Evaluating and Optimizing Plasma Spray Parameters on Thermal Barrier Coatings Using Response Surface Method

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1 Abstract

Effect of plasma spray parameters on hot corrosion resistance of YSZ (Yittria Stabilized Zirconia) thermal barrier coatings using design of experiments (DOE) response surface method was investigated. Three parameters in three levels have been chosen to be studied. First parameter was total number of layers. Three types of coating were synthesized: a) two layered samples, consisting of a 100% MCrAlY layer and 100% YSZ; b) three layered samples, in which chemical composition was gradually changed from MCrAlY to YSZ; a 100% MCrAlY, 50%MCrAlY-50% YSZ, and 100% YSZ. c) five layered samples consisting of a 100% MCrAlY layer, 75% MCrAlY-25% YSZ, 50%MCrAlY-50% YSZ, 25% MCrAlY-75% YSZ and 100% YSZ. Second parameter was spray distance which was varied from 80 to 120 mm, and last parameter was powder feed rate that was increased from 10 to 30 g/min. All samples were coated on IN 738-LC as a substrate. ANOVA analysis and experimental results showed that all parameters had significant effect, without any interaction with each other. Within the scope of the response surface method, the most important parameter was number of layers; with 99.7% significance (P value=0.3%). It was also observed that hot corrosion resistance is a non-linear function of number of layers: the more the number of layers, the better hot corrosion resistance. More over increasing spray distance improved the corrosion resistance. Whilst it was decreased by increasing powder feed rate. Maximum hot corrosion resistance was obtained in five layered coating, with spray distance of 120 mm and 10 g/min feed rate, which could endure 120 hours in corrosive atmosphere at 800°C.

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Keywords: Thermal barrier coating, Hot Corrosion resistance, Plasma Spray Parameters, Design of experiments, Response surface method.

2 Introduction

In recent years developing and manufacturing ceramic thermal barrier coatings (TBCs) has been the subject of many investigations [1-7]. TBCs are used in hot path turbine components, such as transition pieces, blades, vanes and combustion chamber since metals can't withstand the environment of turbines. Applying TBCs on the surface of components will increase the durability of hot path parts as well as increasing efficiency of turbine [6-8]. TBCs conventionally consist of two layers: a MCrAlY layer as a bond coat (in which M can be Ni, Co or both of them), and a stabilized Zirconia layer as top coat.

TBCs are subjected to severe conditions such as oxidation, hot corrosion and thermal shock during their life [8-10]. So increasing hot corrosion resistance is one of the most important properties of the coating that must be taken under account.

Plasma spray parameters as well as primary powder's characteristics influence on the microstructure of the coating and therefore the performance of the coating is affected [11-13]. Life and performance of the coating mainly depend on plasma spray parameters such as standoff distance, gun power, flow rate, powder feeding rate, etc.

Statistical design of experiments has been shown to provide efficient approaches to systematically investigate the process parameters of thermal spray. For example, the Taguchi method was efficiently used by Kingswell et al. [13]. Response Surface Method (RSM) is a collection of mathematical and statistical techniques, that is useful for modeling and analyzing problems in which a response of interest is influenced by several variables and the objective is to optimize this response [14].

The goal of this study was to investigate effect of standoff distance, powder feed rate and number of layers and optimize the hot corrosion resistance of Yittria Stabilized Zirconia (YSZ).

3 Materials and Experiments

3.1 Design of Experiments

In this research there were three parameters. Standoff distance, powder feed rate and layers number of coating. In order to reduce the number of experiments, lower the cost and make the data reproducible and reliable; response surface method (Box-Behnken type) was tested using Minitab 16 software. By considering two repeats for the central point, there were fifteen tests. Table 1 shows the designed experiments.

3.2 Materials

Materials that are used in this research are shown in Table 2.

3.3 Hot Corrosion Tests

Hot corrosion test is done by using electrical furnace at 800 °C with 45% Na_2SO_4-55% V_2O_5 salt. Specimens were inspected by microscope every 4 hours until the failure occurs. Once a crack was seen on the sample, test was stopped to check for further investigations. After hot corrosion test, compound of the corrosion product was analyzed by X-ray diffraction (XRD) model XMD30 and the structure was studied using Scanning Electron Microscope (SEM) model *TESCAN VEGAII*.

4 Results and Discussion

4.1 Effect of Layers Number

ANOVA analysis (Table 3) has shown that the most important parameter in hot corrosion resistance of TBCs is number of layers. Linear coefficient of this parameter is -33.28 and its square is 11.57. Studying parabolic curves (Figures 1 and 2) and variance analysis reveals that significance of this parameter is 99.7% and its square is 96.2% significant. So corrosion resistance is a non-linear function it. These results explain the accuracy of choosing RSM method, as it is the unique method that can recognize non-linear parameters in complicated processes and calculate the regression equation. R-square of this equation is 76%. ANOVA analysis also reveals that there is no interaction between tested parameters.

Experimental results are listed in Table 4. As surface of TBCs are porous and cracked, in conventional two layered TBCs corrosive salt penetrates via these pores and react with Yittira, so YVO_4 is formed (this result is verified by XRD test and seeing rod shaped structure in SEM pictures), so the surface loses Yittria consequently destabilizes Zirconia thereupon polymorphic transformation happens and as a result the coating cracks due to volumetric changes. While in multi layered coating in addition to YVO_4, other compounds such as $CrVO_4$ and $AlVO_4$ is formed, therefore surface loses less Yittria and failure occurs later (Figures 3 and 4).

Table 1: Experiments design by response surface method

	C1	C2	C3	C4	C5	C6	C7
	StdOr>>	RunOr>>	PtType	Blocks	spray dista>>	powder feed r>>	layers >>
1	1	1	2	1	80	10	2
2	2	2	2	1	120	10	2
3	3	3	2	1	80	30	2
4	4	4	2	1	120	30	2
5	5	5	2	1	80	20	1
6	6	6	2	1	120	20	1
7	7	7	2	1	80	20	3
8	8	8	2	1	120	20	3
9	9	9	2	1	100	10	1
10	10	10	2	1	100	30	1
11	11	11	2	1	100	10	3
12	12	12	2	1	100	30	3
13	13	13	0	1	100	20	2
14	14	14	0	1	100	20	2
15	15	15	0	1	100	20	2

Table 2: Used materials

Substrate	Bond Coat	Top Coat	Corrosive Salt
Inconel 738 low carbon	Amdry 962 (Ni 22Cr 10Al 1.0Y)	Metco 204 NS-G (8YSZ)	45% Na_2SO_4-55% V_2O_5

Table 3: ANOVA analysis results

Term	P	T	SE Coef	Coef
Constant	0/000	21.350	3.533	75.429
Distance	0.078	1.967	3.305	6.500
Feed Rate	0.028	-2.572	3.305	-8.500
Layer	0.003	3.934	3.305	13.000
Layer×Layer	0.038	2.392	4.838	11.571

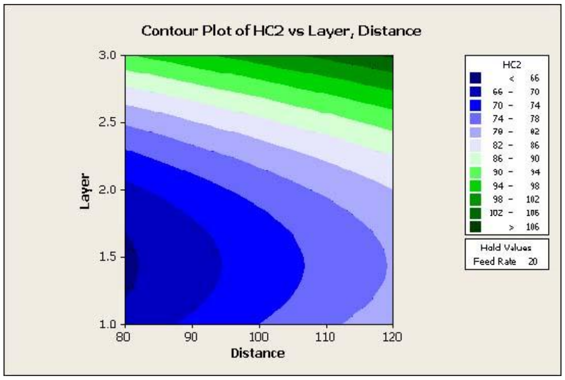

Figure 1: Cantour plot of hot corrosion resistance vs. standoff distance and number of layers.

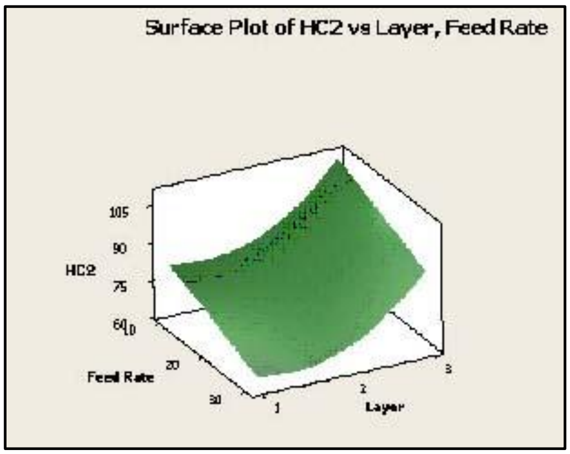

Figure 2: Surface plot of hot corrosion resistance vs. Feed rate and number of layers.

Table 4: Hot corrosion test results

Sample	1	2	3	4	5	6	7	8
Time to failure (hrs)	76	88	60	72	76	88	80	96
Sample	9	10	11	12	13	14	15	
Time to failure (hrs)	76	56	120	104	76	80	76	

4.2 Effect of Standoff Distance

ANOVA showed that this parameter is 92.2% significant and its linear coefficient in regression is 0.32. As shown in Figure 5 increasing standoff distance increases hot corrosion resistance by decreasing particles velocity during the collision, so a porous coating with lower density would be created. Ilavsky et al. [15] reported that increasing standoff distance from 65 mm to 145 mm, porosity will rise from 10% to 14%, and surface cracks decrease by half. Increasing standoff distance also would decrease residual stresses on the surface. Totally decreasing surface cracks and residual stress postpone the failure and penetration of corrosive salts to the coating.

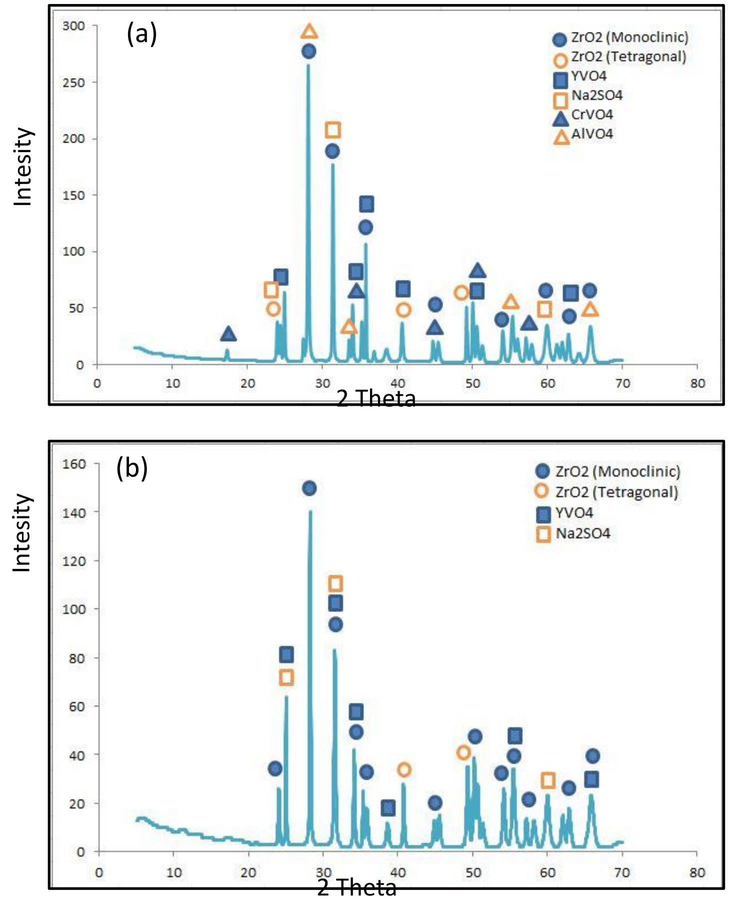

Figure 3: XRD patterns (a) before and (b) after hot corrosion tets at 800℃.

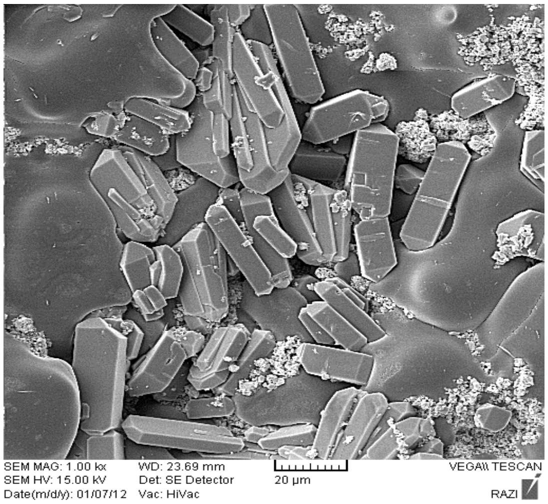

Figure 4: SEM picturefor surface of coating after corrosion test.

4.2.1 Effect of Powder Feed Rate

Investigations showed that this parameter has 97.2% significance and its linear coefficient is -0.85. The higher the powder feed rate is, the lower resistance would be obtained. Decreasing powder feed rate causes more particles to be melted during the spray process in the price of increasing porosity on the surface. By decreasing powder feed rate in each pass, lower powder would be sprayed on the surface, though stresses would be lessen and finally general quality of the coating increases. Porosities are discontinuous paths between coating and corrosive environment, so harmful corrosive salts can go through the coating and destruct interface of coating and substrate and as a result performance of coating would be destroyed.

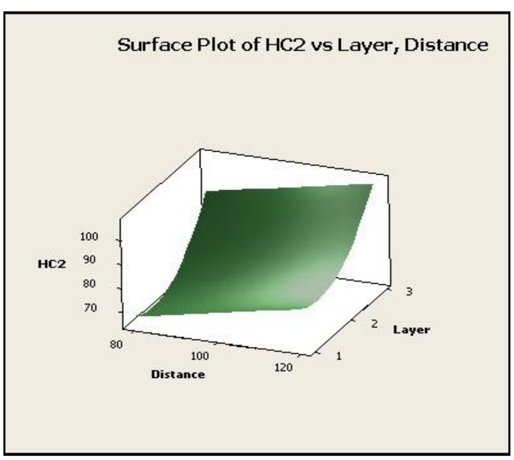

Figure 5: Surface plot of hot corrosion resistance vs.number of layers and standoff distance.

5 Optimization

Obtaining significance of each parameter and their effects, regression equation would be calculated. That is:

Corrosion Resistance= 75.492 + 6.5×Distance − 8.5×Feed rate + 13×Layer + 11.571 × Layer^2 **(Eq.1)**

In order to optimize performance of coating in corrosive environments, using Minitab software Derringer method was used. According to studies on high temperature gas turbine components that work in hard conditions, such as corrosive ambience, the minimum acceptable value for corrosion resistance is 70 hours. According to optimization graph in Figure 6, optimum resistance for corrosion resistance is 115 hours by 100% composite desirability factor. In order to validate the obtained value, a sample was coated with suggested parameters (that is shown in Table 5) and calculated error was 6.4% that was acceptable so theoretical model was reliable.

Table 5: Comparison of predicted value and experimental value and error percent.

Parameter	Predicted Value	Predicted result	Experimental result	%Error
Distance	120 mm	115	108	6.4%
Feed Rate	10 g/min			
Layer	5			

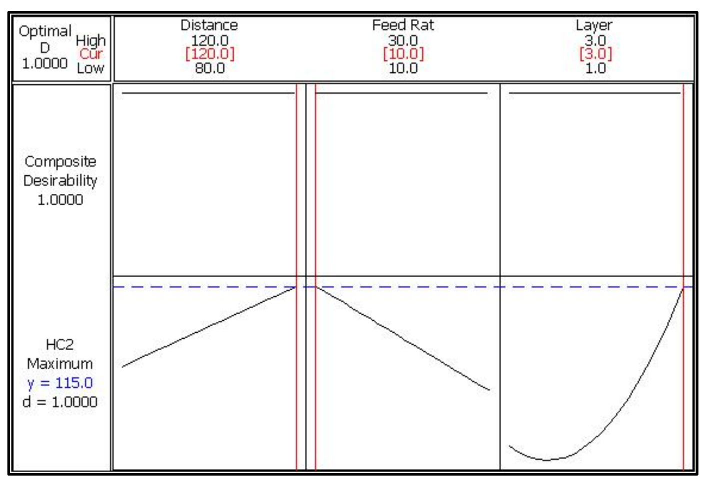

Figure 6: Optimizng graph by Derringer method.

6 Conclusion

1- The most important parameter among studied parameters was number of layers. As the variation of chemical composition from substrate to ceramic coating decreases, hot corrosion resistance increases.
2- Increasing standoff distance and decreasing powder feed rate will increase hot corrosion resistance.
3- Plasma spraying a multi layered coating is non-linear complicated process, in which number of layers has non-linear behavior so factorial method or other methods cannot be used to predict the results and the most appropriate method is response surface method.

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