

Control of Coating Properties of Abradable Seals by On-Line Process Diagnostics

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Abstract

The efficiency of gas turbines is highly dependent upon the clearance between compressor housing and rotating blades. Abradable seal coatings are employed to minimize the clearance and control the over-tip leakage by allowing the blade tips to cut into the coating and herewith implementing a method of self-adjustment. These coatings consist of a thermally sprayed multiphase material, comprising a metal matrix, a dislocator and a defined level of porosity. Thermally sprayed abradable linings aim at a well balanced profile of properties relevant for the application as abradable seals. Amongst others these include: abradability, ageing resistance, corrosion and oxidation resistance as well as surface finish and bond strength to substrate materials. Due to the high demands in aircraft industry, the coating properties also have to match strict requirements with regards to quality control. Hence the spraying process has to be stable and well controlled. In this work, an APS sprayed abradable coating was sprayed with different sets of parameters and analysed by an on-line diagnostic system. The coating microstructure and properties were evaluated and related to the diagnostic results.

Introduction

Increasing mileage in air transportation along with increasing requirements concerning environmental aspects make high demands on the efficiency of modern jet engines. To meet these requirements, many efforts in optimizing engine lay out design have been made, leading to benefits such as optimized aerodynamic design and higher bypass ratios. Beyond these constructive improvements, only minimum flow losses from engine intake to nozzle outlet, including the rotating compressor as well as turbine stages, are acceptable. Reduction of leakage by improved sealing can result in significantly improved efficiency as well as power output, time-on-wing and compressor stall margin [1-4]. Due to manufacturing tolerances on the one hand and in-service behaviour of rotor blades on the other, reducing the over-tip leakage has been a challenging task in recent years. A promising way to solve this problem is the use of abradable

linings between housing and rotating blades, that 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 at the same time the abradable seal coating has to withstand erosive wear due to the particle laden jet and ageing 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. Typically they comprise a metal matrix material together with either a solid lubricant or a significant level of porosity to allow cutting of the blade tips with minimum blade wear. Figure 1 shows a typical cross section of an abradable coating based on a NiCrAl/Bentonite material system. The very porous microstructure with bentonite embedded in a NiCrAl metal matrix is clearly observable.

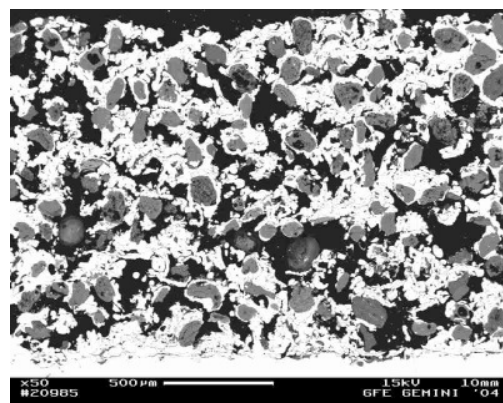


Figure 1: Cross section of a typical abradable coating (dark phase: porosity, grey phase: bentonite, bright phase: NiCrAl metal matrix)

The choice of the metal matrix material is mainly depending on the in-service temperature level and blade material the coating has to face. Common and commercially available material systems are e.g. Ni/Graphite and AlSi/hBN [1] for compressor and CoNiCrAlY/hBN/Polyester for turbine sections of aircraft jet engines (Figure 2).

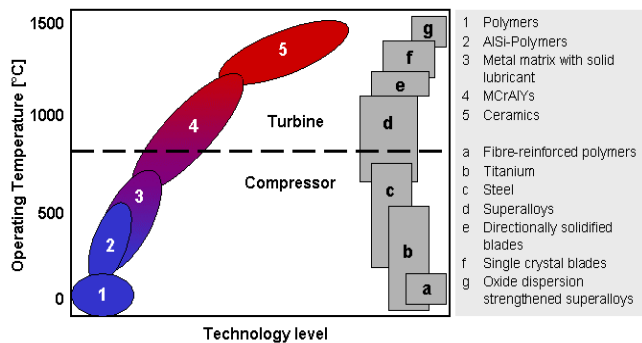


Figure 2: Material systems for abradable seals [2]

However, there is very limited knowledge about the influence of process parameters on coating properties and process stability in general. Since quality control especially in the aeronautic business is of vital importance, methods of monitoring and controlling coating quality are a crucial factor for producing high performance coatings with a well balanced profile of properties. To date the most important test method to evaluate the quality of a sprayed abradable coating system is the Rockwell hardness value HR15Y. Typical hardness values for abradable seal coatings are in a range of 40 – 70 HR15Y, depending on the material system and spray method. Modern spray diagnostic systems are promising tools, that are believed to allow a non-destructive quality control by inspecting the particle jet during the spraying process.

In this study the on-line diagnostic system SprayWatch (Oseir Ltd.) was used to analyze the interrelations of the basic process parameters primary and secondary plasma gas flow, carrier-gas flow and current on the recorded diagnostic data (particle temperature, particle velocity and flux) and the HR15Y value of a plasma sprayed abradable coating system.

Experiments

Spray trials have been carried out in atmosphere with a Sulzer Metco F4 plasma spray gun, implemented in a Sulzer Metco MultiCoat® control unit. As feedstock material a novel Ni-based multiphase powder, Durabrade™ 2621, was used. This material contains hexagonal boron nitride to provide a solid lubricant phase in the boron nitride. The variation of spraying parameters was based on a set of previously optimised parameters. The foregoing optimisation of basic parameters was done with regards to HR15Y hardness values as well as abradability, that was evaluated in rig tests. Table 1 shows the set of constant spray parameters.

Table 1: Constant spray parameters (F4 gun)

Spray Distance	150 mm
Gun Traverse Speed	500 mm/s
Vertical Increment	3.0 mm
Nozzle (Anode) Ø	8 mm
Powder Injector Ø	1.8 mm
Injector Distance from Nozzle Axis	8 mm
Injecting Angle	105°

The varied parameters (independent variables) include gas flows of the primary and secondary plasma gases argon and hydrogen, respectively, as well as current. Furthermore the carrier-gas flow was varied, since injection of the multiphase powder is expected to be very sensitive to that parameter. A summary of the parameter variations is given in Table 2.

Analysis of the measured data was done by means of statistical evaluation with the commercial software STATISTICA. Analysis of three-level factors for determination of linear and square influences as well as multiple regression analysis was used to analyse correlations between the spraying parameter variation, diagnostic data and HR15Y hardness values.

Table 2: Summary of parameter variations

No.	Gas Flow Ar [SLPM]	Gas Flow H ₂ [SLPM]	Gas Flow Carrier Ar [SLPM]	Current [A]
1	46	5.5	3.5	450
2	46	5.5	3.5	450
3	46	5.5	3.5	450
4	46	5.5	3.5	450
5	38	4.5	3	400
6	38	4.5	4	400
7	38	4.5	4	400
8	38	4.5	3	500
9	38	4.5	4	500
10	38	6.5	3	400
11	38	6.5	4	400
12	38	6.5	3	500
13	38	6.5	4	500
14	54	4.5	3	400
15	54	4.5	4	400
16	54	4.5	3	500
17	54	4.5	4	500
18	54	6.5	3	400
19	54	6.5	4	400
20	54	6.5	3	500
21	54	6.5	4	500

Results and Discussion

Analysing the dependence of the hardness value HR15Y on variation of spraying parameters, there is a clear influence of

all varied parameters, except carrier-gas flow. In the ANOVA table the statistical significance of each effect is tested by comparing the mean square against an estimate of the experimental error. The p-value indicates the level of confidence for the statistical significance of a term; for example a p-value of 0.10 means a statistically significant relationship between the variables at the 90 % confidence level. A p-value of less than 0.05 is commonly regarded as an acceptable level of confidence. Linear influences of argon and current are significant on HR15Y with a p-value close to zero and are therefore highly significant. Also hydrogen is very significant, while square influences of argon are less significant with a p-value of 0.36. The carrier-gas flow has a p-value of 0.62 and is within the studied parameter variations not statistically significant for the hardness.

The Pareto chart (Figure 3) graphically shows the significance of the variables and interactions; the length of the bars and displayed values represent the factor for the variable in a linear equation that was found by fitting a multiple linear regression model for describing the relationship between dependent (hardness) and independent variables (process parameters). The p-value as criteria for a significant influence is also displayed in the Pareto chart.

As example, an estimated response surface is displayed for the influence of argon and current on the hardness value in Figure 4. The response surface shows the preferred smooth appearance, that can be regarded as an indicator for a correct description of the dependency. As can be seen high hardness values require high current and low argon levels.

Table 3: ANOVA table – HR15Y dependence on spray parameters

	Sum of Squares	Df	Mean Square	F-Ratio	p-Value
(1)Ar [SLPM](L)	6164,00	1	6164,0	46,951	0,000005
Ar [SLPM](S)	115,16	1	115,2	0,877	0,363821
(2)H ₂ [SLPM](L)	1170,00	1	1170,0	8,912	0,009246
(3)Carrier Ar [SLPM](L)	33,15	1	33,2	0,253	0,622604
(4)Current [A](L)	2826,21	1	2826,2	21,527	0,000321
Error	1969,30	15	131,3		

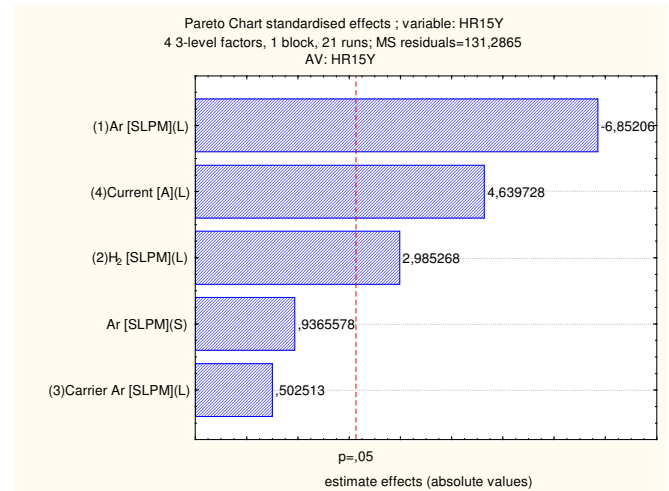


Figure 3: Dependence of hardness on spray parameters

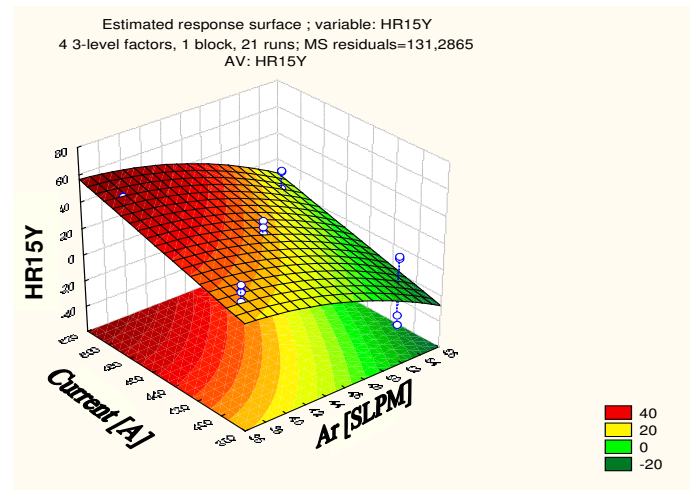


Figure 4: Estimated response surface of HR15Y depending on Ar and current

The Pareto charts for the dependence of measured particle temperatures, particle velocities and flux on the varied process parameters are shown in Figures 5-7. With the variation of spray parameters, a variation in particle speed from 63 to 107 m/s and particle temperatures ranging from 2125 to 2660 °C were measured. The measured particle temperatures are significantly dependant on all varied spray parameters with current having the least significant influence. Measured particle velocities are, on the other hand, only dependant on the gas flows of primary and secondary plasma gases. The measured flux represents the standardized number of particles, that passed through the measuring volume in a certain time. The Pareto chart reveals, that flux is only dependant on current.

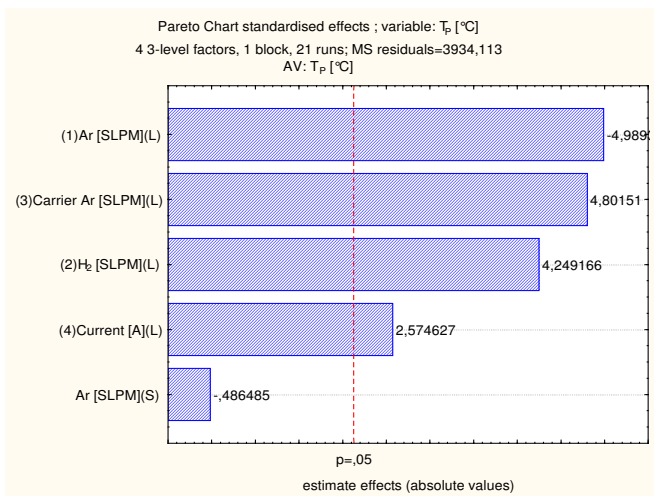


Figure 5: Dependence of measured particle temperatures on spray parameters

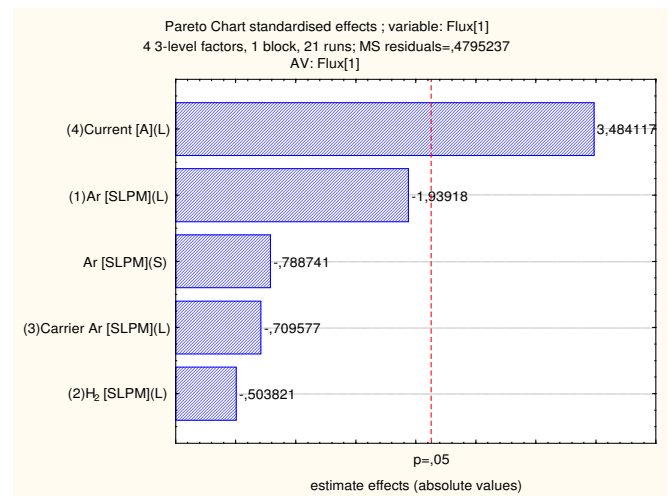


Figure 7: Dependence of measured flux on spray parameters

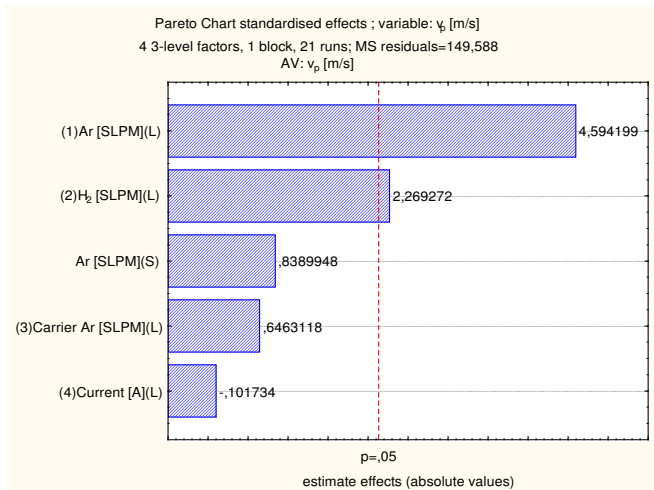


Figure 6: Dependence of measured particle velocities on spray parameters

For correlating diagnostic data with hardness, the measured SprayWatch data have to be specified as independent variables. Multiple regression analysis was used to study correlations between hardness and measured particle temperature, velocity and flux values. Table 4 shows the p-values for the relationship between diagnostic data and HR15Y. It reveals a highly significant dependence of hardness on the measured particle temperature, a marginal p-value for flux and a very high value for the measured particle velocity.

Table 4: p-values for dependency of hardness on diagnostic data

	T_p	v_p	Flux
p-value	0.0012	0.8537	0.0594

Summary and Conclusion

The analysis of the relationship between coating hardness and spray parameters verify the statistical significance of chosen varied parameters, except carrier-gas flow. The observed influence of argon flow on the hardness is based on the influence of the primary plasma gas flow on plasma temperature as well as on gas velocity. Increasing argon flow leads to decreasing particle temperatures due to the cooling effect on the gas jet and increasing particle velocities because of the higher gas flow rate through the gun nozzle. That relationship can also be recognised by the analysis of diagnostic data and their dependence on process parameters. Colder spray particles are supposed to result in a less dense and hence softer coating, while faster particles should lead to a contrary effect. In addition, a higher temperature of the gas jet can cause higher hardness as a result of enforced oxidation of the metal phase of the spray material. The found negative

influence of argon flow on hardness indicates a preponderance of the cooling effect in the studied parameter field. That is also supported by the analysis of relations between diagnostic data and hardness, which show a significant influence of temperature only. The non-present influence of velocity on hardness can hardly be attributed to a particular cause and has to be further investigated. The influence of current is based on the higher power input with increasing current values and therefore increasing temperatures of the plasma plume and gas jet and according effects on particle properties and coating hardness respectively. The influence of hydrogen flow on hardness is similar for aforementioned reasons, apart from a positive effect of hydrogen flow on temperature and thus coherent influence of changes in hydrogen flow on hardness.

Since the studied feedstock material consists of a multiphase powder with components of different densities, an influence of carrier-gas flow on coating hardness was expected. The missing significance could be explained by an inadequate variation of the carrier-gas flow. If too small variations of carrier-gas flow e.g. do not change the injection and distribution of particles in and downstream of the plasma jet to a certain extent, the statistical analysis can not reveal an intrinsically existent dependency. However, analysis of diagnostic data reveals a statistically highly significant influence of the varied carrier-gas flow on measured particle temperatures. Therefore the variation of carrier-gas flow caused a detectable change of particle trajectories, resulting in varying penetration depth and residence time of particles in the plasma plume. The independence of hardness on carrier-gas flow needs to be investigated in further studies.

The analysis of the correlation between diagnostic data and hardness reveals an unexpected non-significant influence of particle velocity on coating hardness for the studied parameter field. Nevertheless a relationship between diagnostic data and hardness could be found that allows a prediction of resulting coating values with a reasonable level of confidence. Further investigations are required to verify, endorse and complete these results.

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