1

Introduction

1.1

Requirements for Materials and Coatings in Powerplants

We do not want to write another book on thermal spraying, plasma spraying, HVOF (see Section 2.4.3) and other spraying processes. We will not repeat what is already written in excellent books, reviews, and journals. Many general descriptions of thermal spraying can be found today in the Internet on web pages of equipment suppliers, material and gas suppliers, coating shops and research facilities. Our intentions are to show some ways how to achieve a stable reliable coating production for power-generation equipment within reasonable time and at optimum cost. We will address how to identify problems and mistakes in advance. We will show how to minimize development effort and to improve product quality.

First, we will try to simplify and summarize the topic of this book:

Electric power generation today and in the future is using and will use steam turbines, gas turbines and turbogenerators, steel tubing and heat exchangers and boilers. Components consist of many parts that are welded, brazed or assembled. Each part has a specific function within the powerplant. The original equipment manufacturers (OEMs) and the powerplant customers like utilities or other power producers consider as the most important parameters of a powerplant:

- Investment cost
- Operation cost
- Long-term reliability
- Availability and scheduled, short maintenance

These parameters translate into requirements for components like material cost, optimized fuel cost, high operation temperatures and long operation times without in-operation control possibilities.

Today, all powerplant hardware is coated wherever no affordable and reliable structural material can be found that resists the operation environment.

For simplification we start with the view of a metallurgist:

Metallurgists select materials for specific applications or for a variety of applications. A powerplant is basically built from metals. The structural materials and functional materials are metals and metallic alloys:

Thermal Spraying for Power Generation Components

K. E. Schneider, V. Belashchenko, M. Dratwinski, S. Siegmann, A. Zagorski

Copyright © 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

ISBN: 3-527-31337-0

- Steel, low alloyed up to high chromium steels
- Nickel alloys
- Cobalt alloys
- Copper and brass

In some rare cases titanium alloys are used. This picture is completely different from aero engines where the weight of a part is important. In power-generation parts weight is only important as material cost and for rotating parts if weight causes mechanical stresses.

Designers select materials for operational conditions like:

- Mechanical stresses, loadings, strains
- Operational temperatures
- Temperature changes
- Environment, atmosphere
- Design lifetime (times and cycles)
- Expected safe operation times

and of course for cost reasons.

If a material class is not able to withstand the operational temperatures cooling is required by available cooling media that are mainly air, steam, or water. In closed-cycle cooling other media like hydrogen are being used.

In many cases a division of material properties for a variety of tasks is required. Base metal has to have the required strength. Coatings withstand the environmental attack or add additional properties like wear resistance. In cooled components thermal-barrier coatings reduce the temperature gradient within the structural material. The designer selects the structural material and the coating by iterating the loading, component thicknesses and cost.

1.2

Examples of Coatings in Gas Turbines

We promised to address powerplant components. However, when we look more closely we find the following situation:

In steam turbines thermal-spray coatings are not in standard use. In certain cases erosion damages are solved by replacing missing material by a thermal spray overlay of erosion-resistant material containing tungsten carbide or chromium carbide.

Large-scale application is found in boilers where the tubes are coated by wire spray. For example, FeCrAl and FeCrAlY coatings are used generally as high-temperature oxidation protection to resist corrosive gases in boiler atmospheres.

The more complex applications are found in gas turbines, especially at higher temperatures. Therefore we will concentrate on examples from industrial gas turbines.

Fig. 1 Siemens Westinghouse gas turbine (courtesy of Siemens).

Basically there are three types of components:

- Large single structural components like casings
- Multiple medium-sized components with plane or slightly curved surfaces, like combustor parts
- Multiple complex-shaped components, like turbine vanes and blades

The following example of a stationary gas turbine illustrates the situation (Fig. 1):

The air intake (1) is a steel construction most probably painted with a zinc-rich paint. The compressor blades and vanes (2) are made out of Cr steels where in certain operation regimes aqueous corrosion, pitting corrosion might end up in corrosion fatigue or stress corrosion conditions. Here the OEM will decide to use higher alloyed steels, titanium alloys or protection of the parts by coating. For clearance-control purposes the counterparts of the rotating compressor blades might be coated with so-called abrasion coatings.

The hot section parts in the combustor (3) and turbine (4) are made out of nickel- or cobalt-based alloys. In some cases ceramics are used. If oxidation and hot corrosion becomes important coatings are also used. In some cases for air-cooled components the cooling is assisted by ceramic thermal-barrier coatings that reduce the operational temperature of the structural material the part is made of. The exhaust (5 and 6) again is made out of zinc-plated or zinc-sprayed steel. Rotor and stator casings are steel components, sometimes coated. For certain operation conditions nickel-based alloys are used for rotor disks.

Wherever parts are rubbing against each other in operation or in order to control gaps between components wear-resistant coatings or so-called abrasion coatings are being used.

Years ago it was already noted that in aero engine components up to 80% of all components are coated by thermal spraying. Today, in stationary gas turbines probably 50% of components are coated. In earlier days galvanic processes like

chrome plating, chemical vapor deposition methods (CVD) or pack processes (explained later in Section 2.1) had been used. Today many of them are replaced by thermal-spray processes.

Table 1 shows examples of coated components, materials, coatings and the basic requirements for the coating application. Details of coating compositions and requirement for feedstock will be found later in the Section 2.2.

Table 1 Components of stationary gas turbines, their base and coating materials.

Component	Base metal	Coating	Coating process	Coating requirement
Air intake	Steel	Zinc, epoxy	Painting	Oxidation, aqueous corrosion, erosion
Compressor blading	12%, high Cr steel, TiAl_6V_4	Aluminum, ceramic, PTFE	Painting	Aqueous corrosion, erosion, stress corrosion, corrosion fatigue
Compressor leakage control	12%, high Cr steel, TiAl_6V_4	Abradables: metal matrix, solid lubricant, and polyester	Plasma spraying	Leakage reduction
Assembled structures	Steel castings, Ni base castings and sheets	CrC, WC + Ni, Co	Wire spray, APS, HVOF	Wear, friction welding
Casings	Low alloyed castings	NiCr_{xx} , NiAl_{xx}	HVOF	Oxidation
Combustor parts	Ni, Co superalloy, Ni-based sheet	NiAl, MCrAlY	APS, HVOF	Hot corrosion, oxidation, bond coat
Cooled combustor parts	Ni, Co superalloy, Ni-based sheet	ZrO_2 8Y ₂ O ₃ 1 ¹⁾	APS, HVOF	Thermal barrier, surface temperature reduction
Gas turbine blades and vanes	Ni, Co superalloy	Cr, Al	CVD, Aluminizing, Chromizing	Hot corrosion, oxidation, bond coat
		M(Ni,Co)CrAlY (+ Re, Ta.)	LPPS, HVOF (+2nd process)	Hot corrosion, oxidation, bond coat
		PtAl	Galvanic Pt Aluminizing	
		AlSi	Slurry painting + sintering	
		ZrO_2 8Y ₂ O ₃	APS, HVOF	Thermal barrier, surface temperature reduction

1) Yttria Stabilized Zirconia (YSZ).

1.3

Definition of Thermal Spraying (THSP)

We will use the definition of thermal spraying as given by ASM²⁾:

“A group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semimolten condition on a substrate to form a spray deposit.

The surfacing material may be in the form of powder, rod, cord, or wire” [1].

Another detailed description is found in the US patent classification [2].

Subclass 446 – sprays coating utilizing flame or plasma heat (e.g., flame spraying, etc.):

Processes wherein (1) a gaseous flame is used to heat and project a coating material toward a substrate or (2) a coating material is converted to or engulfed by a highly ionized gas composed of ions, electrons and neutral particles in which the positive ions and negative electrons are roughly equal in number, and projected on to a substrate

In addition, the following notes are included:

- (1) Torch spraying is considered a form of flame spraying and is included in this and indented subclasses.
- (2) Electric-arc metal spraying is properly classified in this and indented subclasses.
- (3) Explosive or detonation spray vaporization, wherein the vaporized coating is applied in the form of a spray is properly classified in this and indented subclasses.
- (4) Thermal spraying is properly classified in this and indented subclasses.

In short: Thermal spraying are all coating processes that coat surfaces with heated particles that are deposited by a high enthalpy kinetic gas stream. The feedstock used could be wire (if the material can be drawn as wire) or powder.

1.4

Thermal-Spraying Systems

Thermal-spray equipment can be classified according to the energy source needed to heat and accelerate the particles. In the European standards EN 657 [3] as well as in the equivalent international standard ISO 14917 [4] the different systems are described. A typical overview of thermal-spraying processes is shown in Fig. 2. For power-generation components thermal spraying by gas and electric arc discharge spraying are applied.

2) ASM = American Society of Materials.

Fig. 2 Overview of the different thermal-spray processes in analogy to EN 657 [3].

1.5

Coatings for Power-Generation Components

What is specific in coatings, especially in thermal spraying for power-generation components? Why do we need another book on the subject thermal spraying? There are so many excellent reviews around. When looking for thermal spraying in the Internet search engines like Google will show millions of web pages.

Thermal spraying has been used for decades for applying coatings on components of industrial structures in order to protect them against corrosive attack or wear. The first applications go back to the year 1909. A Swiss patent was applied for by Dr. M. U. Schoop for using flame-spray techniques [5].

In order to answer the question “what is specific in coatings for power-generation components?” let us start with the design requirements shown earlier and apply them to coatings:

- Mechanical stresses, loadings, strains
- Operational temperatures
- Temperature changes
- Environment, atmosphere, chemical attacks
- Design lifetime (times and cycles)
- Expected safe operation times
- Cost

The metallurgist translates these requirements into:

- Coating chemistry
- Coating microstructure, e.g. phases, oxides, grain size, porosity
- Coating thickness

For production and purchasing people these requirements have to be put into specifications for manufacturing and purchasing. The specification and the corresponding quality-assurance procedure have to ensure that the coating will meet the requirements of the powerplant operator:

- Investment cost
- Operation cost
- Long-term reliability
- Availability and scheduled, short maintenance

The specifications for manufacturing and purchasing will address:

- Repeatable manufacturing process with defined process parameters
- Defined coating material, e.g. powder specification
- Required coating thickness and tolerance
- Required coating microstructure
- Allowable coating defects and microstructure
- Defined coating substrate interface and tolerances of bonding defects³⁾
- Defined coating surface, e.g. roughness, oxide layer, residual stress and tolerances

The answer to the question why this book is written is:

We found a lack in combination of several disciplines that make a reliable, affordable coating. Only the teamwork of design, manufacturing and supplier is able to provide the right product.

We will show as a thread running through this book that only the intelligent combination of process physics, accumulated experience and operator training can supply coatings with the required quality.

Finally, by complying with such manufacturing and purchasing specifications the OEM or the overhaul shop will guarantee the reliable operation of the coated part in powerplant service.

1.6

The Complete Manufacturing and Coating Process

Coating never is a standalone process within manufacturing, repair or refurbishment of a component. Let us take the example of a turbine blade. Figure 3 shows a typical manufacturing chain for a new component.

³⁾ Bonding defects are details in the interface coating substrate that are not allowed according to specification.

Fig. 3 Gas turbine blade manufacturing process.

Before the investment casting takes place alloy has to be procured. Ceramic cores shaping the interior of the cooled blade have to be injected and fired to provide stability during casting at temperatures in the order of 1500 °C. Wax is injected around the core and a shell mold is applied. By removing the wax the cavity in the shape of the cooled blade is formed.

Vacuum casting, finishing and heat treatment provide an airfoil that later will be coated. Other processes like machining, electro discharge machining (EDM) will follow before coating. It is evident that certain processes have to take place before coating and others will follow the coating process. The latter processes have to be done in such a way that the coating is not damaged by these operations. The coating process is not independent of the other processes.

In more detail every coating process consists of 3 steps:

- Surface preparation
- Coating application
- Finishing/post treatment

All thermal-spraying processes require these 3 steps as well. When concentrating on the coating application we find the following situation: Coating by thermal spraying can be divided into 3 topics shown in Fig. 4 as the example of low-pressure plasma spraying (LPPS):

Fig. 4 Major parameters of influence of plasma spraying (courtesy of ASA).

Fig. 5 LPPS process and system (courtesy of Sulzer Metco).

All three influencing parameters have a specific effect on the coating quality. The spraying equipment provides the coating thickness and microstructure, fixture and masking influence the coating thickness distribution. The powder forms the coating microstructure by chemical composition and grain-size distribution. Of course, this representation may be rather schematic and does not reflect the whole complexity of internal structures and cross-links between the topics.

Details of process and system are given in Fig. 5.

It can be clearly seen that the number of influencing parameters increases. There are not only the spraying equipment and handling system together with the control equipment that determine the coating quality. There are the outside factors such as gases, electrical power and cooling water that enter the system. All these parameters can be controlled within the production facility. However, the powder quality is controlled by the powder supplier.

A more detailed view of additional parameters is given in Fig. 6. It shows that gas supply, power source, controller and cooling features represent important factors for coating quality.

When analyzing the coating process many process parameters (without powder material) can be found.

A system analysis divides each parameter into more subparameters. Each of the subparameters will influence the coating quality in a specific way. In addition, some of the parameters are not independent. They will influence each other.

Another look at the coating process from a shop floor perspective, i.e. from practical experience is given in Fig. 7.

Even more parameters are shown that can be adjusted or occur during coating production.

All the examples show that there are a high number of parameters to be considered in order to produce a high-quality coating in serial production.

Fig. 6 System analysis for plasma spraying (courtesy of ALSTOM).

Fig. 7 Factors influencing the thermal-spraying process.

The excellent review on plasma spraying [6] estimates that 50 to 60 parameters have to be considered.

When looking through the literature and conferences one gets the feeling that everything is addressed and already resolved. Many technical universities seem to have an activity in “plasma spraying” or “thermal spraying” in order to evaluate spraying parameters and their influence on coating properties.

However, experience in production and procurement of powerplant equipment shows that always the same or new mistakes are made. Unknown coating defects

arise. Changes in personnel result in a new learning curve. Deviation of established working parameters results in changes in coating quality and in a number of improvement actions.

1.7

Coating-Process Development

The basic principle for coating of power-generation parts is:

When a new coating process is to be established a process development has to take place. This process development has to result in reliable, stable production. The main task is to find the *operational window*, i.e. the manufacturing regime where small deviations in process parameters have negligible effect on the product quality.

A factorial test matrix will result in a huge number of tests required, which is already restricted by the fact what kind of power-generation parts have to be coated. Either they are single pieces, like one casing per turbine, or when they come in larger quantities like turbine blades they are very expensive easily summing up to thousands of Euro per destroyed part.

Table 2 shows an example of a coating-development matrix for coatings for a turbine blade and the expected correlation with the coating specification.

Let us use an example: take Table 2 and make crosses in each field where an experiment is required.

If a turbine blade has to be coated by all three processes like APS, HVOF and LPPS, it becomes evident how many tests are required. In addition the table shows how important “in process control”⁴⁾ is. This is especially necessary because in many cases there are no nondestructive methods available for controlling online the coating quality.

Process development must result in a repeatable stable manufacturing and quality-assurance process. Every coating process shows a scatter in quality results specified in the coating requirements. The results can be measured by applying a 6-sigma routine and determining process capabilities. A 6-sigma process assures that only 3–4 defects per million [7] are allowed. A 4-sigma process exhibits already 6210 defects per million.

Just to show an example: Assume a gas turbine with 400 coated blades. If the coating is a 4-sigma process then you will find 2–3 blades in the turbine with defective coating. The coating life determines the maintenance interval of the whole powerplants. Therefore the process capability is important and has to be measured.

This process capability requires a good interaction between design and manufacturing. The result is a product that can be manufactured by a defined and released manufacturing process.

4) “In process control” means controlling the established process parameters during coating.

Table 2 Coating-development matrix.

Coating parameters						
	Equipment			In process control		
	APS	LVPS	HVOF	APS	LVPS	HVOF
Precoating <i>Surface quality</i> <ul style="list-style-type: none"> • Cleanliness • Roughness • Oxidation • Preheating • Cooling • Transferred arc cleaning 						Bonding Bonding Bonding Bonding Porosity Porosity Bonding
Spraying <i>Parameters</i> <ul style="list-style-type: none"> • Current/power • Powder • Powder feed rate • Spraying gun • Tooling • Deposition efficiency • Diagnostics • Gas flow • Vacuum <i>Relative movement</i> <ul style="list-style-type: none"> • Speed • Angle 						Thickness Thickness Thickness Thickness Thickness Thickness Thickness Stability Coating quality Thickness Porosity Coating quality Roughness Cost
Post treatment <ul style="list-style-type: none"> • Heat treatment • Surface treatment 						Coating quality Roughness Cost

Because not all conditions can be tested for time or cost reasons and theoretical simulations alone are not accurate enough (accuracy of input data, calibration requirement) there is a lot of practical experience involved.

Therefore pragmatic simulation and modeling technology are required. These tools have to be calibrated, optimized and validated by practical experience and know-how.

Process development is always followed by a learning curve. In all cases the number of coated pieces is small. Therefore the development has to result in stable processes by using experience or modeling and simulation. In the past, the experienced operator or plasma sprayer was the only resource.

Simulation and modeling is a difficult task with many parameters to be considered. But in principle it could be easy:

The starting point for simulation in thermal spraying is

- *Input: Powder material, gas, energy.*

The result is

- *Output: Coated component with a specified coating quality.*

However, when you look closer you will identify complications. The thermal spray powder consists of millions of single particles of different sizes and masses. Each particle has a slightly different chemistry and morphology. The coating is produced on the component by layers of splats formed by a moving spray pattern across the surface. The spray equipment itself has fluctuations in arc discharge, gas regulation and powder supply.

In the past, people applied coatings developed through the “trial and error” and the know-how of experienced people. This has led to the following situation: a “natural” scatter of coating properties like thickness or porosity.

Because coating is sometimes considered an art, coating manufacturers are rated as average, excellent or low performers even when they use identical equipment, identical subsuppliers and apply identical manufacturing specifications.

Questions come up and have to be answered:

- Is there a given process stability? Is there an inherent process capability for a given specification that cannot be improved? What is the right preventive maintenance strategy?
- Is there a chance to end up with coating processes with process capabilities of the order of other manufacturing processes, e.g. like milling.
- How does stability of equipment (e.g. power source) influence the coating quality?
- Is gun-cooling variation a source for spitting?
- What is the effect of carrier gas, etc.?
- What is the influence of the coating powder-manufacturing process?
Is there an optimum?

These considerations have to be made when applying both “trial and error” and simulation approaches. The final answer must be a manufacturing process that uses modeling to a certain extent and builds some kind of knowledge base to be used for new developments and manufacturing and in-service feedback.

1.8

Tasks for “Target” Readers

This book will help to establish the grounds of the knowledge base. This book is not a scientific book. Its target community is the practice, the application:

- *Designer*: He has to understand the capability and limitations of thermal spraying. It is a line-of-sight process. Spray angle, speed and distance of the spraying gun determine the coating quality. Therefore there are certain optimum operational windows.
- *Financial controller*: He will understand deposition efficiency (waste of powder) and the importance of maintenance and spare parts for quick changeover of worn equipment.
- *Coating manufacturing engineer*: He will use offline programming and real equipment in an optimum mix in order to end up with stable processes in production after the shortest development time.
- *Production operators and quality engineers*: They have to understand that a frozen process⁵⁾ together with monitoring of a number of process parameters is the only way to ensure quality.
- *Operators of the equipment*: They understand every variation and its influence on the frozen process.
- *Supplier of material to be coated, e.g. casting houses and machinists*: They understand the requirements of the coater in respect of geometry, surface quality, gas content of castings, cleanliness from machining fluids.

They all have to understand the final target in production:

- *Achieve process stability at minimum total cost*
- *Introduce measuring tools like 6-sigma*
- *Total Quality management (TQM), ISO 9000x*

We will show in this book that only the combination of theory and practical experience will result in a reliable process. It will be evident that the main issue is to keep a drifting process within the required operational window.

5) A frozen manufacturing process is established by process development. All process parameters and the equipment must not be changed after process development. It is assumed that such a frozen process always yields an identical result within a defined tolerance (process capability).

In order to guide the reader through the book we selected the following structure:

In Chapter 2 “Practical Experience Today” we will describe the experience today in coating processes, material supply, hardware and processes. It will show what the important parameters for establishing the operational window are. The following chapter shows the factors influencing the quality and process capability. It addresses the importance of equipment maintenance as well. Theory of plasma and HVOF spraying is addressed in Chapter 4. Chapter 5 explains an approach to the offline simulation of thermal spraying. Standards and qualification of personnel are given in Chapter 6. Based on all the information supplied Section 7.2 shows how monitoring can be applied for controlling the coating process in production. The importance of coating-process development for reliable production is given in Section 7.3, followed by an outlook in Chapter 8.