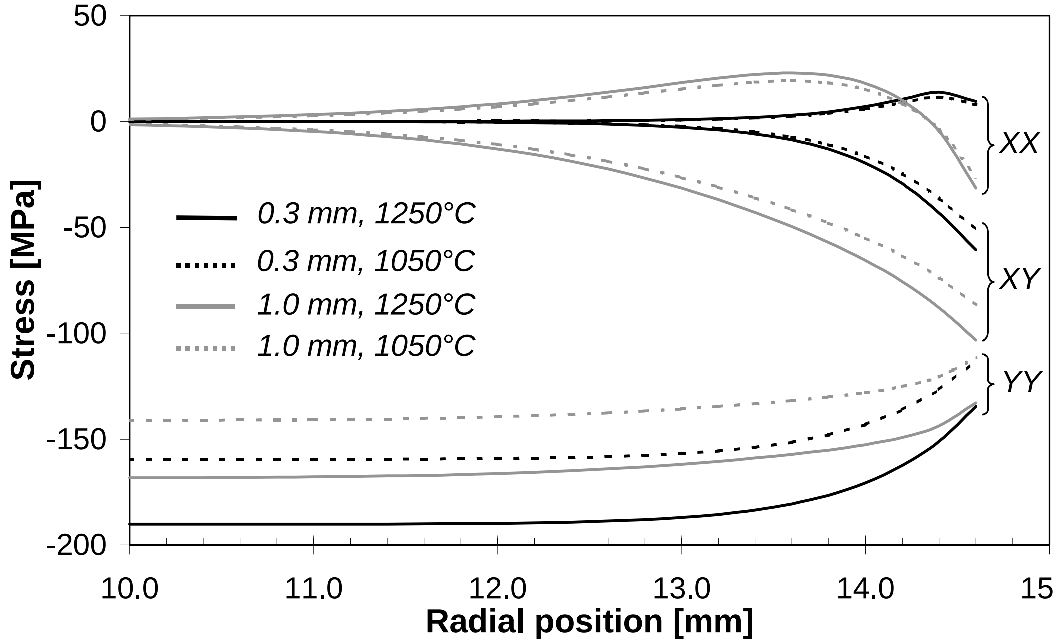

Figure 6 *Calculated in-plane (yy), normal (xx) and shear (xy) stresses in furnace annealed (1050°C and 1250°C) 0.3 mm and 1.0 mm top coat*

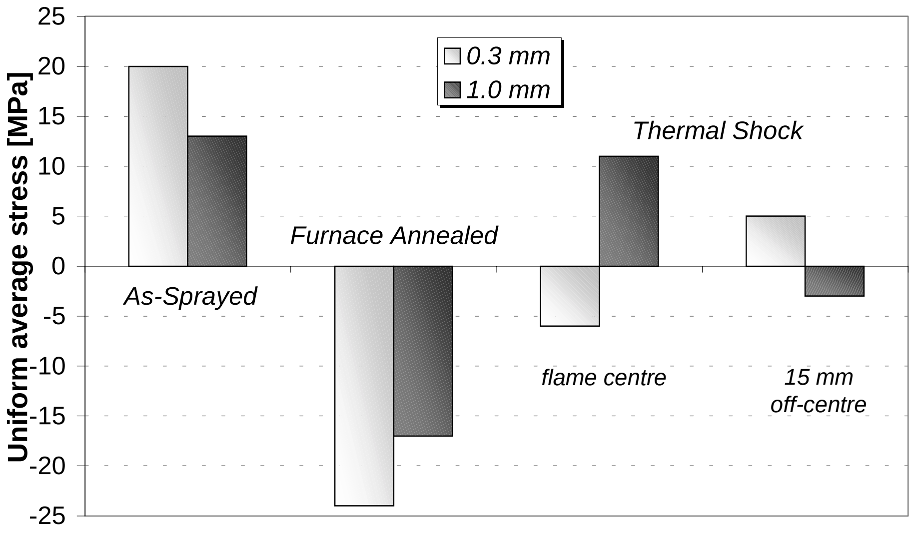

Figure 7 *Equivalent uniform stresses over entire coating thickness in 0.3 mm and 1.0 mm TBCs of as-sprayed, furnace annealed (1050°C) and thermal shock specimens*