JTTEE5 17:612–616
DOI: 10.1007/s11666-008-9236-7
1059-9630/$19.00 © ASM International

Tailor-Made Coatings for Turbine Applications Using the Triplex Pro 200

Katharina Richardt, Kirsten Bobzin, Dieter Sporer, Thomas Schläfer, and Petr Fiala

(Submitted May 20, 2008; in revised form September 24, 2008)

In modern jet engines, the efficiency of compressor stages is highly dependent on the clearance between blade tip and casing. To improve efficiency of gas turbines, the gap between the turbine blades and casing has to be minimized. Abradable coatings permit a minimization of the clearance and control of the over-tip leakage by allowing the blade tips to cut into the coating. Thermal sprayed abradables aim at a well-balanced profile of properties relevant for abradable seals. Amongst others these include: abradability, aging resistance, corrosion and oxidation resistance, and bond strength to substrate. Here, abradable coatings consisting of a multiphase material, comprising a metal matrix and a solid lubricant as well as a defined porosity, were developed using the Triplex Pro 200 to increase reproducibility and deposition efficiency. In addition, the influence of the process parameters on coating characteristics (porosity, hardness) and, as a result, erosion properties and abradability was investigated.

Keywords advantages of TS, APS coatings, coatings for gas turbine components, influence of spray parameters, TBC topcoats, TS coating process

1. Introduction

The plasma spraying process is a well-accepted process for applying functional coatings for different applications. Process optimization and innovative material applications gain more and more interest in regard to continuously increasing functional and structural demands on thermal sprayed coatings. This study describes the parameter development for an abradable composite coating material, relevant for the aerospace industry.

The reduction of the leakage by improved sealing can result in significantly improved efficiency as well as power output, time-on-wing, and compressor stall margin (Ref 1-4). Manufacturing tolerances and in-service behavior of the rotor that allow a reduction of the over-tip leakage have been a fundamental field of research in recent years. Abradable linings between housing and rotating blades are a promising solution, as they allow a self-regulation of the system by a purposeful cutting of the blade tips into the relatively soft coating. The blade wear during that process has to be kept to a minimum, while the abradable seal coating has to be resistant against erosive wear caused by the particle loaded jet, aging, and/or oxidation during service. To meet these demanding requirements, complex thermally sprayed material and coating systems have been introduced to the market and successfully used. In this work, the coating characteristics of an experimental abradable coating material Durable 2621 were investigated. The powder material is a multiphase material, comprising a metal matrix (Ni-based) in addition to a solid lubricant, mostly hexagonal boron nitride, with a well-defined level of porosity.

2. Experiments

The spraying experiments were carried out using the Sulzer Metco Triplex Pro 200 APS-coating system (nozzle diameter: 2.3 mm, powder injector diameter: 1.8 mm).

As plasma gases, combinations of argon and nitrogen were used. With the use of a combination of one and two atomic plasma gases, an optimal acceleration and heating of the powder particles can be reached. In a plasma gas mixture consisting of nitrogen and argon, nitrogen is mostly responsible for heating up the powder material; however, due to its high atomic weight, which favorably influences the pulse transmission, argon affects the particle velocity. Using only argon as a plasma gas, the particle velocity is comparably high, the melting time of the particles in the plasma jet low. This results in a too high polyester content in the coating, and reduces the

This article is an invited paper selected from presentations at the 2008 International Thermal Spray Conference and has been expanded from the original presentation. It is simultaneously published in *Thermal Spray Crossing Borders, Proceedings of the 2008 International Thermal Spray Conference*, Maastricht, The Netherlands, June 2-4, 2008, Basil R. Marple, Margaret M. Hyland, Yuk-Chiu Lau, Chang-Jiu Li, Rogerio S. Lima, and Ghislain Montavon, Ed., ASM International, Materials Park, OH, 2008.

Katharina Richardt, Kirsten Bobzin and **Thomas Schläfer**, Surface Engineering Institute (IOT), RWTH Aachen University, Aachen Germany; **Dieter Sporer**, Sulzer Metco, Schattwald, Austria; and **Petr Fiala**, Sulzer Metco, Fort Saskatchewan, Canada. Contact e-mail: richardt@iot.rwth-aachen.de.

hardness. In this work, the experimental powder material Durabrade 2621 (Sulzer Metco, Wohlen, Switzerland), consisting of NiCrAl/boron nitride and 10 wt.% polyester, was used. The abradable coatings with a required coating thickness between 2 and 2.2 mm were deposited on CoNiCrAlY-bondcoats (Amdry 995C). After spraying and prior to any further testing, the coatings were heat-treated in air at 435 °C for 5 h to evaporate the polyester filler deposited in the coating, and thereby creating additional coating porosity. During the heat treatment, the coating thickness is decreased by 200 ± 80 μm, and therefore, any effects of the substrate in hardness measurements can be excluded.

For analysis of the microstructure, the coatings were embedded by vacuum infiltration; a micro-structural evaluation was carried out using optical microscopy of cross sections of the coatings. The homogeneous distribution of the material components was secured by the comparison of optical image analyses of several micrographs. In-flight particle characteristics were measured using the optical diagnostic systems DPV2000 (Tecnar, St. Bruno, QC, Canada) as well as Accuraspray (Tecnar). Rockwell hardness of the coatings was measured at MTU (Munich, Germany), using a ball indenter, pressed into the surface of the coating. The indentation is based on a two-step application—a preliminary force P followed by an additional test force. The result of the test is read directly from the tester as:

$$\mathrm{HR} = E - e$$

where E = indenter constant-here 100 units and e = permanent indentation depth

Based on the indenter constant $E = 100$ used here, the hardness scale is not limited on positive values; values close to 0 do not mark the lowest hardness possible. Surface roughness (R_a) was measured using a laser profilometer.

After a general parameter development, in order to deposit homogeneous coatings within a required hardness range and a homogeneous particle temperature and velocity distribution within the spray plum (measured with DPV 2000), the influence of the process parameters on coating characteristics and particle properties was investigated. To do so a full factorial DoE was generated. The hardness as a coating property is one main influencing factor concerning the wear behavior of a coating system, and therefore significantly influencing the abradability and erosion resistance (Ref 6). Based on a first coating optimization and erosion, aging, and abradability tests, a hardness range between 25 and 45 HR 15Y is required to reach an adequate coating performance. Arc current and N_2 flow were found to have the most pronounced influence on coating hardness, and hence those two parameters were varied systematically. To evaluate an optimal powder feed rate, it was included in the DoE as well. Fixed parameters were argon flow, standoff distance, and robot velocity. The varied process parameters are shown in Table 1. The samples produced within the DOE were characterized concerning their hardness HR 15Y and microstructure.

Table 1 Varied parameter values for the DoE

Factor name	Lowest value	Highest value
A Current, A	280	320
B Nitrogen, SLPM	3	7
C Powder, g/min	60	120

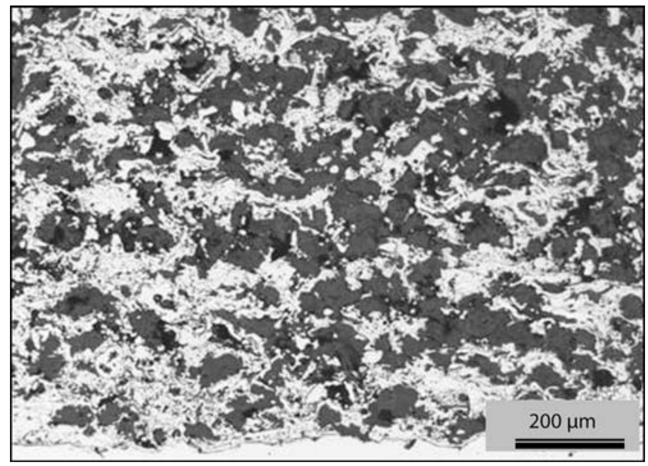

Fig. 1 Microscopic image (SM 2621, Ar: 45 SPLM, N2: 5 SLPM, current: 300 A, powder feed rate: 90 g/min, standoff distance: 180 mm)

3. Results

A microscopic image of the coatings microstructure, developed for further analysis of the correlations between coating characteristics and process parameters, is shown in Fig. 1.

A homogeneous distribution of the ceramic (hbN) and metallic (NiCrAl) components in the coating can be observed by the comparison of different coating sections by light microscopy.

The polyester content, deposited in the coating, was burnt out in a heat treatment, which resulted in a porous microstructure with a porosity, measured with optical methods, of 27% after heat treatment. Erosion tests showed a good erosion resistance and a low blade wear against titanium blades.

3.1 Deposition Efficiency

The highest deposition efficiency (up to 45%) can be observed using a powder feed rate of 30 g/min for each of the three powder feeders (90 g/min total). Using either 60 or 120 g/min total, the deposition efficiency decreases to values of 20-30%, independent of the spray parameters current and nitrogen.

3.2 Coating Properties Surface Roughness, Porosity, and Coating Hardness

The coating properties surface roughness and coating hardness as a response to the varied spray parameters are shown in Table 2. A statistical interpretation of the DoE shows that the strongest three parameters on the hardness of the coating in the order of importance are the nitrogen secondary plasma gas flow, the current, and an interaction of the nitrogen flow and the current (Fig. 2). Significant factors are those extending to the right of the red dotted line (significance limit).

In the DoE each spray parameter was repeated and the hardness results compared. In most cases, the hardness differences of the replicates are in an acceptable range of 0 to 3 HR 15Y; a good reproducibility of coating hardness for the same spray parameters could be observed. Only when using low nitrogen gas flows (3 SLPM) the hardness of the replicates shows differences up to 16 HR 15Y. The hardness of the coating can be controlled by changing the nitrogen flow and/or using higher current values. In general, the biggest changes in hardness can be achieved by using a low nitrogen flow and changing the current or using a low current and changing the nitrogen flow. For a smaller variation of hardness, a higher nitrogen flow and current should be used. To adjust the coating hardness, the current has been identified as a suitable parameter, as it does not affect the deposition efficiency.

Figure 3 shows the hardness development with changing current values. Increasing current values result in increasing coating hardness.

Regarding the surface roughness, no parameter shows a significant influence as shown in the pareto chart (Fig. 4). Surface roughness is primarily determined by the particle size of the thermal spray powder using the parameter window described here. Interaction plots show that the surface roughness cannot be controlled by selectively changing the main influencing spray parameters.

Table 2 Coating properties hardness and surface roughness in dependency on the spray parameters

Powder feed rate, g/min	N_2, SLPM	Current, A	Hardness, HR 15Y	R_a, µm
60	3	320	26	20.5
120	7	320	42	25.8
60	7	320	47	20.4
60	7	280	42	23.4
60	3	280	−31	22.1
90	5	300	34	24.0
120	3	280	−30	15.9
120	7	320	40	18.3
120	7	280	24	28.5
60	3	280	−15	18.9
120	3	320	10	25.7
60	7	280	40	22.8
120	3	320	8	17.4
60	7	320	45	16.9
90	5	300	35	20.6
120	7	280	31	16.5
120	3	280	−33	18.1
60	3	320	42	28.4

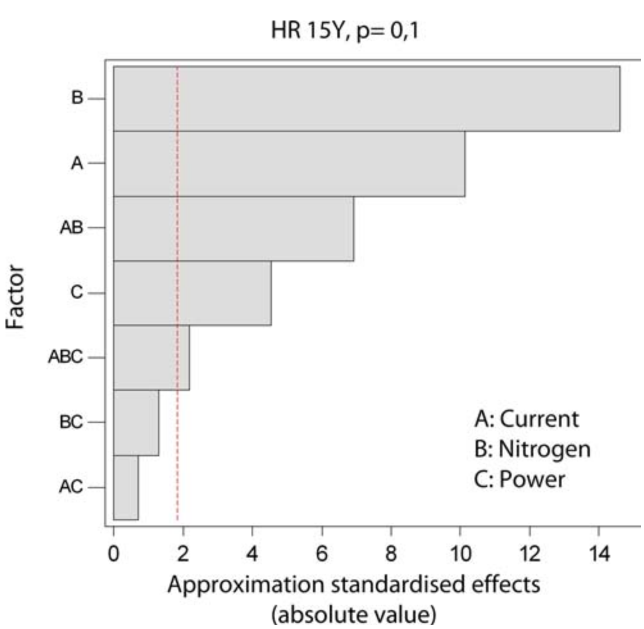

Fig. 2 Pareto chart of standardized effects in response to the hardness

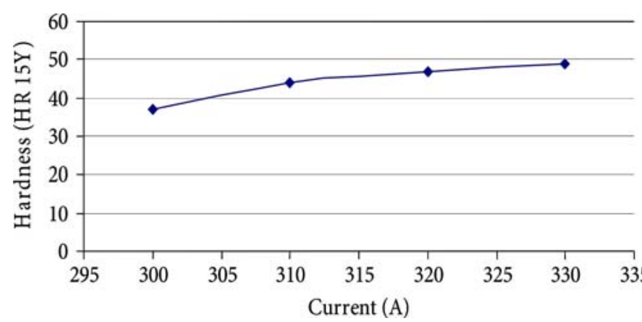

Fig. 3 Current influence on coating hardness

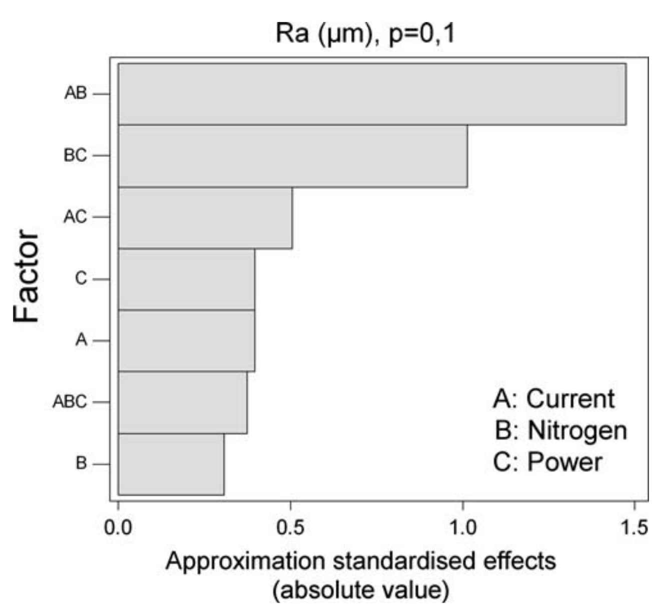

Fig. 4 Pareto chart of standardized effects in response to surface roughness

Before heat treatment, the measured coating porosity ranges at about 5 ± 2%. The measured porosity after heat treatment ranges between 19 and 35%, decreasing with increasing plasma power. This can be explained by a higher degree of heating of the spray powder material with increasing plasma power. This causes more polyester to burn off during the spray process, consequently causing less polyester to be deposited in the as-sprayed coating, which finally causes a lower level of coating porosity. The coating hardness can be correlated with the measured porosity. Higher porosity values lead to a lower coating hardness; samples in the required hardness range show a coating porosity between 23% (HV 15Y = 40) and 35% (HV 15Y = 25).

3.3 Particle Properties Temperature and Velocity

Particle property measurements with the DPV and Accuraspray only allow a measurement of hot (metallic/ceramic) particles, while cold particles (polyester compound) will not be detected. The measured particle temperatures and velocities (Accuraspray) are shown in Table 3.

The nitrogen flow followed by arc current can be observed as the process parameters having the largest influence on particle velocity and temperature. With a higher nitrogen gas flow, which is primarily responsible for heating up the powder particles, the particle temperature and the velocity increases, where the increased particle speed is mainly an effect of the increased total gas flow.

The average particle temperatures increase with increasing plasma power, either by using higher current values or higher nitrogen gas flows. The measured temperatures of the hot particles range from 1980 to 1500 °C. The statistical interpretation shows the significance of the parameters nitrogen followed by the current on the particle temperature. There is only a very weak interaction of the current and the nitrogen flow. Quite significant differences were also assessed for particle speeds. The measured particle speeds range from 76 to 111 m/s. Particle speeds increase with increasing gun power. Significant factors for particle velocity are the nitrogen flow and the current; their interactions do not show any effects on the particle velocity.

Table 3 Particle in-flight temperature and speed as a result of varied spray parameters

Powder feed rate, g/min	N_2, SLPM	Current, A	Particle temp., °C	Particle speed, m/s
60	3	320	1685	98
120	7	320	1870	107
60	7	320	1978	116
60	7	280	1820	108
60	3	280	1520	91
90	5	300	1794	108
120	3	280	1500	85
120	7	320	1980	111
120	7	280	1770	103
60	3	280	1580	93
120	3	320	1750	96
60	7	280	1850	103
120	3	320	1720	99
60	7	320	1940	110
90	5	300	1800	101
120	7	280	1790	98
120	3	280	1470	76
60	3	320	1800	102

With an increased particle velocity the particle temperature also increases and vice versa. This can be explained by the influence of a bigger current and a secondary plasma gas flow on higher plasma temperature and a plasma plume constriction that produces a faster, hotter plasma jet. As a result, particle velocity and temperature exhibit a linear correlation.

A strong correlation between the coating hardness and particle velocity and temperature and a reasonably good correlation between the particle velocity and temperature can be observed as shown in Fig. 5.

Monitoring particle temperature and velocity can be used for online process control, even for the multiphase material used in this work. Both increasing particle velocity and particle temperature cause an increase in coating hardness (Fig. 6 and 7).

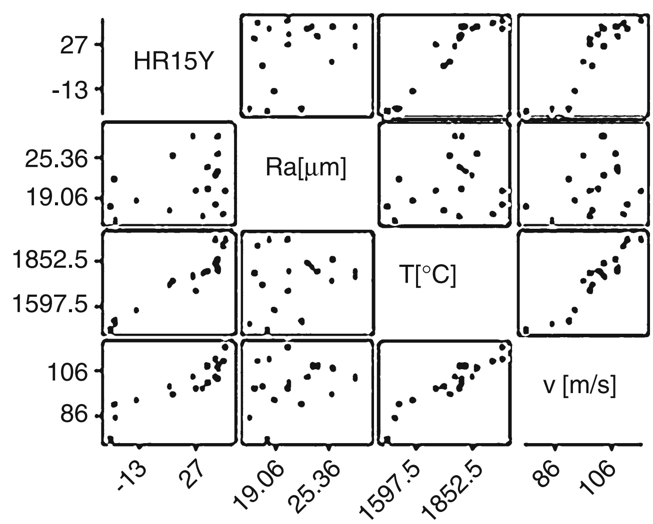

Fig. 5 Correlation of the responses within the DOE

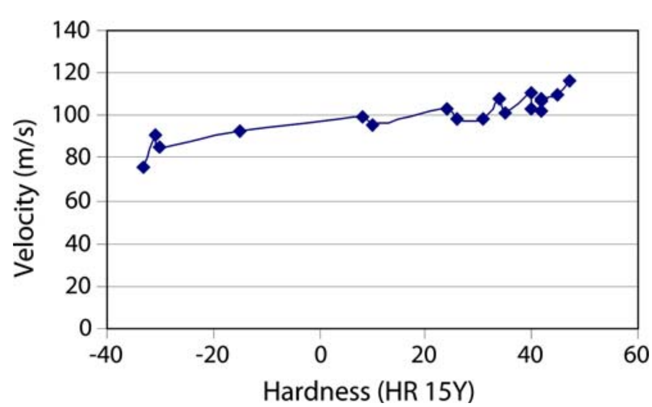

Fig. 6 Development of the hardness with particle in-flight velocity

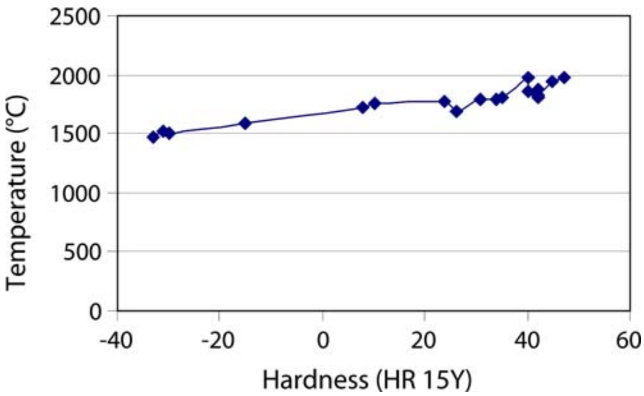

Fig. 7 Development of the hardness with particle in-flight temperature

4. Conclusions and Outlook

In this work, the relationship between coating hardness and spray parameters verify the statistical significance of the process parameters current and nitrogen gas flow. The observed influence of the nitrogen flow on the hardness is based on the influence of the secondary plasma gas flow on plasma temperature as well as on gas velocity. Increasing nitrogen flow leads to increased particle temperatures as nitrogen is mostly responsible for the heating of the powder material. Due to its high atomic weight, which favorably influences the pulse transmission, argon mainly affects the particle speeds. In addition, a strong influence of the current on particle properties, especially the particle temperature, can be observed. The influence of current is based on the higher power input and increasing temperatures of the plasma plume and gas jet, and corresponding effects on particle properties and coating hardness. In addition a higher temperature of the gas jet leads to higher hardness values as a result of enforced oxidation of the metal phase on one hand and a reduced content of polyester deposited in the coating on the other hand.

Concerning the powder feed rate, a optimal value of 90 g/min could be established. Lower or higher powder feed rates result in reduced deposition efficiencies.

The analysis of the correlation between diagnostic data and hardness reveals a significant influence of particle velocity and temperature on coating hardness for the parameter field studied. Nevertheless, a relationship between diagnostic data and hardness could be found that allows a prediction of resulting coating properties with a reasonable level of confidence.

References

1. K.J. Melcher and J. Kypuros, Toward a Fast-Response Active Turbine Tip Clearance Control, *International Symposium on Air Breathing Engines* (Cleveland, Ohio), 2003
2. A.M. Wallis, J.D. Denton, and A.A.J. Demargne, The Control of Shroud Leakage Flows to Reduce Aerodynamic Losses in a Low Aspect Ratio, Shrouded Axial Flow Turbine, *International Gas Turbine and Aeroengine Congress and Exhibition* (Munich, Germany), 2000
3. B.M. Steinetz, R.C. Hendricks, and J. Munson, Advanced Seal Technology Role in Meeting Next Generation Turbine Engine Goals, *Propulsion and Power Systems First Meeting on Design Principles and Methods for Aircraft Gas Turbine Engines* (Toulouse, France), 1998
4. S.B. Lattime and B.M. Steinetz, Turbine Engine Clearance Control Systems: Current Practices and Future Directions, *Joint Propulsion Conference and Exhibit* (Indianapolis, Indiana), 2002
5. D. Sporer, M. Dorfman, L. Xie, A. Refke, I. Giovannetti, and M. Giannozzi, Processing and Properties of Advanced Ceramic Abradable Coatings, *Proceedings of the International Thermal Spray Conference* (Beijing, China), 2007
6. K. Bobzin, E. Lugscheider, J. Zwick, F. Ernst, D. Sporer, N. Hopkins, M. Hertter, and J. Matejicek, Microstructure and Properties of New Abradable Seal Coatings for Compressor Applications, *Proceedings of the International Thermal Spray Conference* (Seattle, Washington, USA), 2006