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Residual Stress Analysis By The Hole Drilling Method Applied to Laser Drilled Thermal Barrier Coatings With Various Bond-Coats

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1 Introduction

The gas turbine combustion chamber of aero-engines requires a Thermal Barrier Coating (TBC) always processed by plasma spraying. The TBC porous ceramic top-layer performs the crucial function of insulating the metal wall from severe heat load and potential melting. Further heat protection is achieved by effusion holes system drilled in specific pattern all around the chamber. Such holes enable an air film that protects the internal wall face of the TBC-coated part. These holes drastically improve the component durability and service life and allow higher efficiency and better performance of the turbine. In the manufacturing and repairing industry of combustion chambers, laser drilling has become the conventional method because it is possible to operate precisely numerous cooling holes throughout both the ceramic and metallic layers [1, 2]. Acute drilling angle is necessary to maximize the cooling effect and to prevent hot points by limiting turbulence of the gas flow in the air inlet zone. However, by selecting high angles of incidence for laser drilling, the ceramic delamination during laser drilling could lead to spallation in service and to direct exposure of the metal to the hot gases. Moreover, the ejected debris might also impact and damage downstream rotating parts. There are two different drilling methods: laser percussion or laser trepan. The faster process is laser percussion drilling because several laser pulses are repeated at the same hole location leading to hole diameter of about 500 μm . Most of works devoted to laser drilled TBC are investigating the role of laser parameters (pulse energy, shape or frequency, drilling angle) or induced mechanical effects (ejected melt, assist gas, ...) that could affect the resulting length of the main

crack at the bond coat / top coat (BC/TC) interface of the leading edge [3-5]. In addition, materials characteristics like composition, density, thickness might have a role on the hole geometry and on cracking [4, 2]. The residual stresses generated during the deposition process and further induced by the drilling process could affect crack initiation and also crack propagation in laser-drilled TBC. Thus, in this work, we focussed on the assessment of the residual stress profiles to investigate the stress modification that could occur in a ceramic/metal layered system when machined by laser. To that end, conventional laser percussion drilling with normal incidence was implemented and further stress analysis was achieved using the incremental hole drilling method before and after laser drilling. In addition, several TBC interfaces with potential different residual stress profiles were studied in order to better understand the stress generation and stress release regarding various bond coats (plasma, plasma-graded, cold spray and heat-treated cold spray). The influence of various TBC bond coats and corresponding residual stress profiles is also discussed in the light of the actual crack initiation and propagation by laser drilling. Furthermore, interrupted laser drilling conditions (1 pulse to 4 pulses) were achieved and interface observations were carried out to measure the BC/TC crack length for each TBC interface.

2 Materials and Processes

2.1 TBC samples with various bond coats

Cobalt base Haynes® 188 alloy plates (dimensions $150 \times 40 \times 2 \text{ mm}^3$) were selected as substrates. The plates were roughened ($R_a = 2.8 \text{ } \mu\text{m}$) by grit-blasting with a $250 \text{ } \mu\text{m}$ corundum grit prior to coating operations. Three types of TBC bond coat were prepared: two of them were obtained by plasma spraying with a F100-Connex torch (Sulzer Metco, Wohlen, Switzerland) and the last one was processed by cold spray using a KINETICS® 3000-M System (CGT-GmbH, Ampfing, Germany). The first type of plasma TBC was similar to conventional industrial plasma TBC involving a $-90 +106 \text{ } \mu\text{m}$ NiCrAlY powder (Amdry 962, Sulzer Metco, Westbury, NY, USA) and a $-125 +11 \text{ } \mu\text{m}$ yttria stabilized zirconia (YSZ)

powder (204NS, Sulzer Metco, Westbury, NY, USA). The second type of plasma TBC was continuously graded by increasing the YSZ powder feedrate while NiCrAlY powder feedrate was simultaneously decreased during spraying the TBC coupon. The third type of TBC was obtained by combining a cold sprayed bond coat with $-38 +5.5 \mu\text{m}$ CoNiCrAlY powder (Amdry 9951, Sulzer Metco, Westbury, NY, USA) to plasma sprayed YSZ top-coat. Main spraying parameters are summarized in Table 1.

For plasma, plasma graded and cold spray bond coats, all the ceramic top coats were achieved with similar plasma parameters. Optical images of the three different types of interface with various bond coats (BC) are shown in Figure 1. In addition to the as-sprayed condition selected for the cold spray CoNiCrAlY sample (Cf. Fig.1-B), an additional sample was prepared by heat-treatment at 800°C during 4h in air. This post-treatment was further implemented to release the residual stress. It is worth to note this treatment was carried out before the ceramic layer being plasma sprayed.

2.2 Laser drilling experiments

TBC samples were drilled at PIMM institute (ENSAM, Paris) in a percussion mode using a YAG laser with $1.06 \mu\text{m}$ radiation (TRUMPF HL201P, HAAS-LASER GmbH, Schramberg Germany). The laser power was selected at 15 kW with 1 ms pulse duration. Each hole was drilled implementing at least 4 pulses to come through the TBC coated plate. Time between each pulse was around 0.5 seconds to reproduce industrial drilling "on the fly". Two geometries of hole were prepared depending on drilling incidence: 90° (i.e. normal to the surface) and 20° . The various TBC samples that were drilled at 90° angle were used to achieve residual stress measurements (hole diameter $600 \mu\text{m}$). The laser drilling at 20° was applied on same TBC samples in order to measure BC/TC interface crack by optical microscope (Axiovert 405M, Carl Zeiss SAS, Le Pecq, France).

2.3 Residual stress measurements

The incremental hole drilling method is used to determine the depth profile of residual stress in a structure [6]. This step-by-step material removal method generates a surface displacement around the hole due to the release of stresses. The displacements after each drilling step can be recorded using strain gage rosette [7] or by optical method [8]. In this study, Electronic Speckle Pattern Interferometry (ESPI) technique with phase signal shifting method has been successfully introduced in case of TBC sample. This method is very convenient because no specific device or surface preparation of the ceramic top coat are necessary. Some hypotheses are assumed: Isotropic and linear elastic behaviour of materials, continuous displacements and homogeneous stress for each step, normal stress negligible and no plastic deformation due to stress release. The residual stress calculation (Equation 1) depends on the experimental strains ϵ_j measured at each increment of depth j and depends on calibration coefficients A_{ij} .

$$\sigma_j = \frac{\epsilon_j}{2A_{ij}} \quad \text{Equation 1}$$

After the new drilling step, a new residual stress distribution must be considered to calculate the strain ϵ_j with the following equation (Equation 2):

$$\epsilon_j = \epsilon_{mj} - \sum_{i=1}^{i=j-1} \epsilon_{ij} \quad \text{Equation 2}$$

Where ϵ_{mj} represents the measured strain and ϵ_{ij} represents the strain created by the new distribution.

2.3.1 Measurement of displacement with ESPI

The temporal phase shifting method is used [8-10]. The beam phase of the interferometry set-up (Figure 2) is shifted with a mirror mounted on a piezo-translator (laser $\lambda=632.8$ nm, angle $\theta=45^\circ$).

In the present study, 4 phase steps are recorded and for each phase step, the intensity $I^k_{(x, y)}$ of a speckle pattern k is equal to:

$$I_0(x,y)(1 + \gamma(x,y) \cdot \cos(\phi(x,y) + \phi^i)) \quad \text{Equation 3}$$

For $k=1, 2, 3, 4$ and where $I_0(x)$ is the intensity of the laser light, $\gamma(x)$ the fringe contrast and $\phi(x)$ the optical phase to be determined. ϕ^i is a value associated with each pixel of the mapped region. The optical phase is calculated with:

$$\tan \phi(x,y) = \left(\frac{I^4(x,y) - I^2(x,y)}{I^1(x,y) - I^3(x,y)} \right) \quad \text{Equation 4}$$

Measuring the phase map of one illuminated drilled area, the surface incremental displacement is determined from the phase map subtraction with:

$$U_x(x,y) = \frac{\Delta \phi(x,y) \lambda}{4\pi \sin \theta} \quad \text{Equation 5}$$

Where $\Delta \phi(x,y)$ is the optical phase difference due to the object deformation. An example of the incremental surface displacement map obtained on a TBC sample after mechanical drilling with a $830 \mu\text{m}$ hole depth (drilling conditions: 5000RPM, cutting tool: 3-teeth milling bit, no coolant) is given in Figure 3.

2.3.2 Residual stress profiles calculation

From Equation 1, the calibration coefficients A_{ij} are calculated through a 3D finite element (FE) analysis (Abaqus software) [11-12] of the experimental displacements measured by ESPI (averaged value along a 1.5 mm line). The calibration coefficients A_{ij} were calculated in case of a TBC system involving three different layers and an incremental hole of 2 mm for both as-sprayed and laser drilled geometries. For the latter, the laser-drilled hole was 0.5 mm in diameter. To that end, an elementary stress $\sigma_j = 1 \text{ MPa}$ is applied at hole boundary in the FE model (See Figure 4) to simulate a stress relaxation, the strains ϵ_{ij} (Equation 2) are calculated to determine the strain ϵ_j .

In the 3D FE model, the substrate and coatings were simulated involving different Young's moduli, Poisson ratios and thicknesses for both as-sprayed and laser drilled TBC samples as summarized in Table 2. In case of plasma graded bond coat, the elastic properties of both ceramic and NiCrAlY were mixed according a linear fitting. This kind of FE modelling to achieve the residual stress analysis with the material removal of multi-layered system is fairly original [11-12]. Two measurement nodes are selected to calculate the strain ϵ_j .

3 Results and Discussion

3.1 Residual stresses in as-sprayed TBCs

Numerous papers are devoted to the residual stress analysis of conventional plasma sprayed TBC involving destructive, semi-destructive or fully non-destructive methods [15, 16]. The residual stress measurement could also be achieved through in-situ curvature measurement and calculations (analytical or by FE) to discriminate both residual stresses owing to the quenching of liquid droplets and to the cooling of the deposit/substrate system [4, 17]. Among the existing methods, the hole-drilling method has shown numerous advantages because it allows to achieve residual stress profiles and with help of FE analysis it could be envisaged to achieve the experimental analysis on specific area of shaped component or within multi-layered system like TBC [12].

Residual stress (RS) profiles of plasma and graded plasma bond coats are compared in Figure 5 and the profiles of cold spray and heat treated cold spray bond coats and shown in Figure 6. The positions of both TC/BC and BC/Substrate in each case are drawn. According to Figure 1-C and Table 2, the location of the TC/BC interface for plasma graded BC led to a thicker intermediate layer if compared to the plasma BC. The RS profiles are very different for each system. In case of plasma BC, the RS profile is in agreement with RS profiles and stress levels found in literature with the modified layer removal method

[16]. Thus, the tensile stresses in the BC near BC/S interface are mainly due to quenching stress and lead to a compressive to tensile steep gradient at the BC/S interface because compressive stress in the substrate could come from plastic deformation due to blasting pre-treatment. Compressive stress within the near surface of the substrate could also be emphasized by the equilibrium of both the tensile quenching stress and cooling stress in this interfacial region. Indeed, cooling tensile stress are generated all over the BC even if only a slight difference between coefficient of thermal expansion exist between the substrate and the bond coat. In the case of plasma sprayed NiCrAlY bond coat, to be consistent with the RS profile obtained, the coefficient of thermal expansion (CTE) shall be higher than those of the HAYNES188 substrate. Therefore, tensile residual stress are probably emphasized in the BC during cooling and further balanced in compressive RS superimposed to peening stress in the substrate. This discussion highlights the need for actual values of CTE for the various bond coats. At the TC/BC interface the gradient is less pronounced because both quenching and cooling RS in the ceramic are neutralized by intra-lamellar and inter-lamellar microcracking (with also porosity that drastically lower the elastic modulus of the plasma sprayed ceramic). In case of plasma graded BC, a similar approach could be done to explain the very different RS profiles as shown in Figure 5. The plasma graded BC exhibited a tensile to compressive stress gradient at the BC/S interface followed by another rather steep compressive to tensile gradient within the graded BC region and ended by an neutral region in the ceramic. The increasing content of ceramic mixed to metal will make the global CTE higher than those of the ceramic in the TC/BC region and lower than those of the metallic substrate in the BC/S region. This is also accompanied by a similar evolution with Young's moduli that will also amplify the stress calculated from the actual measured strain. Therefore, two opposite gradients can be promoted near each interface. Those located near the BC/S interface led also to some tensile stress in the BC near the interface (in agreement with quenching stress in the near-interface region) but also to a high level of tensile stress within the substrate. In this case it means that blasting compressive stress has been neutralized by tensile cooling stress. To more enlighten this discussion, one may note that the thermal history during the graded coating process is very different than those of the plasma bond coat. It led probably to higher onset temperature for the cooling down

because no interruption between TC and BC spraying was operated and also because the addition of ceramic will promote higher temperature in this region. All these thermal aspects combined to a thicker intermediate layer in case of plasma graded would explain the predominant role of cooling stress for the RS profiles of the plasma sprayed samples that has been evidenced in this study.

Much less works are devoted to RS profiles in cold spray coatings [18, 19]. Residual stresses are mainly induced by peening effect and corresponding plastic deformation of the high velocity particles. Thermal effects that could generate cooling stress are more effective for very thick coating (millimetric range) which is not this case study. As-sprayed cold spray CoNiCrAlY led to compressive to tensile gradient at the BC/S interface followed by a rather slight compressive to tensile gradient at the TC/BC interface. The cold spray CoNiCrAlY bond coat with 220 μm in thickness is mainly tensile with a steep gradient at the BC/S interface. RS state derived from peening effect and high plastic deformation should lead to overall compressive stress. In our case, the tensile peak within the cold spray bond coat could not be explained by a multipass coating as suggested in literature [19] because only a single pass was achieved. Nevertheless, tensile residual stress has already been detected in aluminum cold spray coating without ambiguity through deflection measurement made by Suhonen et al. [18]. The role of thermal stress can be at the origin of such mechanical behaviour. In our case this thermal effect might come also from the plasma sprayed ceramic that is further sprayed (after the CS bond coat being cooled down at room temperature). As for plasma bond coat, this result bring out the lack of data about expansion properties of cold sprayed coatings in the as-sprayed state. In Figure 6, it can be seen obviously that heat-treated cold sprayed CoNiCrAlY TBC led to a stress-free sample.

3.2 Residual stress before and after laser drilling

The various RS profiles before and after laser drilling (drilling incidence 90°) are given in Figure 7. The resulting measured stress state is resulting both from stress release due to material removal but also from

potential modifications due to laser-matter interaction involving short duration but high rate thermal and mechanical effects (hot gas recoil pressure). From Figure 7, it is evidenced that the laser drilling process affects drastically and with a long range distance (1mm) the RS state around the hole. It can be seen that the sharp compressive to tensile gradient at BC/S interface of the plasma BC (Fig. 7-A) could be released leading to a stress-free hole region. From other RS profiles (Fig. 7 B to D), it is remarkable that gradients at BC/S interfaces are not drastically modified (except for the cold spray bond coat that enable high tensile stress level within substrate). However, it is found that the TC/BC gradients are all more pronounced after laser drilling. This TC/BC region seems to be very sensitive to RS modification assuming that no significant interface crack was induced by laser drilling. This work introduced successfully the original experimental procedure and particularly the relevance to control the RS state around a laser-drilled hole. Further work is needed to better discriminate the stress release due to material removal from the stress induced by laser. To that purpose, smooth mechanical drilling without heat and strong mechanical effects should be prepared with a similar diameter than those obtained by percussion laser drilling. Further analysis with the hole drilling method applied on such pre-drilled hole will ascertain the actual influence of laser drilling on RS state around the hole. This aspect might be crucial to envisage multi-holes patterns with their influence on the component geometry and also to better understand the role of RS profile on interfacial damaging.

3.3 TC/BC interface crack for various BC

Laser percussion drilling with 20° incidence was achieved on the TBC samples with the various interfaces involving interrupted conditions to follow crack initiation and propagation from 1 to 4 pulses. The resulting TC/BC interface crack is given in Figure 8. It is obvious that bond coat modification could influence drastically the cracking behaviour of laser-drilled TBC with a clear beneficial effect when achieving a graded bond coat. From stress release in heat-treated cold spray bond coat it is inferred that RS could have an important role on cracking behaviour during laser drilling.

4 Conclusion

In this work, different TBC with various bond coats were prepared by plasma and cold spray. The RS were analyzed involving the hole drilling method with ESPI measurements of strains in case of as-sprayed and laser-drilled TBC. This method was successfully introduced to determine RS modification around a laser-drilled hole (normal incidence). RS profiles are drastically modified after laser drilling. Stress could be released or enhanced. Further work is needed to better discriminate the stress release due to material removal from the stress induced by laser. The influence of the bond coat on TC/BC interface crack was also shown for acute angle laser drilling. It is concluded that both residual stress and nature of bond-coat can have a major role to prevent TC delamination during laser drilling.

5 Acknowledgements

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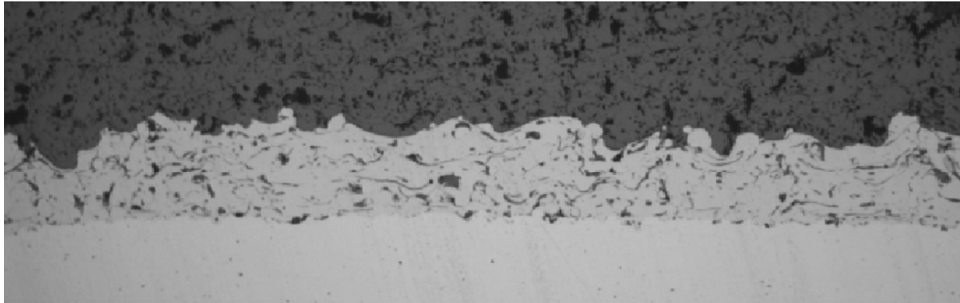
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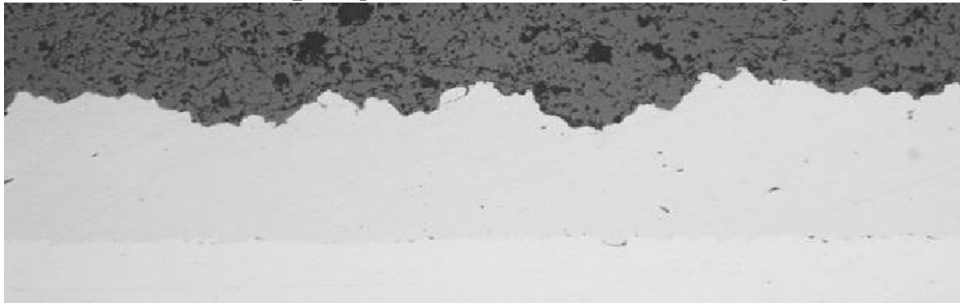
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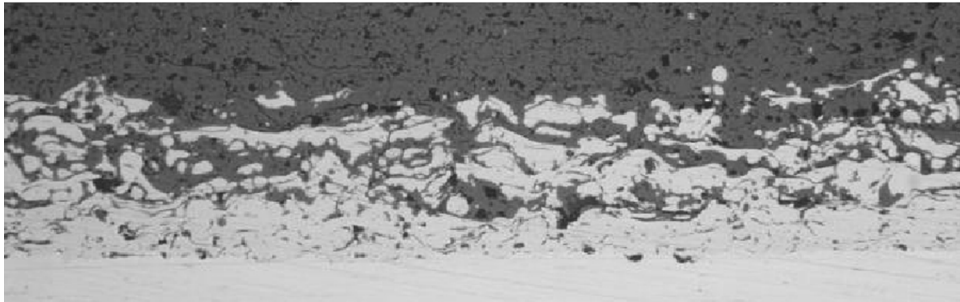
A-Plasma BC (thickness 120 μ m)



B-Cold spray BC (thickness 220 μ m)

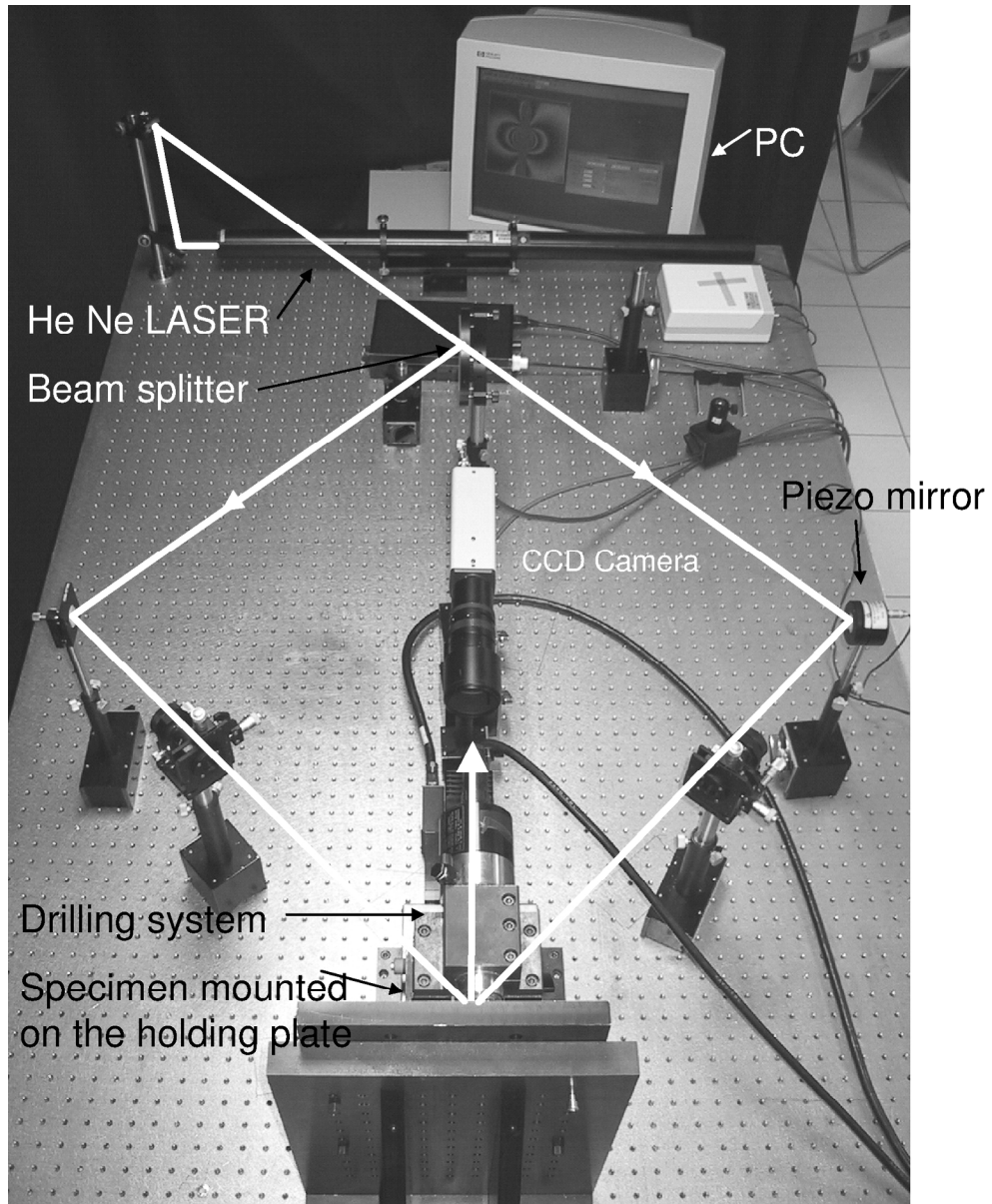


C-Plasma graded BC (thickness 280 μ m)

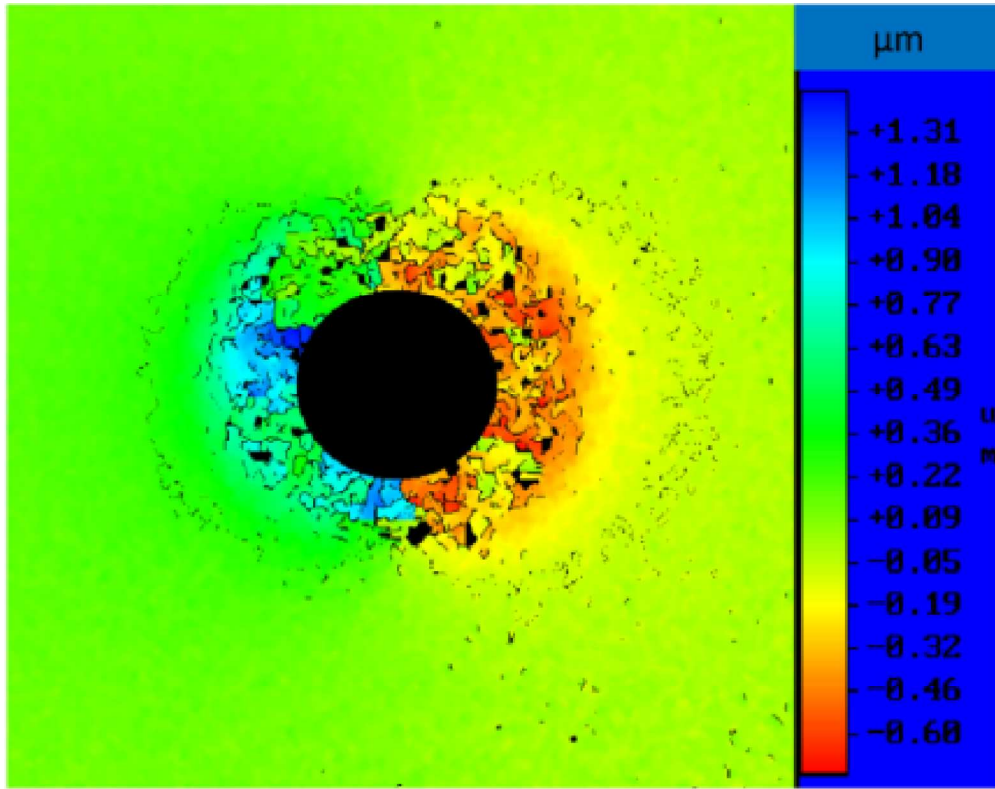


500 μ m

Cross-sections views of the various bond coats: A-plasma, B-cold spray, C- plasma graded
76x95mm (300 x 300 DPI)

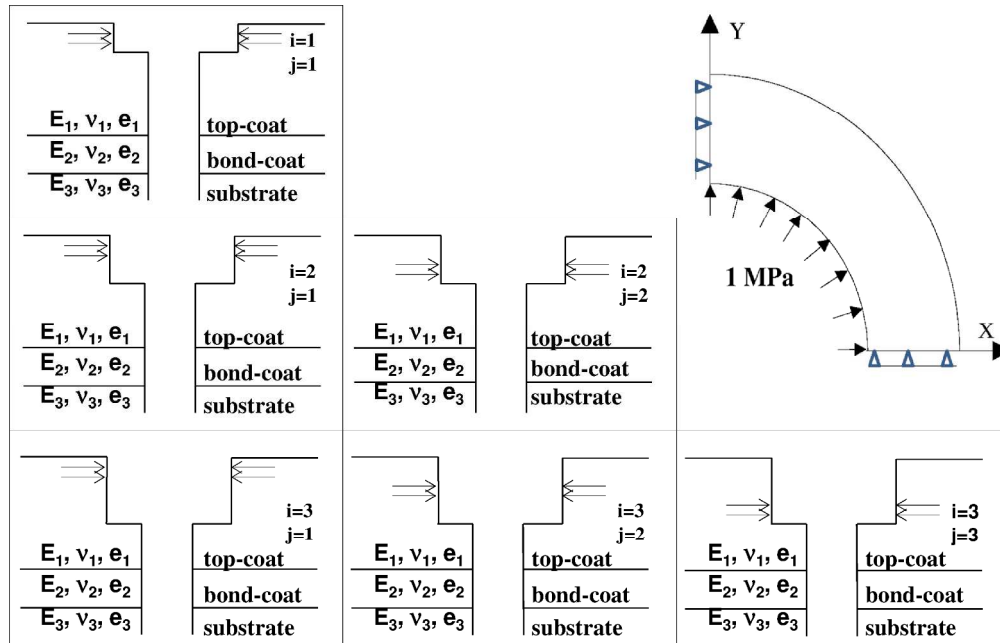


Experimental hole drilling with ESPI set up
157x193mm (300 x 300 DPI)

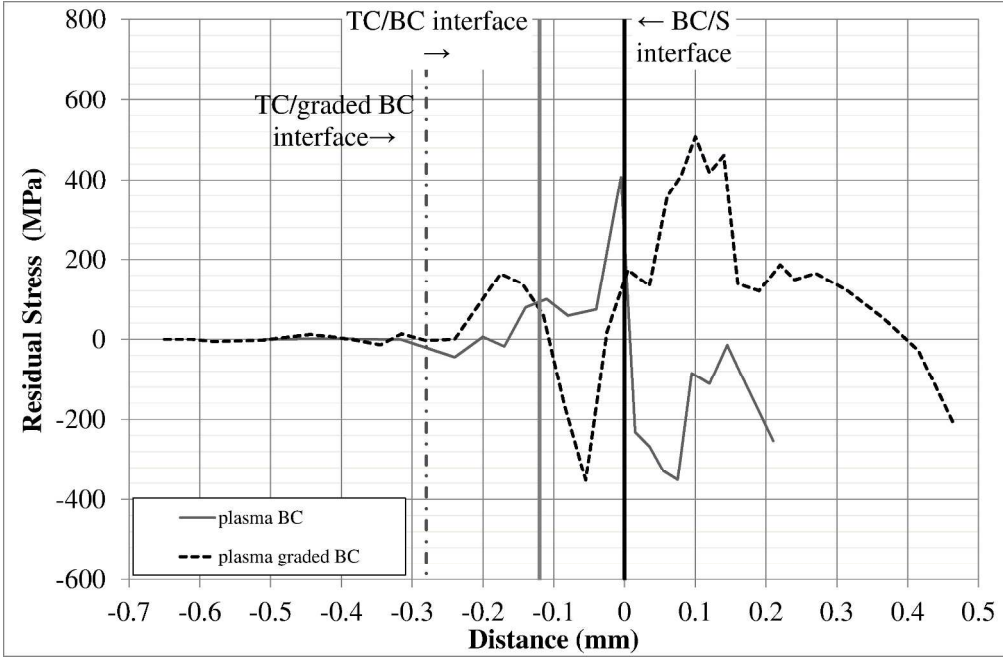


2 mm

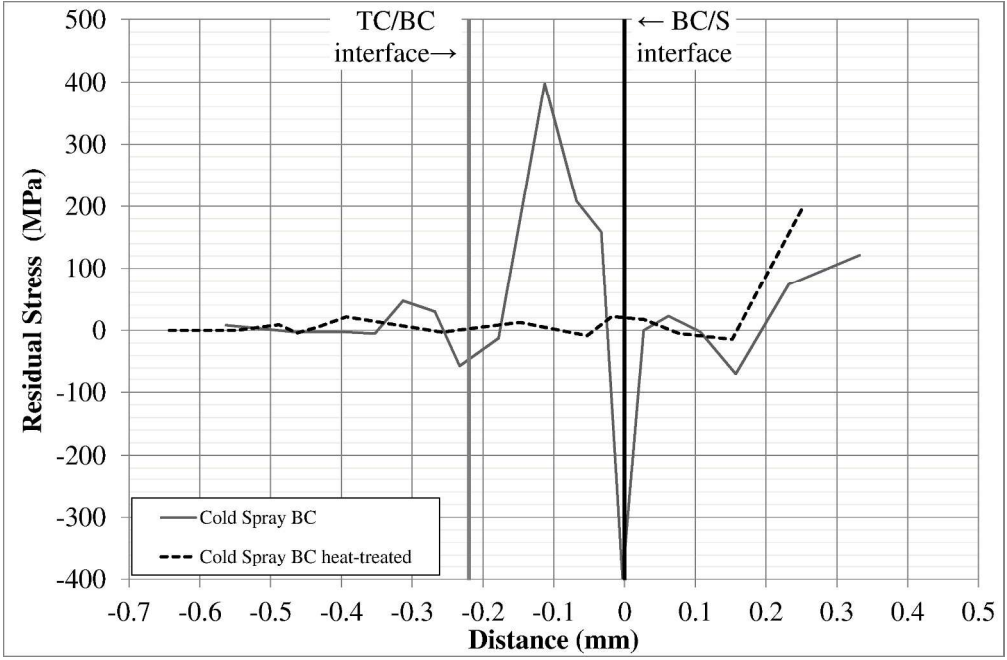
Displacements map around a drilled hole
155x136mm (300 x 300 DPI)



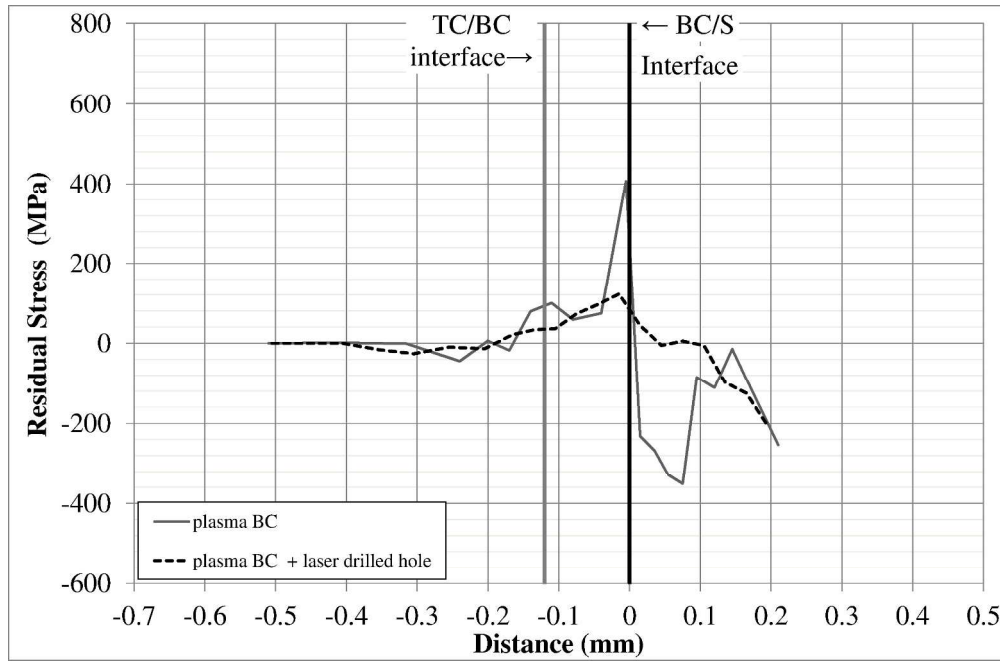
ε_{ij} iterative calculation (load = 1 MPa) for A_{ij} coefficients (ex.3 drilling steps within ceramic)
216x138mm (300 x 300 DPI)



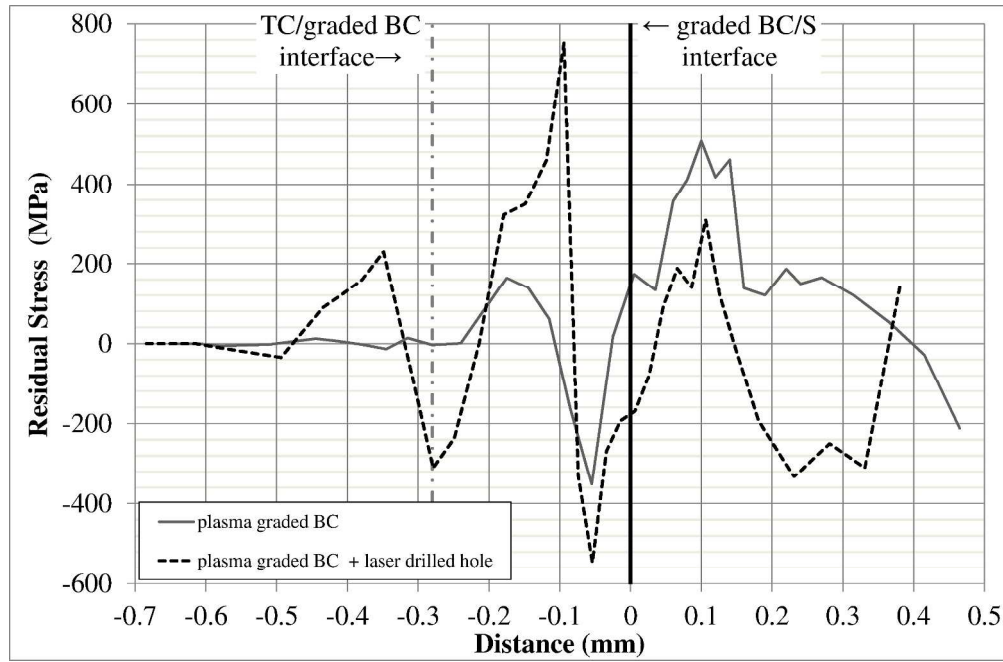
Residual stress profiles of plasma and plasma graded BC
258x168mm (300 x 300 DPI)



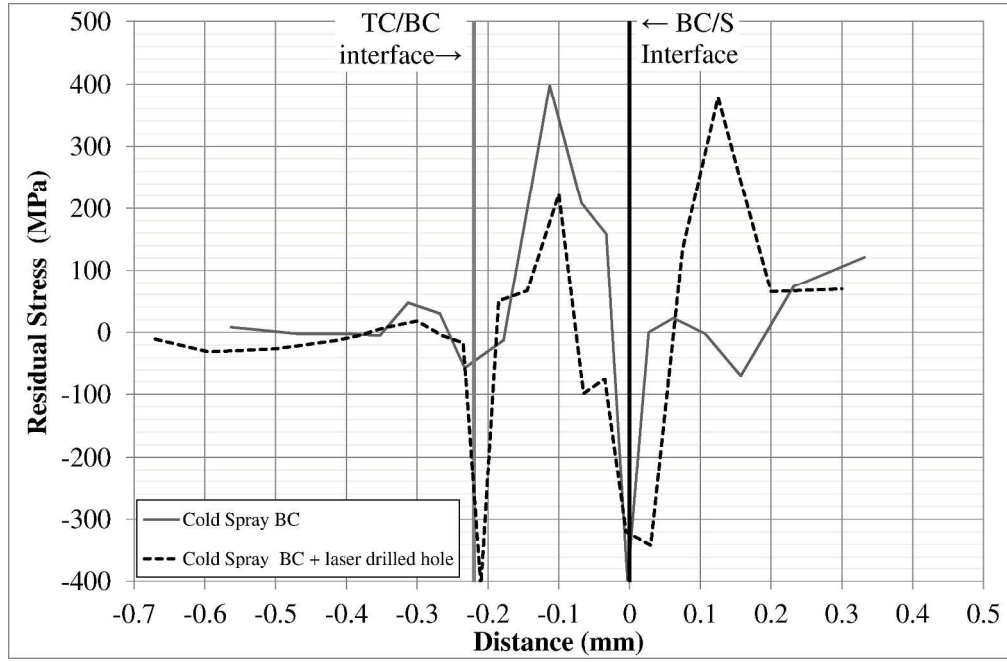
Residual stress profiles of cold spray and cold spray heat-treated BC
258x168mm (300 x 300 DPI)



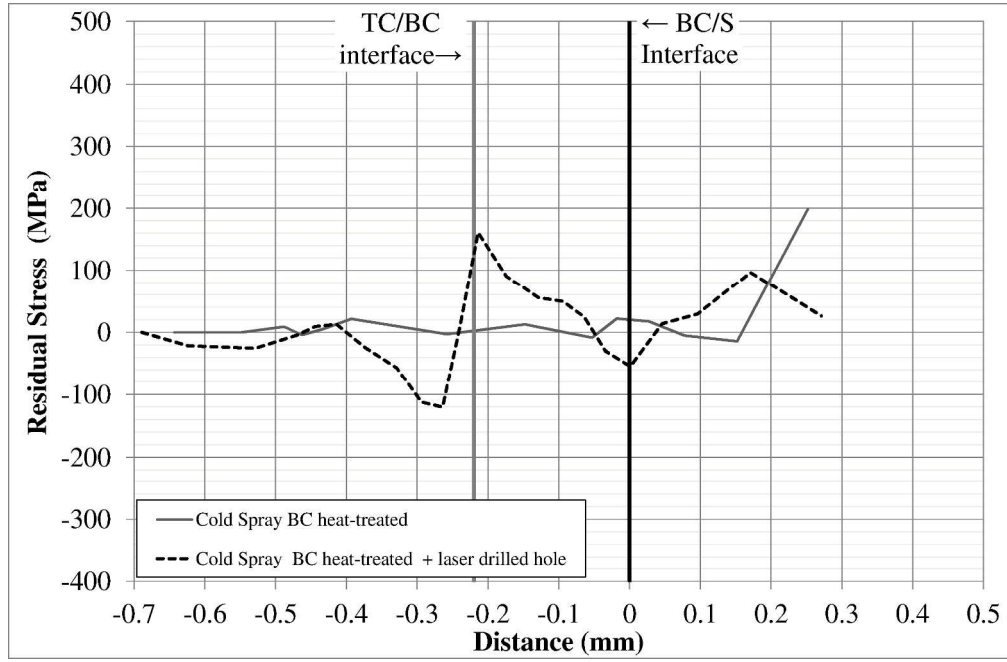
(A to D): Residual stress profiles before and after laser drilling (90° incidence) for various TBC interfaces 258x168mm (300 x 300 DPI)



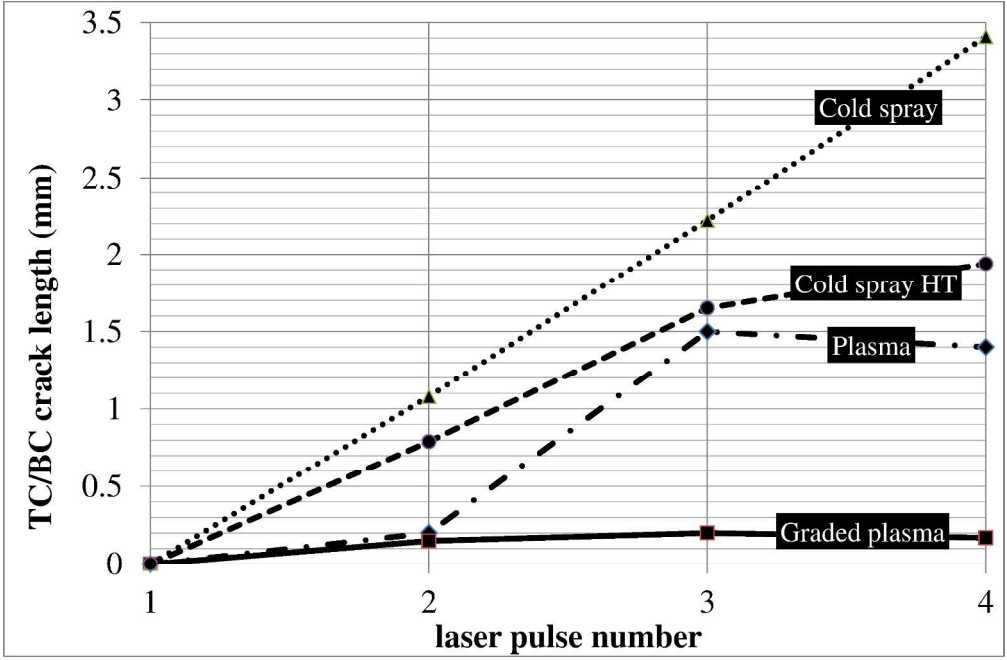
(A to D): Residual stress profiles before and after laser drilling (90° incidence) for various TBC interfaces 258x169mm (300 x 300 DPI)



(A to D): Residual stress profiles before and after laser drilling (90° incidence) for various TBC interfaces 258x168mm (300 x 300 DPI)



(A to D): Residual stress profiles before and after laser drilling (90° incidence) for various TBC interfaces 258x168mm (300 x 300 DPI)



258x169mm (300 x 300 DPI)

Table 1: Main spraying parameters for MCrAlY bond coats and YZS ceramic

PLASMA SPRAY	
Plasma gases (L/min)	Ar/H ₂ : 30/4
I (A)	500
Stand-off distance	80 mm
COLD SPRAY	
Process gas, pressure, temp.	He, 3.0MPa, 500°C
Standoff distance	41 mm
Gun traverse speed	200 mm/s
Nozzle	24TC by CGT
Incremental lateral step	1 mm
Number of passes	1
Powder feedrate	~45 g/min

Table 2: Materials data for 3D FE analysis

	Plasma BC ^[13]	Plasma graded BC ^[13]	Cold spray BC ^[14]
e ₁	0.46 mm		
E ₁	55 GPa		
v ₁	0.25		
e ₂	0.2 mm	0.26 mm	0.21 mm
E ₂	198 GPa	198→55 GPa	98 GPa
v ₂	0.3	0.3→0.25	0.3
e ₃	2 mm		
E ₃	207 GPa		
v ₃	0.3		