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TBCs ON FREE-STANDING MULTILAYER COMPONENTS

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ABSTRACT

PyroGenesis Inc. has developed a unique process for the production of components designed to operate in the hot section of gas turbines. The new process involves spray forming multilayer components by Vacuum Plasma Spraying (VPS) onto molds and subsequently separating the mold from the near net-shape free-standing component. Advanced TBCs have been developed and incorporated into the multilayer structure in an effort to extend the component's high temperature performance capabilities. The spray formed components are heat treated to improve the mechanical properties of the superalloys. PyroGenesis has used the VPS near net-shape forming process to fabricate closed components with a TBC inner layer, consisting of calcia silica (Ca_2SiO_4) and zirconia partially stabilized with yttria (PSZ), a CoNiCrAlY bond coat, and an IN-738LC outer layer. Preliminary results indicate that the spray formed components have excellent mechanical properties, can operate at much higher temperatures than similar conventionally fabricated components and require less cooling. The TBCs showed uniform thickness and microstructure with a smooth surface finish. The bond coat and structural superalloy layers were very dense with no signs of oxidation at the interface. After heat treatment, the mechanical properties of the IN-738LC compare favourably to cast materials. Finally, the cost of spray forming multilayer components is lower than the cost of conventional fabricating options.

INTRODUCTION

Combustion system components of gas turbine engines are constructed from high service temperature materials, such as ceramics and superalloys. For complex hot gas containment components, such as combustor liners and transition ducts, the current fabrication process consists of: (i) mechanically forming several sections of the component; (ii) thermal spraying the inner surface of each section to form the thermal barrier coating (TBC); (iii) welding the sections; (iv) thermal spraying the protective TBC coating on the welds, whenever possible; and (v) laser drilling thousands of small holes into the structure through which cooling air is passed, to provide for additional film cooling. Several significant problems exist with components which have been fabricated in this fashion. One problem is the inhomogeneity at the welds. Weld regions act as weak sites from which failure may initiate due to poor quality finish of both the ceramic top coat

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and metallic bond coat of the TBC. The rough surface of the TBC, inherent to this approach and particularly of the weld regions, leads to an undesirable change in flow pattern of the hot gas. Moreover, because the current fabricating process consists of mechanically forming sections of the component, there is a limitation on the choice of applicable superalloys (only superalloys with relatively high elongation can be used). Finally, the cost of drilling the thousands of small holes required for cooling is exorbitant and the use of cooling air significantly adds to the size of the compressor.

There have been numerous studies on spray forming of metals and ceramics via VPS [1, 2, 3, 4]. However, to the authors' knowledge, there has not been any published work on spray forming complex shape components with a ceramic inner layer, followed by multiple metallic layers. A closed component with an inner ceramic layer has potential applications for thermal barrier or wear protection components. In the absence of film cooling, the use of a conventional thermal barrier coating does not provide adequate insulation to protect the component. The temperature drop across conventional TBCs is approximately 120°C. In order to protect the combustion liners and transitions ducts of an advanced turbine operating without film cooling, a temperature drop across the barrier of approximately 350°C is required. Thus, both a new fabrication technique and a dramatically improved TBC is needed for the proposed application.

PyroGenesis' experience in VPS-applied zirconia based TBC systems (both top and bond coats) for gas turbine engine applications has revealed superior thermal cycling performance at a lower cost over the commonly used TBC's, where the bond coat is deposited by VPS and the top coat by APS. NASA's Marshall Space Flight Center [5] has reported a five fold increase in thermal cycling over the conventional TBC, when both the bond and top coats are applied via VPS. Furthermore, PyroGenesis has experimented with advanced TBC's which can be much thicker than conventional zirconia and offer significantly improved thermal protection.

PyroGenesis has committed itself to addressing the problems associated to current combustion system components and their fabrication method, by combining the advantages of spray forming and advanced TBCs with those of the VPS technology.

PROCESS DESCRIPTION

A suitable mold material was selected and surface machined to the inner geometry of the desired component. The mold was then cleaned and placed inside the VPS chamber, ready for service. The following unit operations were then used to fabricate multilayered combustion system components by VPS spray forming:
(i) mold preconditioning; (ii) preheating the mold to a suitable temperature and depositing the TBC layer; (iii) preheating the mold to a higher temperature and depositing the bond coat and the structural superalloy; and (iv) removing the mold from the near net-shape component. Figure 1 illustrates the process.

The design of the mold is of particular importance in the VPS spray forming process. The mold is used both to define the shape of the component and to control the energy balance of the process, a critical issue in controlling the stresses within the spray formed structure.

The mold surface was preconditioned using the plasma jet; this was a critical step which ensured proper bonding between the mold and the deposit during spray forming, yet allowed for proper detachment at the same interface upon cooling. The deposition onto the mold started with the TBC layer (up to 1.5 mm thick), followed by a CoNiCrAlY bond coat layer (150 μm), and finally reinforced with a thick IN-738LC structural layer (5 mm). Between layers the mold was preheated in an effort to minimize stresses within the deposited structure. Upon completion of the deposition step, the coated mold was cooled to room temperature in an inert atmosphere. The difference in the coefficient of thermal expansion between the mold and the deposited layers provides natural debonding to occur at this interface. Upon the removal of the mold, a near net-shape component was obtained with a uniform TBC incorporated into the inner surface.

The component was then heat treated to transform the lamellar grain structure which is typically produced by spray forming to a fine equiaxed grain structure with significantly improved mechanical properties. Finally, the heat treated component was machined to the desired shape and tolerances.

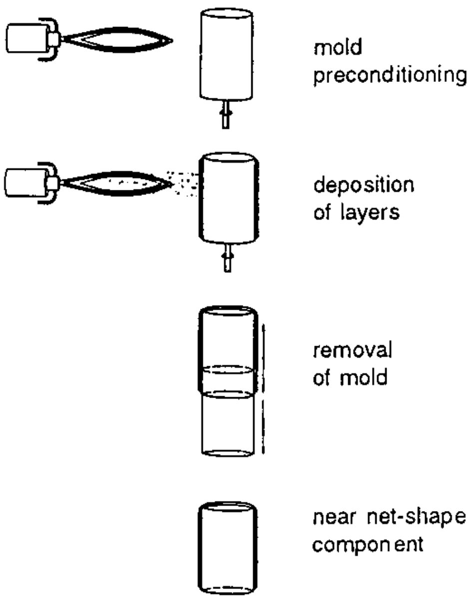

Figure 1. Schematic of VPS near net-shape forming process.

RESULTS AND DISCUSSION

Macroscopic Features. Several macroscopic features were evident on the near net-shape component. The inside surface of the component, or the top coat surface of the TBC, had a very smooth (Rz < 20 μm) surface finish which mirrored the surface finish of the mold. The component's inner geometry was slightly larger (0.6%) than the machined mold due to the slight thermal expansion experienced during processing. If required, the mold could be easily machined under final tolerance to compensate for the expansion.

Microscopic Features. The microstructure of the component cross-section is presented in Figure 2. The porosity level of the TBC top coat could be controlled, between less than 1% up to 20%, to maximize its thermal barrier characteristics and thermal shock resistance. The porosity level of the

TBC presented in Figure 2 is approximately 7%. The CoNiCrAlY bond coat and IN-738LC structural layers were applied in dense form; porosity levels were below 1% for both layers. Typical to VPS-applied metals, both of the metal layers reveal an absence of oxidation.

Figure 3 is a micrograph of IN-738LC after etching. The sprayed microstructure reveals the typical features found in as-sprayed coatings: lamellar and dendritic structures. After heat treatment the microstructure is more homogeneous, with fine grains and lower in porosity (Figure 4). The average grain size, after heat treatment, is approximately 1μm.

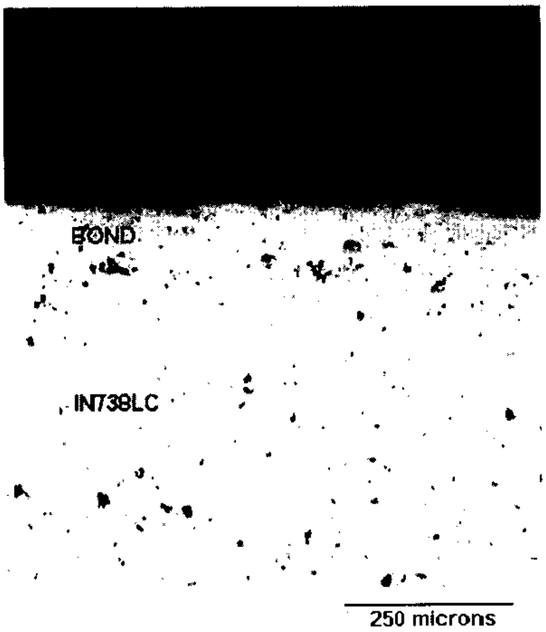

Figure 2. **Micrograph of component cross-section (unetched).**

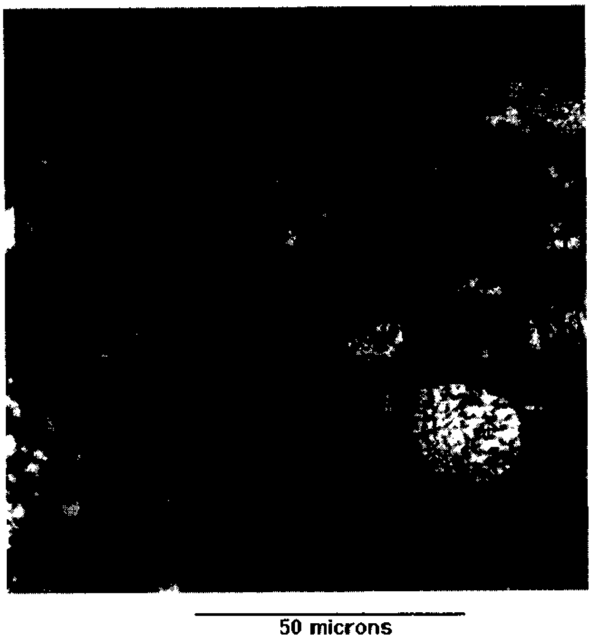

Figure 3. **Micrograph of as-sprayed IN-738LC (etched).**

Mechanical Properties. The mechanical properties of the VPS-applied IN-738LC were measured and compared to cast IN-738LC (Table 1). The as-sprayed properties of the superalloy show higher tensile strength and lower ductility, characteristic of thermally sprayed metals. After heat treatment, however, the elongation increases dramatically while maintaining high strength. In fact, the mechanical properties of the sprayed and heat treated IN-738LC are superior to those of cast IN-738LC. The tensile strength of the sprayed and heat treated superalloy remains relatively high at elevated temperatures.

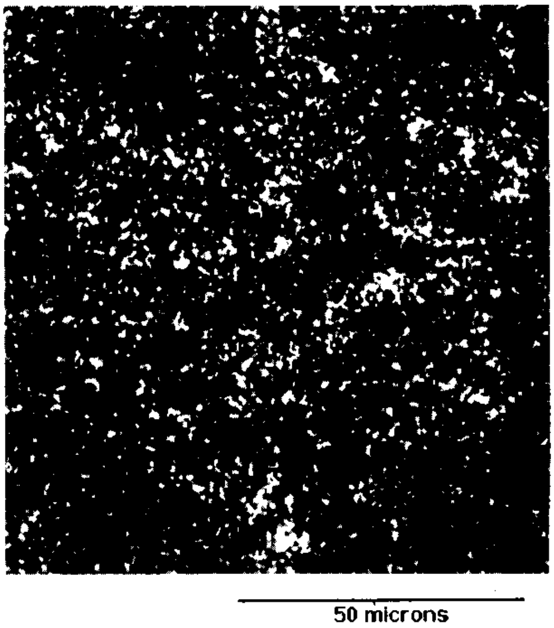

Figure 4. Micrograph of VPS-applied and heat treated IN-738LC (etched).

Table 1. Mechanical properties of VPS-applied and Cast IN-738LC.

	Cast* @RT	VPS @RT	VPS+HT @RT	VPS+HT @800°C
YS (MPa)	896	-	960±10	666
UTS (MPa)	1034	1195±12	1161±13	752
Elong. (%)	9	0.6±0.2	9.5±0.5	-
Hard (HV)	-	338±72	352±12	-

* from technical data published by INCO Inc.

TBC Development. A number of TBC options were considered for the envisioned application. The target was to create a TBC thick enough to offer a ΔT of 350°C. The thickness of the TBC depends on the thermal conductivity, and therefore, composition and morphology, of the TBC. Table 2 shows the theoretical thickness required for three TBC options.

Table 2. TBC Options for 350°C ΔT

Material	k (W/m K)	Thickness
PSZ	0.8	0.7 mm
Al_2O_3	6	4.9 mm
Ca_2SiO_4	1.7	1.4 mm

While PSZ offers the lowest thermal conductivity, a durable 700 μm monolithic PSZ layer is unlikely. Our experience suggests that PSZ layers thicker than 300 μm are susceptible to cracking and delamination either during spraying or upon thermal cycling. Pure alumina is also not suitable due to its relatively high thermal conductivity.

Following a preliminary screening of 12 TBC options, two compositions were identified for further testing: (i) a MCrAlY/PSZ graded and laminated structure; and (ii) a PSZ/Ca_2SiO_4 graded structure. The two selected TBC options were sprayed onto flat coupons and tested for thermal shock resistance, thermal cycling, and oxidation at 1100°C.

A microstructure of the as sprayed MCrAlY/PSZ TBC is shown in Figure 5. The MCrAlY used in this study is AMDRY

995 (CoNiCrAlY). While the thermal shock test (heating to 1,100°C and rapidly quenching in water) showed satisfactory results for this TBC option, the oxidation tests proved that graded MCrAlY layers oxidize very rapidly above 900°C. A microstructure of the TBC after 25 hrs in air at 1,100°C is shown in Figure 6. Under these conditions the coating expands in volume and delaminates. Based on this catastrophic failure, no thermal cycling tests were performed for this option.

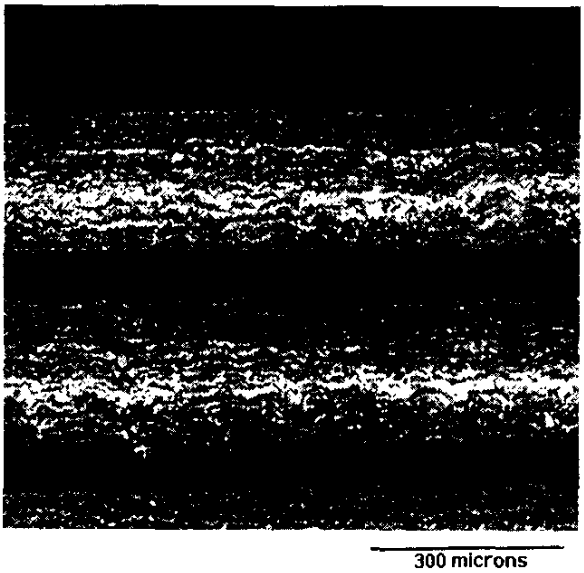

Figure 5. Micrograph of as-sprayed graded and laminated MCrAlY/PSZ TBC.

The PSZ/Ca_2SiO_4 TBC consisted of a 200-300 μm layer of PSZ followed by a 300-650 μm PSZ/Ca_2SiO_4 graded layer and a 300-1,000 μm layer of Ca_2SiO_4. A typical micrograph of this TBC option is shown in Figure 7. This option showed excellent resistance to thermal shock and minimal weight gain due to oxidation at temperatures as high as 1,300°C.

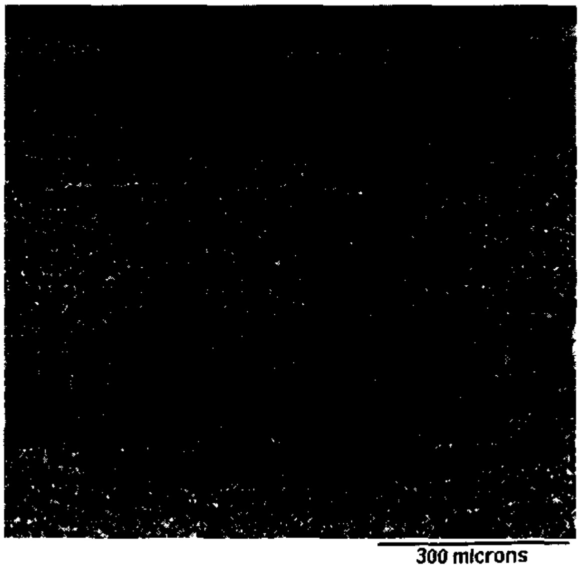

Figure 6. Micrograph of MCrAlY/PSZ TBC after 25 hrs oxidation at 1,100°C.

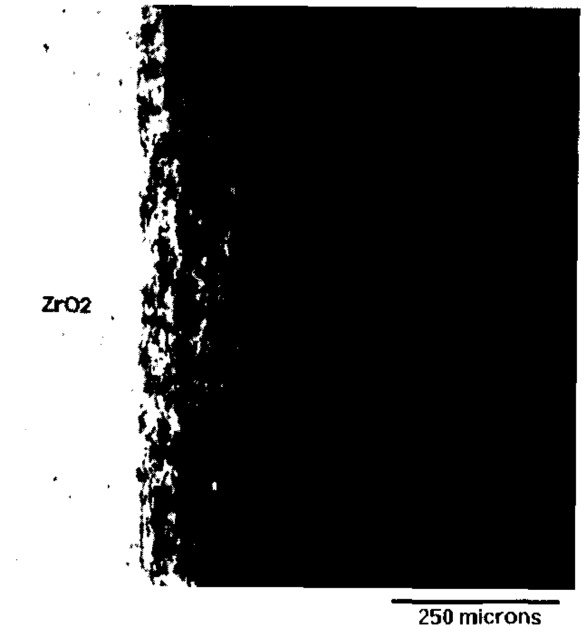

Figure 7. Micrograph of as sprayed PSZ/Ca_2SiO_4 TBC.

Thermal cycling was performed on the PSZ/Ca_2SiO_4 TBC by heating flat coupons to 1,100°C with an oxyacetylene torch and cooling rapidly with compressed air. Following 300 cycles no delamination was observed.

A number of PSZ/Ca_2SiO_4 TBCs were produced on flat stainless steel substrates and tested for their thermal barrier properties. The test was performed by heating the TBC face with two high intensity infrared lamps and measuring the temperature of both the hot TBC surface and the cooler stainless steel surface. A list of the samples evaluated in this study is shown in Table 3.

Table 3. PSZ/Ca_2SiO_4 Samples Tested for Thermal Conductivity.

Sample	Average Thickness (μm)		
	PSZ	Graded	Ca_2SiO_4
Z-10	245		
C-4			559
ZC-7	238	303	317
ZC-3	308	330	650
ZC-10	210	424	455
ZC-6A	225	584	303
ZC-9	248	655	921

Sample Z-10 represents a conventional PSZ TBC sprayed by VPS. Sample ZC-9 represents a TBC which theoretically should provide a ΔT in excess of 350°C and thus meet the performance requirements for advanced combustion liners and transition ducts without film cooling.

The results from the thermal conductivity study are presented in Figure 8. Figure 8 shows that the ΔT between the hot and cold faces of a uncoated stainless steel coupon is approximately 200°C when the hot phase reaches 1,000°C. By comparison, a conventional PSZ TBC structure offers a ΔT of 275°C (Sample Z-10). Under the same operating condition an advanced 1.8 mm thick PSZ/Ca_2SiO_4 TBC offers a ΔT of approximately 420°C (Sample ZC-9). Thus, the thermal barrier properties of the PSZ/Ca_2SiO_4 developed in this study can be almost 3x better than a conventional TBC, which should be sufficient to meet the requirements of the proposed application.

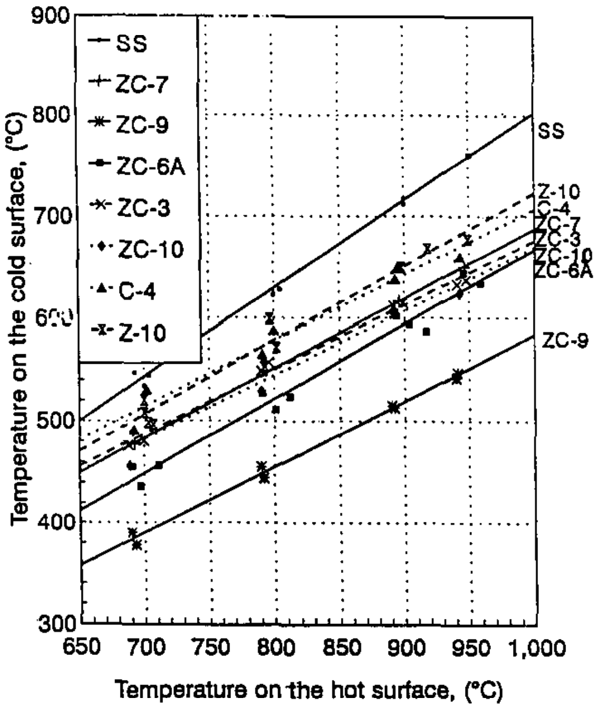

Figure 8. Thermal properties of PSZ/Ca_2SiO_4 advanced TBCs.

SUMMARY

The feasibility of VPS near net-shape forming multilayered free-standing components has been demonstrated. This innovative fabrication process was used to produce a combustion system component of a gas turbine engine. The improved qualities of VPS near net-shape formed combustion system component include: (i) an advanced TBC capable of offering ΔT in the order of 350°C; (ii) a superior high-temperature structural superalloy; (iii) smoother inner TBC surface; (iv) no irregularities (welds) within the component; (v) excellent mechanical properties; and (vi) consistent reproducibility. The cost of fabricating the components using the VPS net-shape forming technology is significantly lower than conventional methods. Furthermore, it is hoped that the need for film cooling can be eliminated.

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