Segmented 8% YSZ thermal barrier coating solutions using cascaded arc gun technology

Robust thermal protection for the hot section of gas turbine engines continues to develop as engine thermal efficiency increases. Segmented thermal barrier coatings (TBCs) exhibit better thermal cycle behavior and improved erosion resistance over conventional TBCs. Coating solutions using Oerlikon Metco's cascaded arc spray guns and high quality, plasma densified 8% yttria-stabilized zirconium oxide materials not only meet design requirements, but provide excellent benefits in terms of coating reproducibility, repeatability and application cost efficiency.

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Introduction

Gas turbines are Carnot-cycle heat engines. This means their thermal efficiency and core power is directly related to the gas temperature entering the turbine section of the engine as shown in Fig. 1. For this reason, improvements to the cooling and thermal protection systems of turbine hot section components have been a major contributor to the success of gas turbine engines. The thermal protection of components is achieved with a so-called thermal barrier coating (TBC) system that is typically comprised of an oxidation-resistant metallic bond coat on top of which a ceramic with low thermal conductivity — mostly zirconia-based — is deposited. Today, TBCs are critical design elements in gas turbines, and because the gas temperatures of modern designs exceed the melting point of the underlying metal parts [Fig. 1], any TBC failure can endanger the entire engine.

Globally gas turbine engines are a US$ 78 billion industry in 2016 [1] with 70% used for aviation applications (turbofan, turboshaft, turboprop and APU engines) and 30% for land-based applications (mechanical drive and power generation). The latter produce approximately 26% of the global electricity demand while the former accounts for almost 100% of the propulsion power of large commercial and military aircraft.

Increases in the energy efficiency of gas turbines engines that increase the electricity output of land-based models or the the thrust-to-weight ratio and durability of jet engines, have and will continue to rely on developments in TBCs.

Segmented Thermal Barrier Coatings

The first applications of TBCs were on stationary engine components. In the late 1980s, TBCs were first used on rotating blades. This application requires maximized strain tolerance of the TBC, which is typically achieved with a special architecture of the ceramic top coat that can be summarized as vertical segmentation. Vertical segmentation, in general, can take different forms as shown in Fig 2. One form is vertical column segmentation which is achieved by creating a columnar build-up of the ceramic TBC material either by growth from the gas phase in an EB-PVD or PS-PVD process or by cluster deposition via, for example, so-called suspension plasma spray (SPS). Columnar segmentation via the EB-PVD process is the preferred method of applying TBCs on the rotor blades of jet engines.

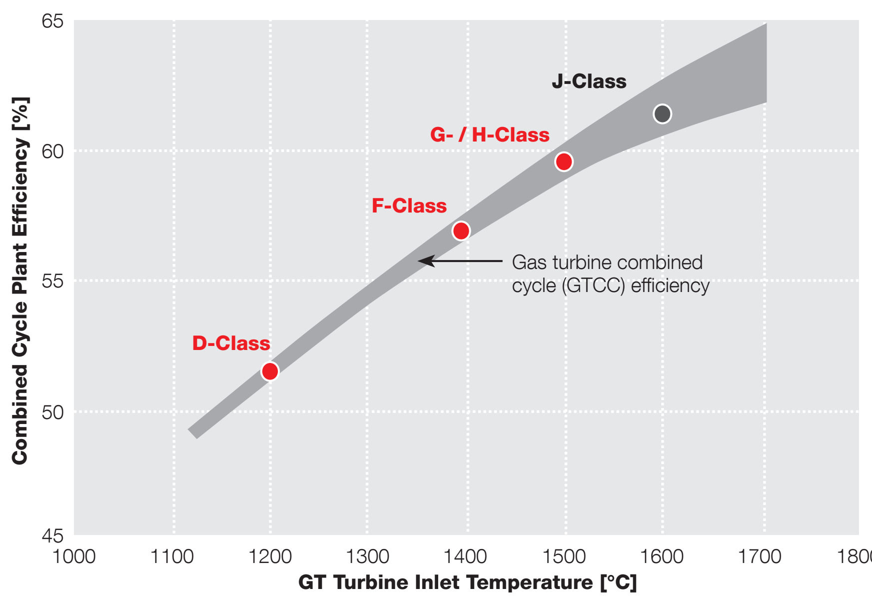
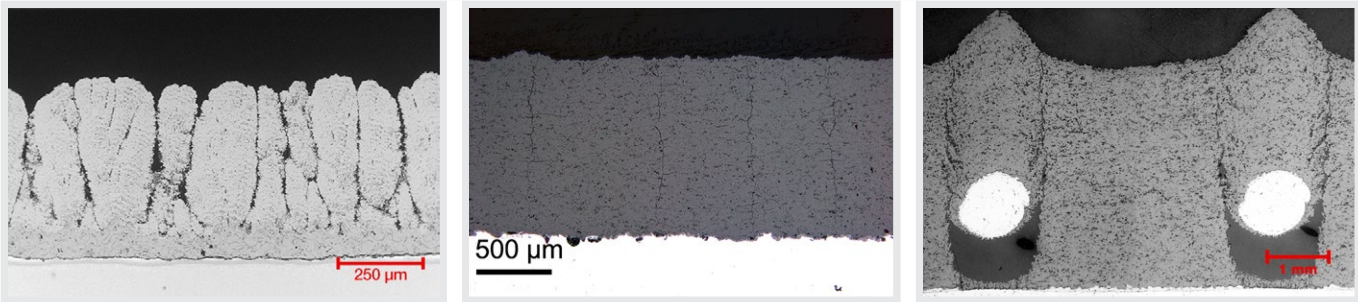


Fig. 1: Dependency of the overall efficiency of combined cycle power plants on the temperature of the gas entering the turbine module of the gas turbine engine.

Vertical column segmentation	Vertical crack segmentation: inherent cracking	Vertical crack segmentation: surface texture / structure induced cracking

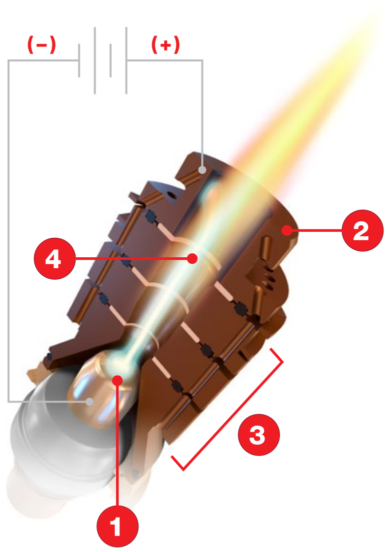


Spacing of vertical segmentation: **15 to 150 µm**; nucleation rate or surface roughness controlled	Spacing of vertical segmentation: **100 to 750 µm**; spray parameter controlled	Spacing of vertical segmentation: **500 to several thousand µm**; geometrical design controlled

Plasma Processes:

PS-PVD SPS (cascaded)	APS (cascaded) SPS (cascaded)	APS (conventional or cascaded)

Fig. 2: Segmented thermal barrier coatings produced at Oerlikon Metco by various plasma spray processes including APS and SPS with cascaded arc technology.



1. (–) Cathode: point of arc emission
2. (+) Anode: point of arc attachment
3. Neutrodes: electrically isolated
4. Constrained arc path
   - Increases voltage
   - Creates a defined arc
   - Significantly lowers voltage instabilities

Fig. 3: Cascaded arc design of a plasma gun arc chamber.

Further shown in Fig. 2 is another form of segmentation is vertical crack segmentation (also know as dense vertically cracked). This type of segmentation is achieved by atmospheric plasma spraying the ceramic top coat through control of the spray parameters (inherent cracking) or by deposition of the ceramic over a 3D-structured surface, for example a cast or a weld-deposited grid (surface structure induced cracking). Crack segmented coatings are one of the standards for rotor blades of power generation gas turbines. Another standard is non-segmented TBCs with a controlled (high) presence of porosity and micro-cracks.

The segmentation of the ceramic thermal barrier coating is an ideal tool to improve the strain tolerance of the coatings. The segments open during tensile loading of the component surface and close during compressive loading, similar to the behavior of a concertina's bellows.

This paper will review a few aspects of the production and performance of crack segmented thermal barrier coatings produced with cascaded arc plasma gun technology.

Cascaded Arc Gun Technology

The cascaded plasma approach was pioneered by Metco to control and stabilize the arc voltage. The cascaded arc chamber is characterized by fixing the length of the arc over a series of electrically isolated neutral rings, so-called neutrodes, within the arc chamber [Fig. 3]. The extended and fixed arc length has the advantage of stabilizing the plasma plume and eliminating high amplitude power oscillations. This results in a number of important benefits, namely a higher voltage, lower amperage operation, reduced voltage oscillation and the elimination of the influence of gas flow and type on the arc behavior.

Fig. 3 shows the cascaded arc chamber for a single cathode plasma gun design (SinplexPro gun). In contrast, the TriplexPro gun

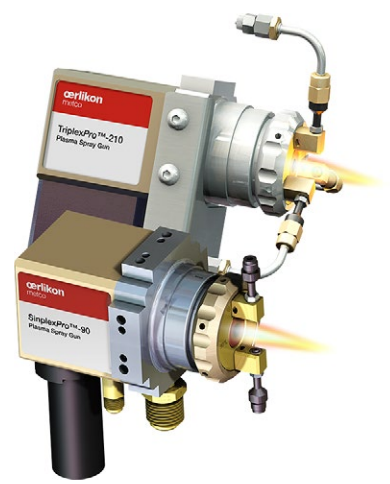


Fig. 4: Cascaded Arc Guns, TriplexPro and SinplexPro, as used in this study to produce segmented TBCs.

divides the total gun current over three electrodes. This further improves the coating process through more uniform and efficient heating of the plasma gas and spray material, less erosion of the anode at the arc attachment points and a better definition of the locations of the arc attachments. The three arcs operating at higher overall voltage have the advantage of very stable gun operation over extended periods of time. Fig. 4 shows the two cascaded arc guns used in this study.

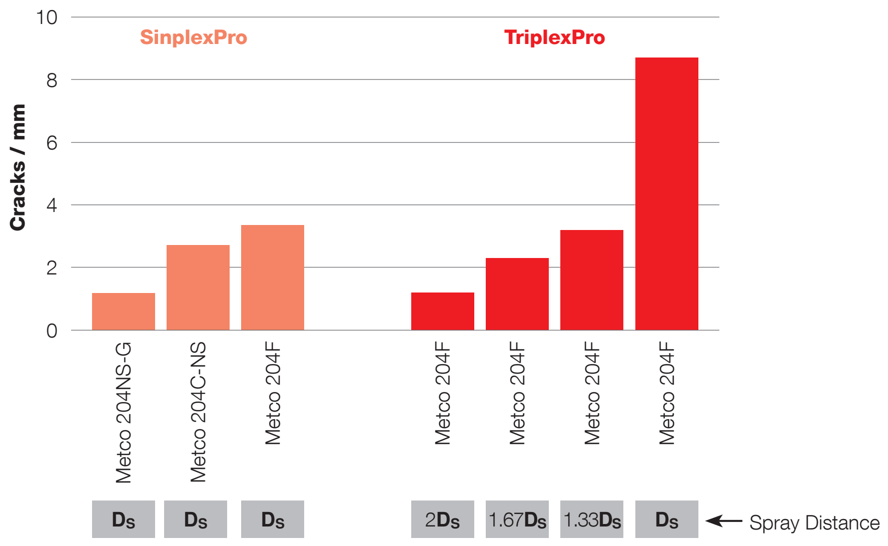


Fig.5: Crack densities of TBC materials sprayed with SinplexPro and TriplexPro using varied gun settings and spray distances.

Coatings with Segmentation Cracking –Manufactured using Cascaded Arc APS

For one aspect of this study, TBCs were produced that had an Amdry 995C bond coat and varied top coats made from Oerlikon Metco plasma densified 7 – 8 wt% yttria-stabilized zirconia powders (8% YSZ) powders. The coatings were sprayed using varied spray settings such as plasma enthalpy, feed rate and spray distance.

For the coatings sprayed with SinplexPro, the gun power was kept constant at a moderate 45 kW and a gun-to-work spray distance, denoted as "D_S" for this study. The variable was the thermal spray material. Three standard 8% YSZ materials were used as shown in Table 1.

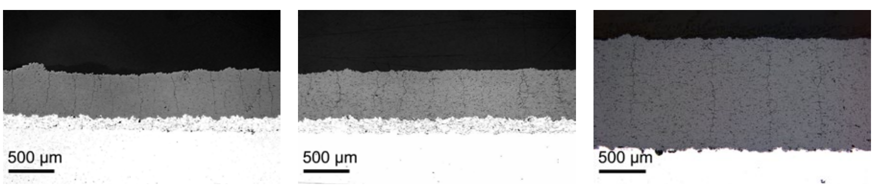
Product	**D50** [µm]	**Nominal Size** [µm]
Metco 204F	20 to 30	-45 +15
Metco 204NS-G	50 to 57	-140 +45
Metco 204C-NS	68 to 77	-140 +45

Table 1: Oerlikon Metco 8% YSZ materials used for this study.

Fig. 5 shows the crack density for the coatings achieved. The density of cracks in the coatings range from 1.2 to 3.4 vertical cracks / mm of coating length with the highest crack density achieved for the Metco 204F powder, which has the finest powder particle size. Remarkably, even the Metco 204C-NS, having the coarsest powder particle size, could be turned into a coating with a good crack density of 2.7 cracks / mm and a deposition efficiency of 64% when sprayed at spray distance D_S and with a powder feed rate of 40 g/min. This compares favorably to TBC coatings with vertical crack segmentation as described by Guo, Murakami and Kuroda [2] where a coating with a maximum crack density of approximately 4 cracks / mm was achieved at 41 kW gun power, a spray distance of 60 mm and a feed rate of only 20 g/min.

For coatings sprayed with TriplexPro-210, the material was fixed as Metco 204F [Fig. 5] and plasma enthalpy and gun stand-off distance were varied to produce coatings of 500 µm and 1000 µm coating thickness. Fig. 4 clearly shows that the highest crack density is achieved with the shortest gun stand-off distance. This confirms results [2] where it was demonstrated that for other fixed spray parameters the temperature of the metal substrate onto which the coating is sprayed plays a decisive role in the formation of segmentation cracks in such a way that the highest number of cracks per unit length was found for the highest substrate temperature. This corresponds well with the shortest spray distances producing the highest crack density.

Other than the gun stand-off, the plasma enthalpy also plays an important role in the evolution of the microstructure of segmented TBCs. At a given stand-off distance and powder feed rate, high enthalpy spraying produces a rather dense coating with a high crack density [Fig. 6]. Lowering the plasma enthalpy reduces the crack density, but increases the achievable coating porosity. Increased porosity can be a desirable feature even for a TBC coating with crack segmentation as increased porosity reduces the thermal conductivity of the coating. Increasing the feed rate reduces the crack density further but can significantly improve the economics of depositing thick TBCs with crack segmentation [Fig. 6]. Extremely high powder feed rates of up to 150 g/min have been demonstrated with TriplexPro and Metco 204F powder.



Plasma enthalpy	21.903 kJ/kg	18.162 kJ/kg	18.162 kJ/kg
Feed rate	45 g/min	45 g/min	150 g/min
Spray distance	1.33D_S	1.33D_S	1.33D_S
DE	59%	47%	not reported
Crack density	3.2/mm	2.2/mm	1.7/mm
Porosity	1.8%	7%	not reported

Fig.6: Thermal barrier coatings with segmentation cracking produced with TriplexPro-210 gun at various spray settings.

YSZ top coat	Top coat characteristic	2000 cycles at T_1	7000 cycles at T_1	7000 cycles at T_1 + 1000 cycles at T_1 + 200 °C
Metco 204F	High segmentation crack density	✓	✓	✓
	Medium crack density	✓	✓	✗
	Low crack density	✓	✓	✗
	Porous and segmentation cracks	✓	✓	✗
Reference YSZ	Porous	✗		

Table 2: Results of cyclic burner rig testing of 8 YSZ segmented TBCs. Coatings have a thickness of 1 mm. ✓ = pass; ✗ = fail.

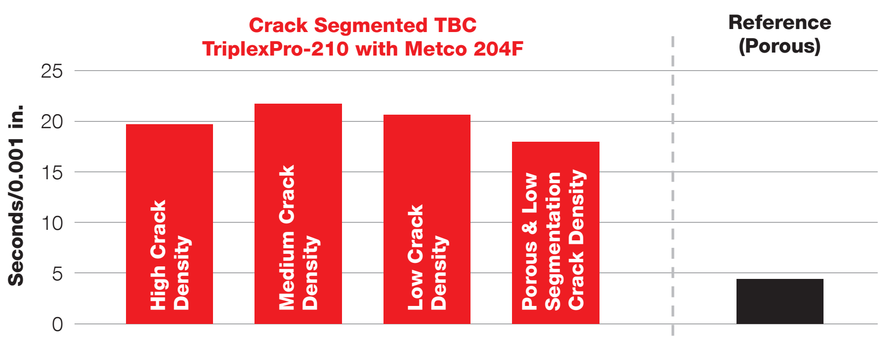


Fig. 7: Performance of segmented and porous 8% YSZ (Metco 204F) thermal barrier coatings in solid particle erosion test in accordance with E50TF121 / ASTM G76. Coatings are 1 mm thick.

From the results of the burner rig tests shown in Table 2, it becomes evident that the segmented coatings outperform the porous reference coating and that within the segmented TBCs, the coating with the highest crack density performed the best. At the same time, the segmented TBC coatings showed a much higher erosion resistance than the porous APS reference coating [Fig. 7]. Altogether, the crack segmented coatings provide a significant improvement in performance over the porous baseline coating. In addition, the cascaded arc gun technology applies these segmented coatings very economically.

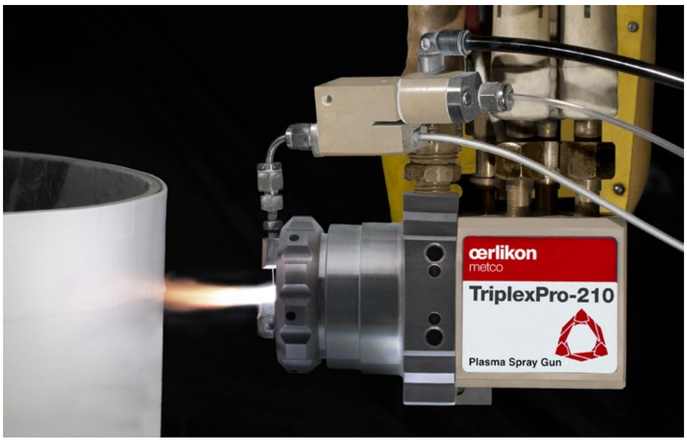
Coatings with Segmentation Cracking – Coating Performance

In order to assess the performance of segmented TBCs produced via conventional APS with cascaded arc gun technology, coatings with varied densities of segmentation cracks and porosity levels were tested against a standard APS porous reference coating in erosion and cyclic burner rig testing.

High (3.3/mm), medium (2.3/mm) and low (1.5/mm) levels of crack densities and one coating with low (2.2/mm) crack density but increased porosity were produced using the TriplexPro-210 cascaded gun by varying the spray distance and plasma enthalpy.

Coatings with Segmentation Cracking - Manufacture using Cascaded Arc Suspension Plasma Spray

Apart from conventional atmospheric plasma spray (APS), suspension plasma spray (SPS) can also be used to manufacture segmented TBCs. Suspension plasma spray makes use of fine sub-micron powder particles that are fed to the spray gun in the form of a suspension of ceramic and liquid



- Submicron-sized powders can be fed via suspensions
- Achievable structure regimes range from highly porous to segmentation cracked to columnar or can take mixed forms
- Cascaded plasma technology (TriplexPro-210) provides an excellent gun platform for SPS

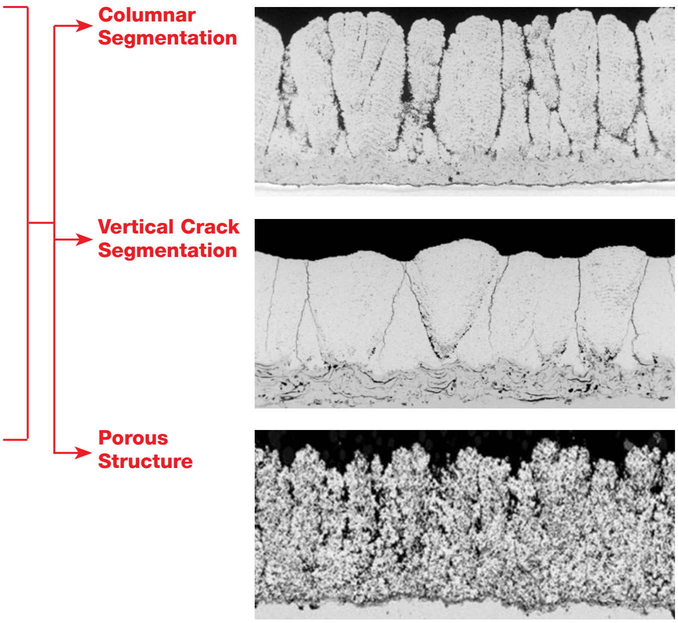


Fig. 8: Structure regimes of Thermal Barrier Coatings produced with suspension plasma spray using TriplexPro cascaded arc gun technology.

(usually ethanol). In the case of SPS, the segmentation can be in the form of cracks or columns as shown in Fig. 8, which shows the structure regimes possible with the SPS process and using the TriplexPro-210 gun.

Summary and Conclusions

Cascaded arc plasma gun technology provides the advantage of most uniformly heating and melting the zirconia powder materials used in manufacture of thermal barrier coatings (TBCs) for application in the hot section of gas turbine engines. This can be used to manufacture segmented TBCs that have improved cyclic life and erosion resistance compared to conventional porous TBCs.

Cascaded arc gun technology has significant advantages in producing segmented TBCs with conventional APS. High powder feed rates can be used when spraying segmented TBCs with SinplexPro and TriplexPro. In addition, good deposition efficiencies are being achieved with these guns. The combination of these characteristics provides for a very economical, fast and efficient production method of segmented TBCs. In addition the cascaded arc process is very stable which guarantees for high repeatability and coating quality consistency.

In this paper, the influence of larger stand-off distances and various size cuts of zirconia powder materials on the resulting coating microstructure, in particular the density of segmentation cracks in the coating, has been investigated. It was shown that spray distances of up to $2D_S$ still produced segmented structures with TriplexPro. These larger stand-off distances help the gun manipulation and robot programming for spraying complex parts such as turbine blades and vanes.

For SinplexPro, it was demonstrated that various powder cuts, including rather coarse powder (Metco 204C-NS), can be used to produce segmented TBCs at moderate gun power settings. The generated data allows for a range of gun and powder combinations to be envisaged for the manufacture of segmented TBCs.

Further, cascaded arc technology has also been demonstrated to be an excellent platform to produce segmented TBCs with the suspension plasma spray (SPS) process.

Thermal spray system layouts are available from Oerlikon Metco which define a standard spray cell that accomodates all necessary elements needed to produce segmented TBC systems.

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Keywords

APS, atmospheric plasma spray, cascaded arc, columnar segmented coating, dense vertically cracked, erosion resistance, gas turbine, hot section coating, inherent cracking, structure induced cracking, segmented coating, suspension plasma spray, TBC, thermal barrier coating, thermal cycling, vertical column segmentation, vertical crack segmentation, yttria-stabilized zirconia

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