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Thermal Spray Manufacturing Issues in Coating IGT Hot Section Components

P. Sahoo, T. Carr, R. Martin, and F. Dinh

The desire to improve the performance of gas turbine engines has led to higher operating temperatures in the turbine sections of the engine. Materials used for hot section turbine blades and vanes are not resistant to hot corrosion, and therefore require protective coatings. This paper reviews the current art and technology of thermally sprayed MCrAlY and TB coatings onto hot section components. The issues in applying such coatings will be discussed, along with references to manufacturing issues on the shop floor. The difficulties inherent in applying a line-of-sight coating to complex geometries will be discussed. The testing, evaluation, and performance characteristics of typical coatings are discussed.

Keywords coatings, hot sections components, manufacturing, MCrAlY, TBC, thermal spray

The demand for higher energy efficiencies from aerospace and utility gas turbines has required closer internal tolerances, higher rotational speeds, and higher turbine inlet temperatures. To cope with the higher temperatures and speeds, new high-strength, high-temperature alloys have been used in the gas turbine. Today, however, advanced directionally solidified (DS) and single-crystal (SC) alloys are currently operating near their strength limits, and alloy development has reached a point of diminishing returns. Improved coatings are needed to realize the full potential of new DS and SC alloys. Along with stand-alone overlay coatings, the use of thermal barrier coatings (TBCs) is becoming increasingly important (Ref 1).

Background

Westinghouse's experience in land-based gas turbines began in 1945 with the development of a 2000 hp gas turbine generator set designated W21 (Ref 2). Table 1 summarizes the development of various generations of turbines. It can be seen that over the decades the rotor inlet temperature (RIT) has increased significantly.

Coatings

Westinghouse uses a variety of coatings, both as overlay and bond coats for TBC. A summary of the coatings and processes currently used in the hot-section components is given in Table 2.

The selection of coatings is based on several factors, primarily, service conditions the coating has to withstand and the economic attributes of cost of application and ease of application. Traditionally, coatings specified for a particular application are based on years of laboratory and field testing. Normally, several coatings are tested at the same time to determine the most beneficial. Such a "rainbow test" is fairly common when evaluating the same coating from various vendors or when making various types of coatings under a set of test conditions.

Once a coating has been selected for production qualification, a set of acceptance criteria is established. Such a specification covers the entire gamut of processing steps, from raw materials approval through coating, and final finishing procedures prior to shipping.

The primary requirement is obviously meeting the coating quality and proving reproducibility and repeatability. The coating quality includes both the microstructural features and the thickness distribution on the coated surface. The thickness distribution is dictated by aerodynamic and design constraints concomitant with manufacturing feasibility. The coating quality, as previously mentioned, is based on prior testing and evaluation.

For example, consider a vane segment that requires a thermal barrier coating. This would comprise a MCrAlY bond coat and a ceramic top coat. Figure 1 indicates the typical locations for

Table 1 Summary of gas turbine development at Westinghouse Electric Corporation

Generation/Type	Rating, MW	Rotor inlet temperature, °C	Year operational
First/W21	1.3	677	1949
Second/W81	5.5	732	1952
Third/W251, W501	20, 42	857, 879	1967, 1968
Fourth/W251B/W501B	31/80	986/993	1971/1973
Fifth/W501F	160	1260	1993

Table 2 Summary of coating types and application processes used by Westinghouse

Coating description	Type	Application process(a)
ATD-61	Co33Ni 21Cr8Al03Y	EB-PVD
RT-22	PWA 273 (Al)	Pack
Co-211	CoNiCrAlY	LPPS
Thermal barrier	Bond coat + TBC ceramic coat (CoNiCrAlY + YSZ)	Thermal spray
RT-44	Pt + Rh/Al	Galvanic/Pack

(a) EB-PVD, electron beam—plasma vapor deposited; LPPS, low-pressure plasma spray

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test specimens. Although not listed in Fig. 1, the desired coating distribution for both the bond coat and top coat should be the same at all locations. Thermal spray application is a line-of-sight coating application process. Thus, the areas to be coated must be directly accessible to the spray apparatus. The rate of coating deposition is also dependent on the angle of impact of the spray

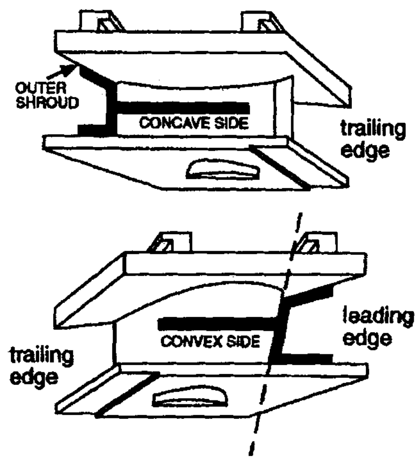

Fig. 1 Simulator test vane indicating location of test tabs for coating trials

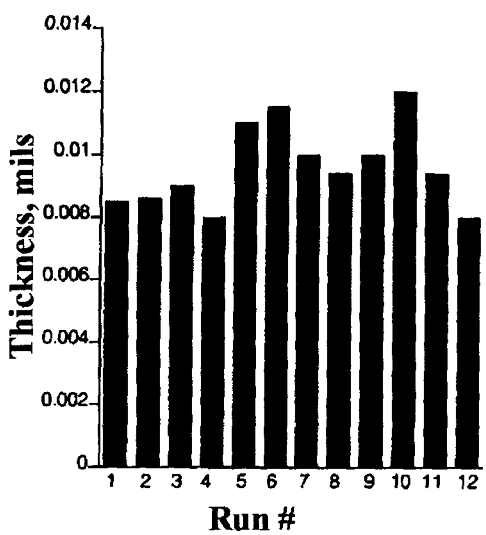

Fig. 2 Coating thickness distribution over twelve runs

jet. Given the highly contoured surfaces of a vane, the angle of impact changes as the spray nozzle travels across the part.

In addition, the presence of cooling holes and their alignment with respect to the airfoil surface sometimes makes it desirable to spray at an acute angle. The complexities that arise from such part-to-gun manipulation leads to nonuniform coating quality and coating thickness distribution. For a TBC system, a desired quality level for the bond coat and top coat on the airfoil section would represent the values given in Table 3.

Table 3 summarizes the primary factors associated with accepting a two-layer TBC coating system. These values are general requirements followed by most gas turbine users. The actual values in the specification will depend on the customer. Most gas turbine original equipment manufacturers (OEMs) have similar acceptance criteria, although each specific property requirement will vary depending on individual service conditions and use experience. In order to meet these criteria, an automated spray system must be used to coat these parts. In addition, recoating of service-run parts adds variance to the processing due to part geometry variability. The factors that contribute to coating variability on a component are:

- Part-to-part variability (component variance)
- Variability in gun-to-part manipulation (automation variances)
- Coating process variability (coating variance)

Other factors, such as finishing, may also impart the final coating characteristic. However, for producing repeatable coating using an automated spray, these three factors must be combined.

The first factor is based on existing design allowances. For instance, redesign of existing blade or vane segment cooling hole configurations or location results in modification to the existing coating process. This is necessary because restriction of

Table 3 Summary of TBC acceptance factors

Property	Bond coat	Top coat
Porosity	1 to 6%	10 to 15%
Interface	10 to 25%	...
Unmelts	1 to 5%	<5%
Oxides	<1.5%	...
Cracks	None acceptable	Customer specified
Thickness	0.004 to 0.014	0.010 to 0.015
Roughness	Metallographic standards	Finish to drawing

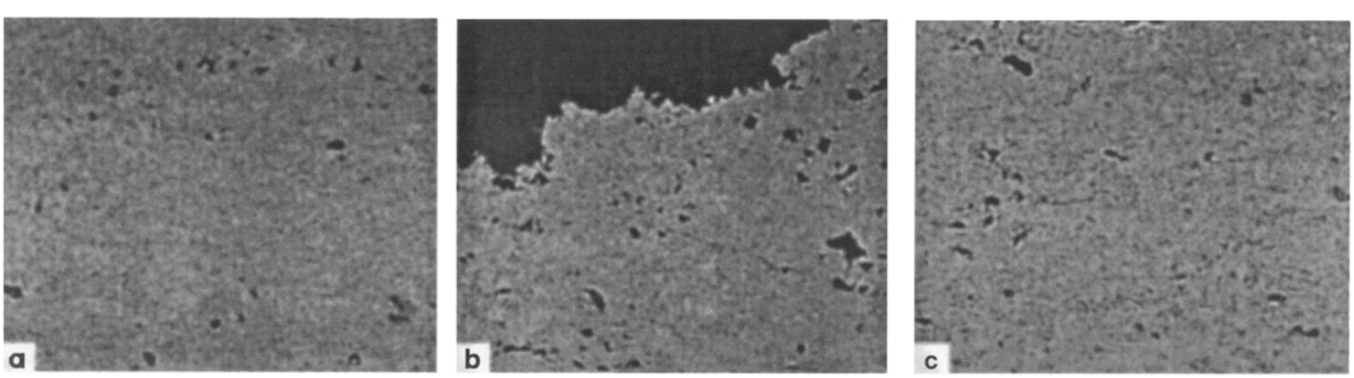

Fig. 3 Microstructures of MCrAlY coating quality on blade (a) and (b) and vane segment (c) at various locations

holes results in insufficient cooling airflow, thus resulting in component overheating.

The second factor is dependent on the manipulation equipment. Based on the complex movements the spray nozzle has to make, the repeatability of various movements can vary from 0.025 to 0.64 mm (0.001 to 0.025 in.). Although this may be viewed as fairly tight, it must be remembered that at fairly long spray distances, a small variance in the angle can result in a large movement of the impacting coating powder.

The third factor has to do with the variability inherent in the spray process itself. Typically, the factors that contribute to variability in the coating application process are numerous. They include, but are not limited to:

- Lot-to-lot variance in powder (shape, morphology, and size distribution)
- Variability in process parameters (mass flow of gases, cooling, fuel-to-oxygen ratio, etc.)
- Operation reproducibility

Given all these inherent problems, keeping the coating quality within specification can only be achieved through rigorous statistical process control (SPC). The application process must be made robust enough to take such process variations into account. Sermatech has followed a path in which a design-of-experiment approach has proven beneficial. In such an approach, a first screening run of many factors at two levels is run. In designing the experiment, the number of runs is kept to a minimum. Subsequent to the first screening run, several runs at multiple levels of the factors optimize the application process. Finally, a statistically significant number of runs are conducted to estimate the process capability.

Figure 2 indicates the repeatability of the coating thickness over 12 runs. The thicknesses were determined at the fillet radius of a W501 R1 vane segment. This location is typically the area most difficult to spray in terms of obtaining a uniform coating profile. From Fig. 2 it is seen that the coating thickness varies between 0.20 and 0.30 mm (0.008 and 0.012 in.). Given the complexity of such a part, this repeatability is considered exceptional.

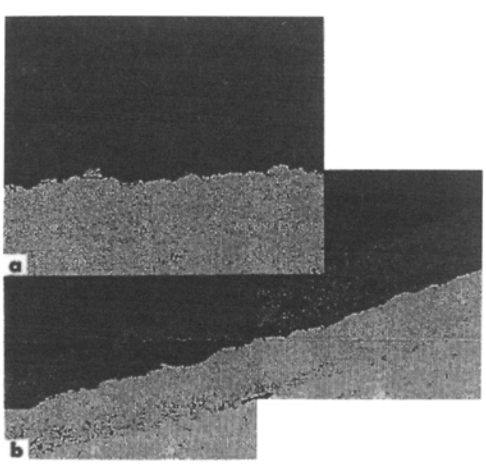

Fig. 4 Microstructures of MCrAlY and TBC on airfoil (a) and fillet radius regions of a vane segment (b)

Figures 3(a) to (c) indicate typical microstructures observed on a blade and vane at various locations. It can be seen from Fig. 3(a) and (b) that the quality of the MCrAlY coating (in items of density and oxide level) is better on the airfoil section, as opposed to the fillet region. This relates back to the previous discussion on coating quality variance. Using a line-of-sight process, such as a HVOF gun, the curvature at the fillet radius introduces the additional complexity of the angle of incidence of the spray jet. Although it is preferred that the path movements be programmed to spray the part at a normal angle at all locations, it is not always possible. Based on production needs and requirements, the acceptable quality at hard-to-spray areas must be relaxed slightly.

In going from an easily accessible airfoil on a blade to the airfoil in a vane, the spray process encounters further complexities. Because of the structure of the vane with its inner and outer buttresses, the path movement is somewhat more constrained relative to a blade. This is further compounded in those vanes that have multiple airfoils. This can adversely affect the quality of the coating. As shown in Fig. 3(c), the MCrAlY coating on a W501 R1 single vane contains slightly more oxides compared to the blade.

Based on Sermatech's work with Westinghouse, some intermediate results on TBC coating development is presented with a view to showing the problems associated with coating a complex geometry. Fig. 4(a) and (b) indicate the bond coat + top coat structure on the airfoil and fillet region of a W501 R1 vane segment, respectively. These are from test tabs located at those regions and not actual vane cutups. It is obvious that under ordinary spray conditions, the structure of the airfoil location is much more uniform compared to a location in the fillet area. Fig. 4(b) shows that the structure of both coats could change substantially with location. Going from the left of the micrograph (fillet radius) to the right (airfoil), the density and microstructure of both coats improve. This is due to the fact that the spray process was optimized at a normal angle (airfoil spray) and not at acute angles (fillet radius). Process modifications are being continuously improved to alleviate such problems.

Conclusions

Field experience gathered by Westinghouse indicates that applying a uniform coating across all gas path areas of a complex part is not feasible. Although improvements in part-to-gun manipulation are being incorporated, the specifications for coating acceptance reflect the difficulties encountered under manufacturing conditions. However, it has been demonstrated that , by using appropriately designed statistical techniques, a robust spray process can be developed to minimize variations in coating quality and distribution across various coated sections. In spite of the difficulty, these MCrAlY and TBC coatings are necessary to enhance the performance of gas turbines.

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