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Increased Reliability of Gas Turbine Components by Robust Coatings Manufacturing

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Abstract The expanding operational windows of the advanced gas turbine components demand increasing performance capability from protective coating systems. This demand has led to the development of novel multi-functional, multi-materials coating system architectures over the last years. In addition, the increasing dependency of components exposed to extreme environment on protective coatings results in more severe penalties, in case of a coating system failure. This emphasizes that reliability and consistency of protective coating systems are equally important to their superior performance. By means of examples, this paper describes the effects of scatter in the material properties resulting from manufacturing variations on coating life predictions. A strong foundation in process-property-performance correlations as well as regular monitoring and control of the coating process is essential for robust and well-controlled coating process. Proprietary and/or commercially available diagnostic tools can help in achieving these goals, but their usage in industrial setting is still limited. Various key contributors to process variability are briefly discussed along with the limitations of existing process and product control methods. Other aspects that are important for product reliability and consistency in serial manufacturing as well as advanced testing methodologies to simplify and enhance product inspection and improve objectivity are briefly described.

Keywords advanced testing methodologies · gas turbine coatings · process control · reliability · thermal spray coatings

Introduction

The increasing global energy requirements and environmental regulations require increasing power and efficiency of the gas turbine engines and reduced emissions. Increasing efficiency and reducing emissions of gas turbine engines are largely achieved by increasing the firing temperature and reducing cooling air and leakage losses. Even the most advanced metallic systems cannot operate at these temperatures. Therefore, coatings have become an integral part of many IGT materials systems, contributing several key functions such as thermal and oxidation protection, and clearance control. A typical thermal barrier coating (TBC) system consists of a metallic (MCrAlY) bond-coat and ceramic (8YSZ) top coat layer. Increasing temperature capability requirements in GT engines have led to the development of several new TBC systems including new compositions for ceramic top coat and bond-coat and innovative coating architectures. The advancements in ceramic topcoat include use of increased amount of yttria, use of other rare earths (REs), combinations of multiple REs, other dopants/stabilizers, other material classes such as pyrochlores (zirconates), orthophosphates, spinels, garnets and perovskites (Ref 1-4). Viswanathan (Ref 5) discusses a comprehensive overview of coatings traditionally used for oxidation and corrosion protection. An overview of the functionalities of metallic coatings for oxidation and corrosion protections is also available in Ref 6.

These novel systems are aimed at meeting the harsher operating conditions and increasing service interval expectations of modern gas turbine engines. As a consequence of the harsher operating conditions in modern gas turbine engines, the TBC surface temperatures and thermal gradients through TBC thickness are much higher, implying more severe penalties, in case of a coating system

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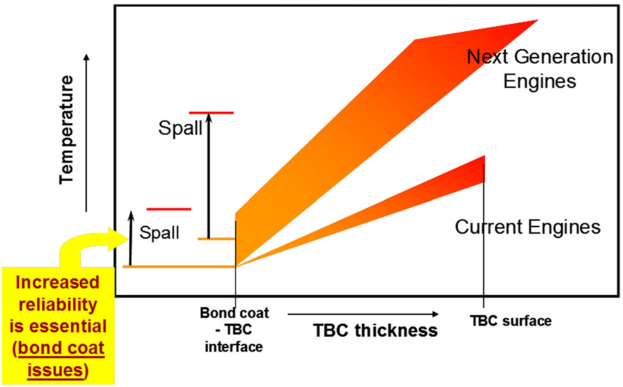


Fig. 1 Schematic showing the comparison of gradients in existing engines vs. those expected in advanced engines

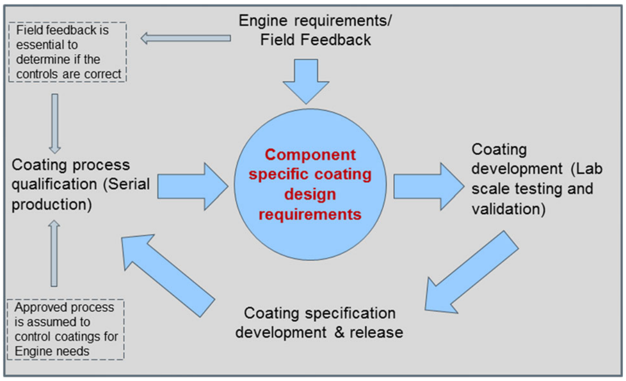


Fig. 2 Typical new coating system development lifecycle

failure. Figure 1 demonstrates this schematically by comparing the TBC spallation events in current and advanced component designs. The substrate temperature increases only slightly for current component designs that allow the components to survive till the next inspection interval for a part replacement or refurbishment. This is significantly different in the case of advanced component designs, where a TBC spallation event will result in a huge increase in substrate temperatures, which could consequently lead to immediate component degradation. This emphasizes that for advanced turbine engine components, reliability and consistency of protective coating systems are equally important to their superior performance. Reduced scatter in manufacturing-related material properties is also required for reliable predictions of coating lives and risk of failure. Therefore, a systematic approach in understanding the process-microstructure-property correlations as well as methodologies to monitor and control an established process are essential for consistent and reliable coating manufacturing.

Typical Lifecycle of Coating Development

A typical lifecycle of a new coating system development (Fig. 2) starts with the development of optimized coating microstructures which results from several iterations of process parameter development efforts. A number of process parameter sets are applied to obtain samples with the desired coating characteristics such as porosity, thickness and surface roughness, which are examined post-spray via standard metallographic techniques. Selected samples with presumed optimal and non-optimal microstructures are then examined by extensive laboratory and rig testing to produce statistically significant results. The testing involves measurements of mechanical and physical properties (e.g., fracture toughness, thermal conductivity) of individual coating system components as well as the testing of cyclic lives of full coating system (e.g., furnace cycle testing and burner rig testing). The outcome of this extensive testing yields the broader (level one) specification limits for the ideal coating system. Process parameters down-selected from the above exercise can then be used to apply coatings to engine parts for validation though engine tests. The results of engine tests yield further refinement and finalization of the specification limits. The resultant specification is then used by the coating spray booths to develop qualified processes. These processes then are used to supply components to be inserted into the engine/s. Field feedback is the ultimate test that over a sufficient number of parts and sufficient period of time yields valuable information about how well the coating process is controlled and in some cases may call for even further refinement of the specification limits. Indeed, the gas turbine engine coating development is a long and tedious process with several intermediate steps and its success very much depends on the strong feedback between the different links as well as adaptability to the required changes.

At all stages of coating process development, the understanding of the interplay of process, microstructure and property is critical. Coating properties are governed by the microstructural variables which in turn results from the coating process parameters. As an example, the burner rig test results on one of Siemens' proprietary coating systems in Fig. 3 show the significant debit on TBC systems lives when coating porosity and thickness is deliberately changed to be out of specification. Similarly, Nowak et al. (Ref 7) have investigated the effect of processing parameters on MCrAlY bond-coat roughness and consequent lifetime of APS-TBC systems. They found that the thermal cyclic lifetime of the APS-TBC system with two-layer HVO-F + APS bond-coat is significantly higher than that of the system with HVOF bond-coat alone and have attributed this to an improved bond-coat roughness profile. They have also noticed that the lifetime of the APS-TBC system with two-layer HVOF + APS bond-coat is sensitive to process

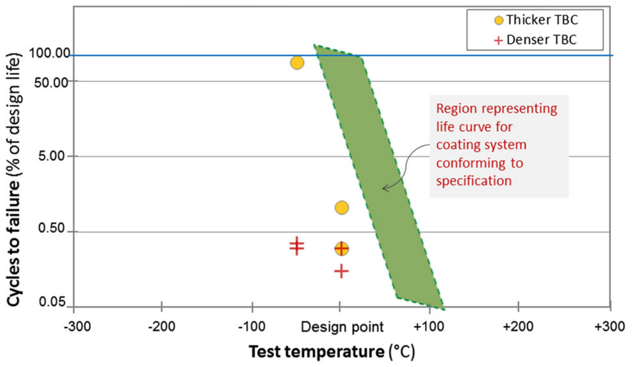


Fig. 3 Burner rig thermal gradient cyclic test results

parameters and consequent microstructure of the thin APS “flash” layer.

Numerous publications from universities, research institutes and industry dedicated to this subject are available in open literature. In particular, Center for Thermal Spray Research at the Stony Brook University has come up with integrated approaches for examining the variabilities in the various sub-processes and instrumentation, while simultaneously considering the interactions among the sub-processes. The so-called method of process mapping (Ref 8-11) strives to correlate the process parameter such as gun current, primary and secondary plasma gas flows, powder feed rate and spray distances to resulting particle states, namely thermal and kinetic energies of particles (first-order process maps), which is related to the resulting coating microstructures (second-order process maps) and finally to the physical and functional properties (performance) of the coating. A multitude of diagnostic sensors are used in the spray booth to capture information on spray stream and evolution of mechanical properties of the coatings. This understanding of process-microstructure-property from process mapping approaches is necessary for robust process design for coating development. The same sensors can be employed for process monitoring and control in production environment.

Significance of Process Reliability Relative to Design Uncertainties

As the engine conditions become more demanding for coatings, the need for more life scatter reduction and reliable coating life predictions becomes imminent. TBC failure/time to spallation is, among other things, driven by bond-coat temperature; therefore, coating life depends upon scatter in temperature which in its turn depends upon the scatter in the both material properties resulting from manufacturing variations as well as the operational and design-related boundary conditions.

The typical values of scatter in heat transfer coefficients and hot gas temperature for gas turbine components are component and OEM specific, and these should be compared with manufacturing process reliability scatter (thicknesses and thermal conductivities) (Ref 12). Monte Carlo simulations provide an insight into the relative importance of design versus materials uncertainties. Bond-coat temperature variations can be calculated using a simple 1D component heat transfer model. It was concluded that depending upon design uncertainties, coatings uncertainties (thermal conductivity and thickness) can have varying levels of impact on bond-coat temperatures, and consequently the component ability to meet lifetime requirements.

ANOVA-based sensitivity study of the metal temperature to the variations of the model’s input parameters shows that life scatter is largely governed by scatter in material properties (see Pareto chart in Fig. 4), when design uncertainties are minimal, implying that reducing variations in manufacturing is paramount for the life scatter reduction and for the accurate coating life prediction. Similar results are reported in other investigations (Ref 13).

Figure 5(a) shows an example of a poorly controlled process from vendor A based on the as-sprayed TBC thicknesses measured on the same location of a number of parts. In contrast, the as-sprayed TBC thicknesses measurements shown in Fig 5(b) represent an example of a well-controlled process from vendor B with a Gaussian distribution of thicknesses.

For the component with low design uncertainties, similar Monte Carlo simulation now including thickness scatter from the poorly controlled and well-controlled processes and the resulting life distribution for TGO growth driven failure was calculated. Subsequently empirical cumulative distributions in Fig. 6 depict the significant increase in probability of failure for the poorly controlled process.

All finished parts from vendor A conform to the TBC thickness specification. However, there is a significant cost of quality associated with this process. Because of poor process control, vendor A needs to perform thickness check on many more parts per order than vendor B. As a result, TBC thicknesses that are out of specification are reworked either by additional spraying, grinding of excess thickness or by strip and recoat. These additional steps increase process cost. The other, more subtle consequence of this uncontrolled process requires understanding of process-microstructure-property correlations.

As discussed in the previous section, thickness variations on a component can be monitored on part-by-part basis on many different components, by using nondestructive measurement approaches as such as eddy current measurements, 3D scanning technologies. This allows

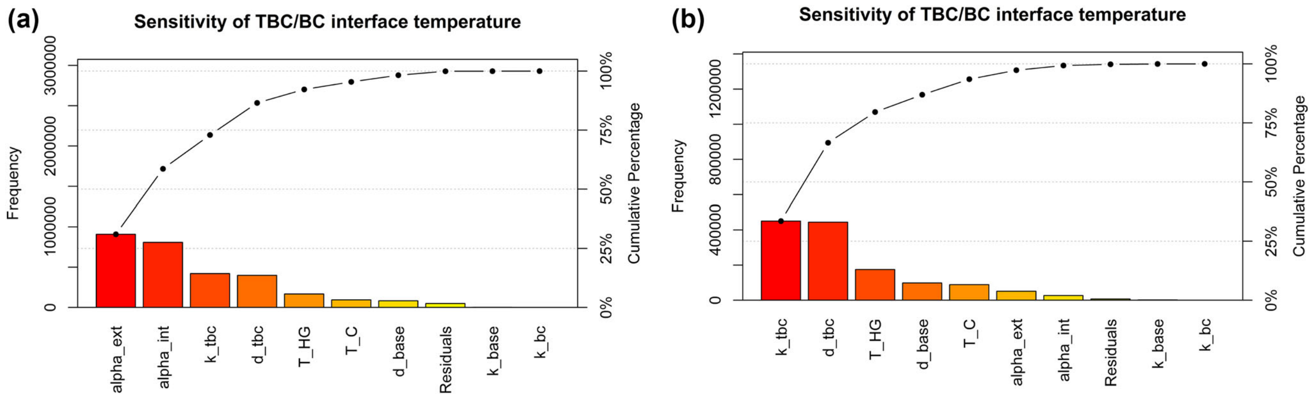


Fig. 4 Sensitivity of interface temperature may be dominated by design uncertainties (a) or by manufacturing-related scatter in material properties depending upon component (b)

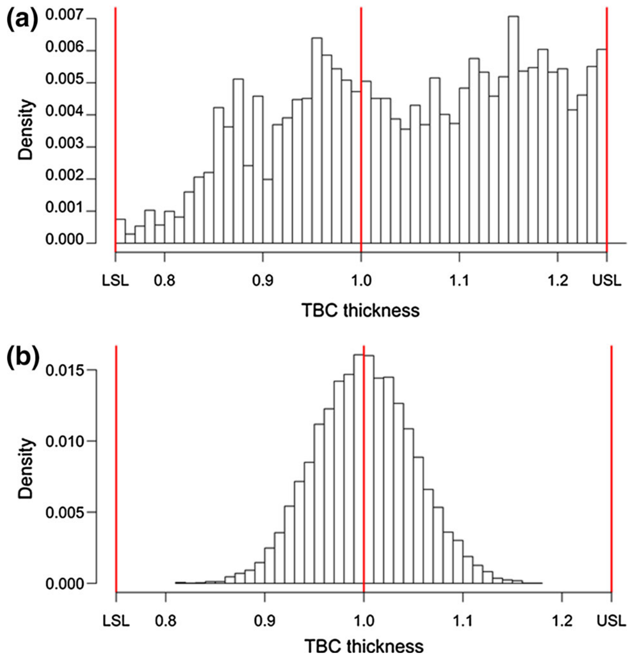


Fig. 5 Example of a poorly controlled process (a) and a well-controlled process (b). The vertical red lines represent the specification limits

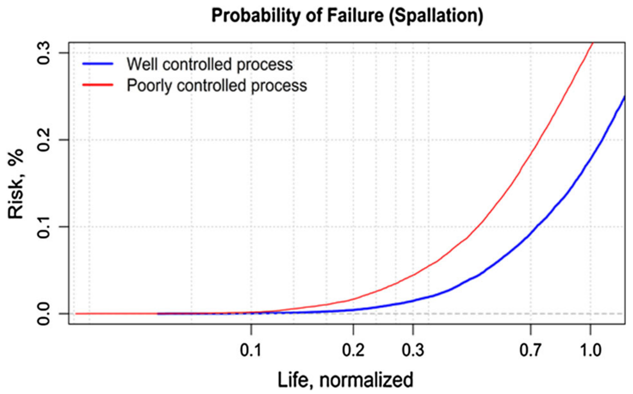


Fig. 6 Effect of manufacturing scatter (in Fig. 5) on life prediction for well-controlled process and poorly controlled processes

collection of data across many vendors and components. However, variation in coating physical properties (such as thermal conductivity and/or porosity), directly on the part, is not available, in a production process. This means that coating's physical properties (such as thermal conductivity) are likely to vary and may not meet design requirements. The implication is that, with an uncontrolled process, even when one specification requirement (e.g., thickness) is artificially brought within the spec (via reworking), it may still not be sufficient. Additional inspections may be needed to ensure other requirements (e.g., porosity) are also met, to avoid serious potential consequences such as field failure. As discussed in earlier sections of this paper, with coatings becoming prime-reliant, coating failure in the field has much severe penalties. Therefore, an uncontrolled/poorly controlled process has both immediate- and long-term costs of quality. What can be done to an uncontrolled process of Fig. 5(a) to transform it to a controlled process of Fig. 5(b)?

Factors Influencing Coating Quality and Reliability

The key to consistent and reliable coating performance is the robustness and control of the coating process. Thermal spray coating process can be influenced by a large number of intrinsic and extrinsic factors. Within the same location (i.e., in a single booth), the process variation from one day to another can occur due to the factors like intrinsic variability of the process (Ref 14), hardware degradation and changes in environment (e.g., humidity). Process variations from one location to another (different booths in the same or different locations) can be caused by factors like different booth configurations, booth calibrations, spray guns, hose lengths, feedstock material, as well as environmental factors. The latter is the reason why direct transfer of spray parameters from one location to another does not automatically produce conforming coatings. Some of these contributors to overall process and coating quality and reliability are described briefly in the following.

On-component NDE approaches for coating properties are not yet possible in production. Hence, as a first step, monitoring the deposition process characteristics provides a basis to control the coating quality on a gas turbine component. This section represents some of the NDE techniques to monitor the deposition processes. In addition, best practices such as tighter powder specification and gun operation are necessary for improved repeatability of the deposition process.

Feedstock Material

Powders used in TBC applications can be produced through different manufacturing processes. For instance, commercially available ceramic yttria-stabilized zirconia (YSZ) powder is produced by plasma fusion of yttria and zirconia agglomerates resulting in the so-called HOSP™ (hollow sphere) morphology, fusing yttria and zirconia and then crushing resulting in dense, angular shaped particles of morphology and agglomerating (spray drying) and sintering processes. Each of these processes results in different morphologies, densities and chemical purity levels which in turn affect the coating process and microstructure. As noted by Allen et al. (Ref 15), several studies have shown that the feedstock material may play a more important role than do subtleties in the thermal spray parameters. Even if the powder particle size distribution (PSD) is kept constant, the morphologies and densities affect the powder feeding, injection into the plume and melting characteristics of particles. Powder PSD is another critical and more well-known factor influencing the coating quality. It is important to understand how a powder manufacturer defines a given particle size range (e.g., 45-125 μm) and what fraction of the powder particles lies outside of the specified range. Well-written specifications defining the full PSD for desired powder can certainly improve powder injection characteristics and hence batch-to-batch variations in deposit efficiency and microstructures and reduce issues such as dust/excess oxidation of metallic powders, clogging or unmelts.

Particle States and Plume Characteristics

Traditionally, process control has been implemented by keeping the input spray parameters at predetermined optimum values. However, as Moreau and Leblanc have noted, controlling the process via manipulation of input process parameters is difficult because of the interplay of a number of variables and is insufficient as it does not capture conditions such as electrode wear state, voltage fluctuations, or changes in particle injection characteristics (Ref 16). These uncontrolled variables can lead to significant changes in the resulting the coating properties. In this regard, in-flight particle diagnostics allow a more direct and simplified approach for process assessment and control (Ref 17-19). Commercially available spray stream sensors provide process thermal and kinetic characteristics via individual particle measurements (e.g., Tecnar DPV 2000) as well as through ensemble measurements methods (e.g., AccuraSpray, Spray Watch). Fincke et al. have discussed the inherent strengths and limitations of particle temperature measurement methods (Ref 20). By offering the capability to assess the spray stream characteristics, these sensors allow direct assessment of the effects of combined changes in input variables as well as process sensitivity to individual parameter changes. The same capability can be used for assessing process variabilities, both inherent and those resulting from hardware degradation. Thus, particle state sensors can be very useful tools for process control and coating reliability.

Other Process Parameters

While particle states and plume characteristics play critical role, the final coating microstructure and properties are also influenced by other process parameters. These parameters include the spray angle, robot speed and trajectory, substrate temperature, and surface roughness and can play increasingly important role depending upon the geometry of the part being coated. Some of these characteristics can be monitored with the in situ/ex situ coating properties (ICP/ECP) sensors as will be described in the following section.

While the use of sensors is gradually becoming widespread, the obstacles for simple and robust process control for real-time feedback during production, and still need to be addressed. Often the tools that generate sufficient data to drive the decision-making process are too complicated for daily production control use. Tools that can be simply applied as a production control method often need a second source of information to identify the right parameters to rectify an out of control condition.

To enable a uniform coating thickness, offline programming with thickness calculation is very effective. In addition to the actual variations in the process and the resulting variations in the coating microstructure and properties, the intrinsic and extrinsic variations in the measurement of properties like thickness, porosity and thermal conductivities are also important. Issues pertaining to this aspect of variability as well as methods to overcome these are discussed in the next section.

Advanced Methodologies for Controlling Coating Features Critical to Quality (CTQ)

For a given set of operating conditions, the TBC spallation resistance is a complex function of part geometry, TBC thickness, thermal conductivity, strain compliance and adhesion to the substrate, arising from appropriate bond-coat roughness. Therefore, at the process level, control of TBC microstructure, thickness, surface roughness and interface quality of various interfaces is critical to TBC quality and consistency. Conventional quality control methods such as the bond cap tensile strength and hardness test have been valuable, yet have their own limitations. For example, tensile bond strength test has high variability in terms of failure modes within the same group of samples. For porous coatings, the results of this test may also be influenced by the type of adhesive used. Similarly hardness testing, which is a relatively more consistent and valuable tool for coating quality assessment, still in most cases, is as an indirect measure of the tribological performance of coating systems. More importantly, several critical attributes of coating quality mentioned above are determined by destructive metallographic evaluation of the microstructure of witness coupons or in some cases, real components. However, the variation from polishing procedures and the subjective nature of subsequent assessment of microstructure is widely recognized. Furthermore, the destructive metallography of actual parts is not realistic as a control during serial production. Therefore, the correlation of microstructure from test pieces to real parts in most cases is still only and inferred one and not direct. Some of the improvements to overcome these shortcomings are suggested below:

Offline Programming and 3D Scanning Method for Uniform Coating Thickness Deposition

The traditional "Teach-in" programming approach involves adjusting the spray program (spray parameters, robot trajectory, etc.) to achieve the required coating thickness and structure which is based on the TBC thickness measurement or metallographic assessment on tabs mounted on the predetermined locations on the scrap part is time consuming and costly and provides limited information (e.g., due to limited number of discretely located tabs, location accessibility constraint, etc.). For complex parts like airfoils, a parameter change to adjust thickness in a certain location might cause undesirable change in another location. This can lead to an endless loop of repeated trials and can consume significant booth time during coating qualification. To this end, offline programming (OLP) when combined with a thickness determination add on can be utilized to drive significant reduction in qualification time and costs, particularly for parts with complex geometries. For a given set of spray parameters, OLP software simulates the total coating thickness as a sum of thickness buildup from individual passes. Figure 7 shows the principle of coating thickness simulation in offline programming and comparison with the metallographically determined thickness. The key advantage of utilizing OLP is the ability to determine the effects of several simultaneous changes in spray parameters on the coating thickness profile over the entire part without using any feedstock materials, booth hardware and more significantly, production booth time. Three-dimensional scanning method (Fig. 8) employs blue light scanning of the part to be coated, and the coating thickness is determined from the difference between the profile heights before and after spraying. This is a nondestructive method of on-part coating thickness measurement. The method allows for all areas to be assessed for thickness including the areas where robot program sections stitch together and tight radii and thus offers benefits over point or tab location assessments which are limited in their coverage. One flip-side of this method is that it may not yield satisfactory results if the component gets distorted during spraying.

Automated Image Analysis Software for Porosity Measurements

Part of the variability in the current microstructural assessment arises from the manual "thresholding" in the standard image analysis techniques. Siemens has developed proprietary software that automatically determines the unique grayscale threshold by superimposing the histograms from the original image and an image processed obtained by local smoothing (Fig. 9). Automating the thresholding process has potential to eliminate operator dependency and associated variations The downside of this method is that it still requires sample sectioning and cannot eliminate mounting/polishing artifacts (insufficient epoxy impregnation, inadequate polishing and pullouts, etc.) and is somewhat dependent on the quality of the image obtained with a given microscope/camera system. Despite these limitations, this method provides a good stepping stone for more consistent porosity measurement across the various laboratories.

Optical 3D Profilometry for Base Alloy and BC Roughness Measurement

It is a nondestructive and contactless method which is more appropriate tool for control in industrial environment due to its faster speed and compatibility of with historical tactile results. The optical method allows output of digital profile that can be analyzed by commercially available

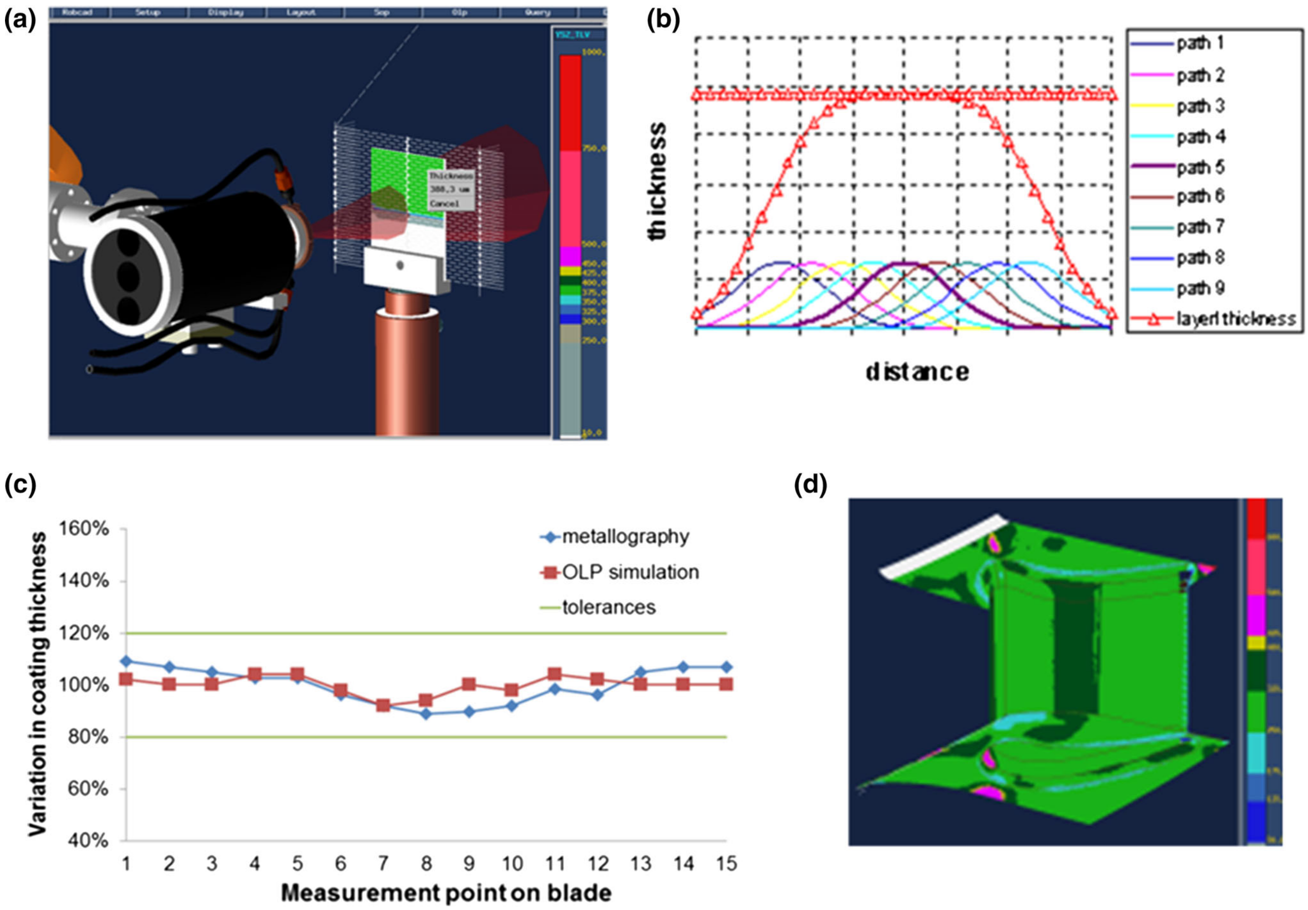


Fig. 7 Coating thickness simulation in offline programming: (a, b) simulation of coating thickness accumulation by application of raster spray pattern, (c) comparison of simulated and measured thickness results for airfoil section of the test component (d) coated with plasma sprayed 8YSZ

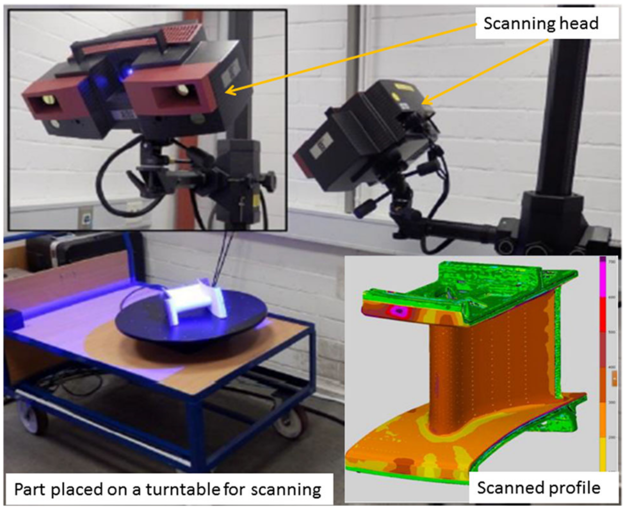
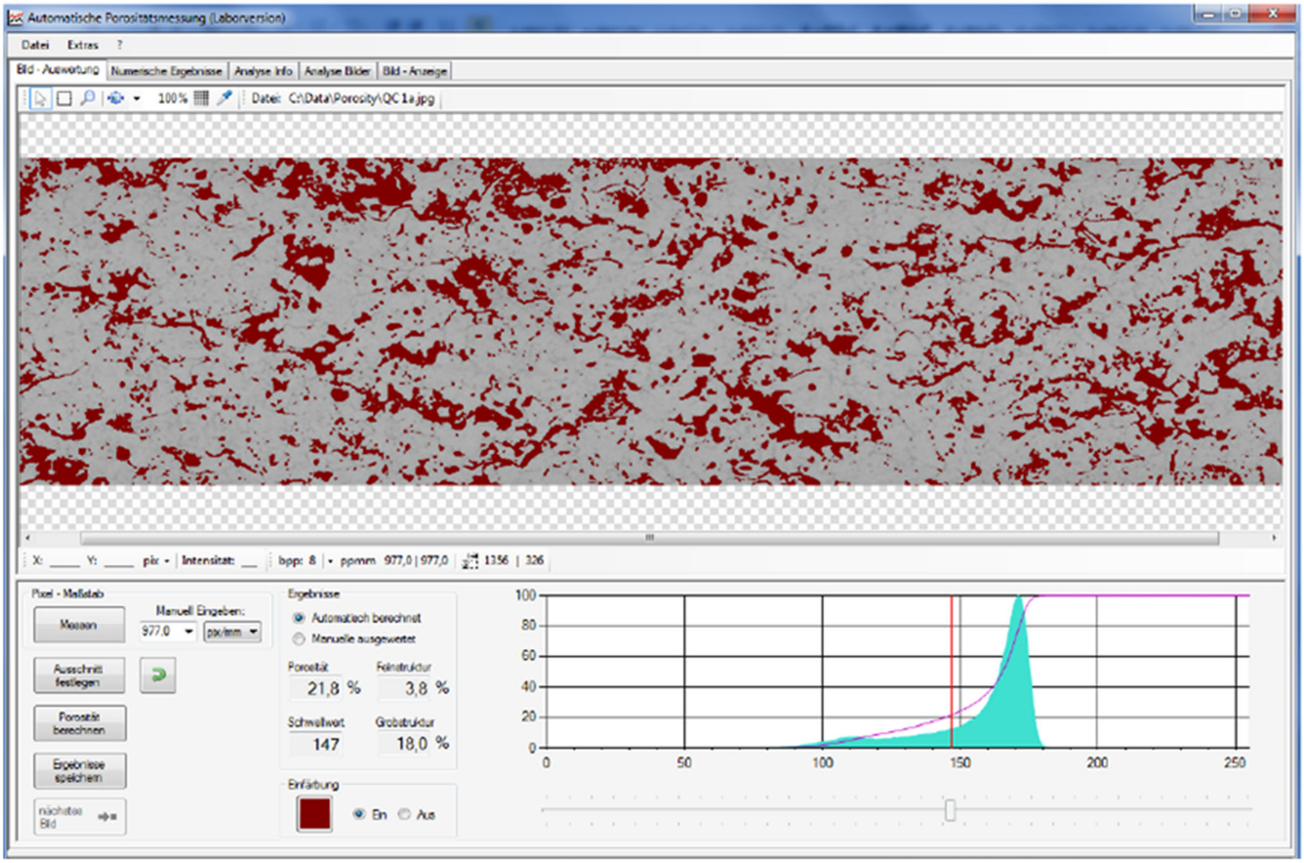


Fig. 8 3D scanning for coating thickness assessment on part

software (Fig. 10). The key advantages of this method over metallographic assessments include elimination of metallographic sample preparation and hence faster speed, and more complete coverage of the areas to be assessed rather than limited locations assessed by witness coupons. One drawback is that the optical 3D profilometry method leaves out some of the details (e.g., fine features/under-cuts on the surface) which may be necessary for R&D purposes. Another limitation is that at the current resolution, the evaluation of interface contamination (caused by the grit particles lodged on the base alloy surface during grit blasting process) via 3D profilometry may not be possible.

Integrated Coatings Property Sensors

The ICP sensors (Fig. 11) allow extraction of deposit stress evolution during deposition as well as elastic properties of the coating (Ref 21, 22). The ECP sensor on the other hand can provide information on the extent of defects in the system (e.g., pores and interfaces) and the nature of the interaction among the material surfaces within these pores and interfaces from a determination of nonlinear elastic property measurement on deposited coatings (Ref 23).



Datei: C:\Data\Porosity\QC 1a.jpg

X: ____ Y: ____ pix | Intensität: __ | bpp: 8 | ppmm 977,0 | 977,0 | 1356 | 326

Manuell Eingeben: 977,0 px/mm

● Automatisch berechnet
○ Manuelle ausgewertet

Porosität 21,8 %

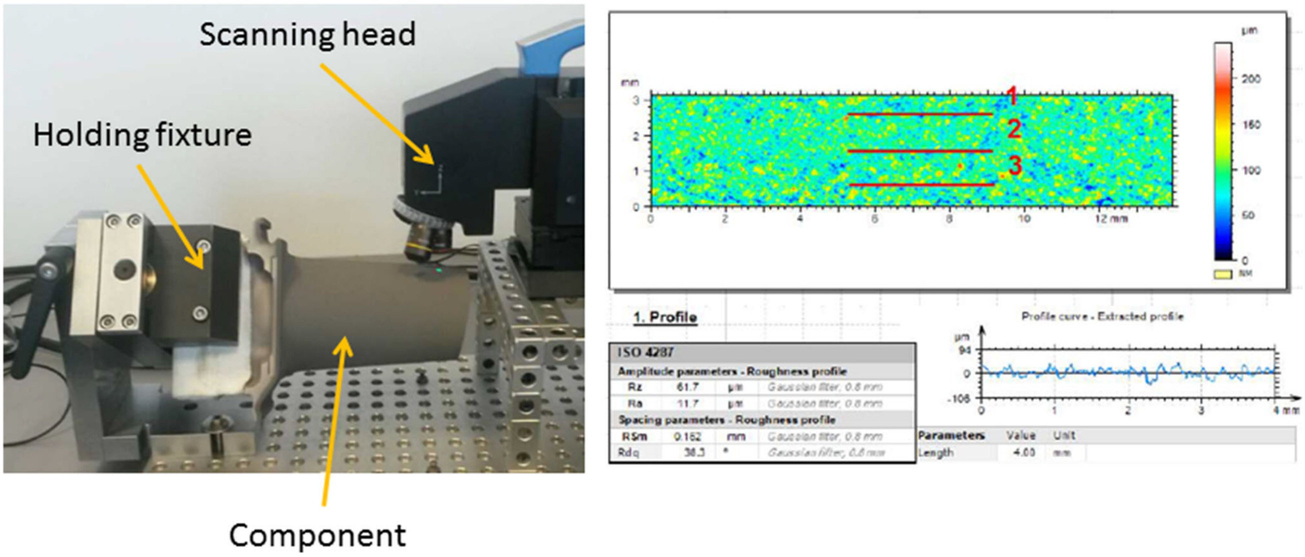
Feinstruktur 3,8 %

Schwellwert 147

Grobstruktur 18,0 %

Einfärbung: ● Ein ○ Aus

Fig. 9 Typical output from image analysis software with automated threshold determination for porosity measurement



ISO 4287			
Amplitude parameters - Roughness profile			
Rz	61.7	µm	Gaussian filter, 0.8 mm
Ra	11.7	µm	Gaussian filter, 0.8 mm
Spacing parameters - Roughness profile			
RSm	0.162	mm	Gaussian filter, 0.8 mm
Rdq	38.3	°	Gaussian filter, 0.8 mm

Parameters	Value	Unit
Length	4.00	mm

Fig. 10 Optical 3D profilometry for base alloy and BC roughness measurement: left setup and right typical output

The new measurement/control tools discussed above are simple to use and significantly enhance the capability. One downside of increased capability tools, apart from the initial capital investment, is that these allow for the detection of previously unmeasurable variations. Initially, this can lead to increased qualification efforts to perfect the process to meet the desired requirements. Also, like any other engineering equipment, the tools mentioned above (including OLP booths, sensors, microscopes and imaging software) must be calibrated to perform optimally as per

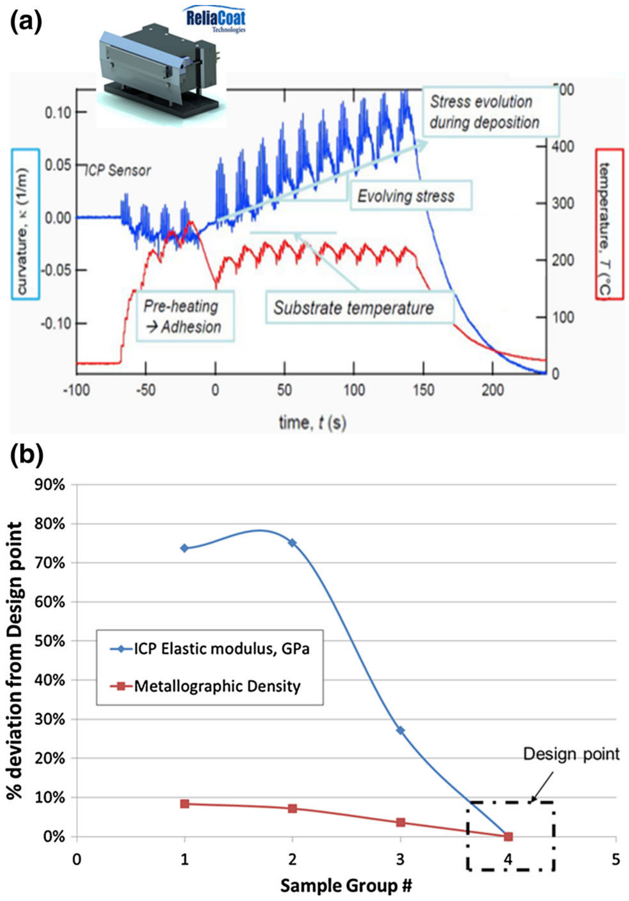


Fig. 11 (a) Real-time curvature and temperature measurements using ICP sensor, and (b) correlation of elastic modulus (ICP) and TBC porosity (independently determined)

industry proprietary approaches. On the positive side though, once adopted in the product setting, the tighter controlled process can lead to a reduction in laboratory-based measurements and assessments and so decrease spray lot approval times and costs.

Other Aspects of Manufacturing Quality Control

While understanding the thermal spray coating process is essential for developing a well-controlled spray process, it is equally important to develop means to follow the process without fail. In industrial settings, very often, process and product inconsistencies result from human errors. This important aspect has received relatively less attention in academic literature. To this end, the first step is to establish a detailed manufacturing quality control process requiring detailed documentation of every critical process step/output. Process documentation is not merely for record keeping for audits but also for the purpose traceability when things go wrong. In coating shops where components are mass-produced and multiple operators perform repeated actions, there is always a possibility of making a mistake, missing a process step or a communication failure. Some examples of such mistakes from actual case studies include:

1. Application of bond-coat on substrates without grit blasting to achieve the minimum desired roughness
2. Grit blasting of component surface post-rough bond-coat (flash coat) application
3. Loading incorrect feedstock powder in the hopper
4. Running ceramic TBC powder through hoses contaminated with metallic/carbide powder
5. Incorrect (missing or unintended) masking
6. Incorrect recipe of spray parameters/robot program used for a given part, etc.
7. Spraying with a worn-out hardware.

Regular maintenance of processing hardware and operator training to different degrees is routinely carried out at many spray shops. However, a key next step would be to establish as many fool-proof mechanisms as possible, which will detect whenever a process parameter is outside of the set limits and prevent proceeding further from that point on. An example is a feedback loop for simultaneous lower limit on plasma torch voltage drop and an upper limit on secondary gas that disables gun ignition and forces nozzle change.

Summary and Conclusions

The reliability and consistency of protective coating systems are becoming increasingly important with the increasing penalties associated with coating failures in the advanced gas turbine engines. The consequent need for accurate coating life predictions and reducing infant mortality requires reducing the scatter in the coating properties resulting from manufacturing variations.

Figure 12 is a demonstrative example of how reducing the scatter in the PVD coating processing and subsequent coating properties increases reliability (i.e., shifting of the Weibull modulus curve for part life to right). Similarly, better understanding of the thermal spray coating process as well as regular monitoring and control of the coating process/hardware can be expected to reducing manufacturing variability and improve coating reliability. Commercially available online process diagnostics/monitoring tools have been helpful in achieving at least some of the above objectives. More widespread utilization of these tools in production environment would require a shift in user mindset, improved ease of use and data interpretation, and in some cases, overcoming the limitations of the existing tools. Advances in post-coating property

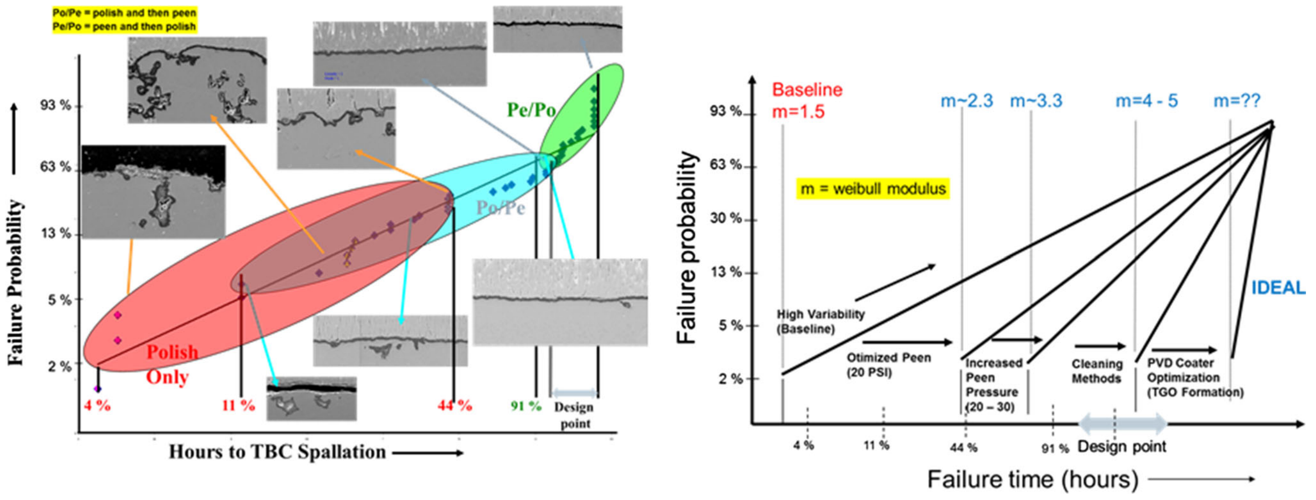


Fig. 12 Reducing the scatter in the coating processing and consequent properties increases reliability

measurement methodologies (aimed at overcoming some of the subjectivity and other limitations of current methods) have been discussed. Maintaining uniform component performance and reducing the scatter in coating life require not only reducing the manufacturing variability in one location but also between different spray shops/locations. In addition to the in-process diagnostics and advanced post-process coating characterization techniques, better communication, improved process harmonization and stringent adherence to the "best practices" across the spray shops are essential to achieve this overall goal.

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