OPTIMIZING HIGH VELOCITY OXY FUEL SPRAY COATING PROCESS PARAMETERS FOR REDUCING EMISSIONS IN ZrO_2/Al_2O_3 COATED INTERNAL COMBUSTION ENGINES

by

Nirmal Kumar Israel WILSON[a*], Gopal POORNANANDAN[a], and Ramesh Kumar CHIDAMBARAM[b]

[a] University College of Engineering, BIT Campus, Tiruchirappalli, Tamilnadu, India
[b] Automotive Research Centre, VIT University, Vellore, Tamilnadu, India

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It is a major issue in the world that only one third of the total fuel input gets converted to work, whereas the remaining two thirds of the fuel input goes unused through the exhaust and cooling systems. In the present years, enormous research has been done for reducing the undesirable emissions in internal combustion engines. In this paper, using high velocity oxy fuel thermal spray method, ZrO_2 and Al_2O_3 were coated over the piston head by fluctuating the important thermal spraying process parameters. A central composite design model was developed for conducting twenty different experiments with different spray process parameters. The coated piston was used in internal combustion engine to evaluate the emissions, which were measured using AVL5 exhaust gas analyzer to evaluate the smoke density and NO_x content. Empirical relations were created between input process parameters with the responses. Analysis of variance was used to evaluate the significance of developed model. Response surface methodology was used to optimize, thereby predicting the parameters of oxygen flow rate at 229 L/m, fuel flow rate at 51.2 L/m, spray distance of 194 mm to predict minimum smoke density of 27.7 HSU and NO_x of 220.8 ppm, which was validated to a high level of accuracy.

Key words: *emission reduction, optimization, response surface methodology, coating*

Introduction

In standard types of internal combustion (IC) engines, a large amount of energy was found to be wasted by means of unburnt fuels escaping through exhaust gas and through cooling systems. Insulation of the piston crown with thermal barrier coatings help in reducing the heat energy losses. Many researchers have done work in reducing emissions in IC engines. Mofigur *et al.* [1] conducted an exhaustive review about the various methods and alternatives that can be used for reducing the emissions in IC engines. Chang *et al.* [2] conducted research work to enhance the efficiency of Diesel engines ther by reducing the level of emissions. Using an atmospheric plasma system, the variations in consumption of fuel, the enhancement in thermal efficiency were observed by fluctuating the voltage in plasma system. Godwin Antony *et al.* [3] and Kumar *et al.* [4] analysed the performance of direct inection engines performance with alternate fuel which is another method of improving the efficiency. Yan *et al.* [5]

* Corresponding author, e-mail: nirmalbtech@gmail.com

conducted an exhaustive review on enhancing the efficiency of spark ignition based IC engines, thereby reducing the undesirable emissions. The characteristics of combustion was studied by increasing the extent of hydrogen addition on the engine performance. Dhyani *et al.* [6] and Kumar *et al.* [7] conducted experiments using exhaust gas recirculation technique and water injection technique in spark ignited IC engines, to reduce the NO_x content in the exhaust. By controlling knocking, the undesirable emissions were drastically controlled. Renaud *et al.* [8] used a new algorithm technique known as particle tracking velocimetry methodology to evaluate the fields of velocity near piston wall, thereby evaluating the turbulence during the combustion process. The effect of the generated friction between the cylinder walls and the piston on the flow pattern of the fuel during combustion were studied. Miyamoto *et al.* [9] and Bertoli *et al.* [10] and experimental studies on enhancing the efficiency of diesel engine and reducing the emissions. The effect of coatings were found to enhance the engine performance thereby reducing the emissions. Thus, in this paper, using (HVOF) thermal spray technique, the piston of IC engine was coated with ZrO_2 and Al_2O_3 to enhance the engine performance thereby reducing emission.

Materials and methods

Base materials and experimental set-up

In this paper, IC single cylinder Diesel engine test rig, with aluminum piston head was used. For coating the piston head, ZrO_2 and Al_2O_3 material was used. The purpose of coating the piston was to enhance the temperature resistance, get appreciably high coefficient of expansion, reduce the friction characteristics, enhancing the thermal shock resistance, reduce the overall weight without compromise in durability. The ZrO_2 possess enhanced toughness, excellent insulation properties and high coefficient of expansion. Using high velocity oxy fuel (HVOF) thermal spray technique ZrO_2 was coated over the piston. Then using the same technique, Al_2O_3 was coated to reduce the damage caused during oxygen emission during combustion. The SAM image of the powdered. The ZrO_2 and Al_2O_3 is indicated in fig. 1. From fig. 1(a) the circular grains of the powdered ZrO_2 can be observed with certain large oval shaped structures distributed sparsely. Figure 1(b) indicates the pear like structure of the Al_2O_3 powder, which is finely ground but with irregular shapes.

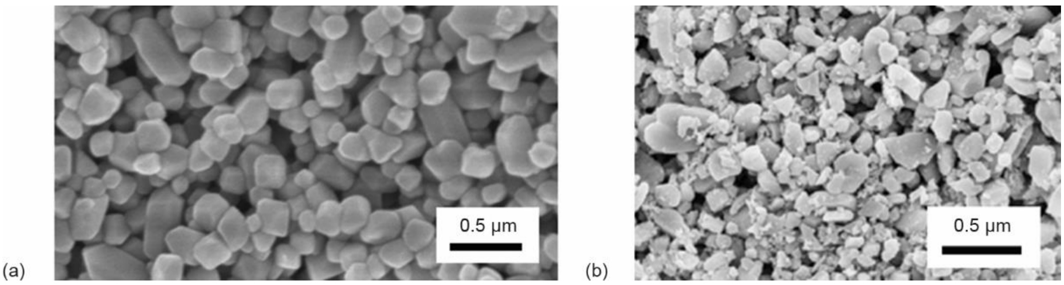

Figure 1. The SEM micrographs of (a) ZrO_2 and (b) Al_2O_3

Using HVOF thermal spray technique, the piston was coated with the two coatings, initially with ZrO_2 and then with Al_2O_3. The HVOF comprises of a gun for spraying, power feeding set-up, flow regulation part, air, and gas feeding unit. The important process parameters considered in this for fluctuation were oxygen flow rate [Lm^{-1}], fuel flow rate [Lm^{-1}], and spray distance in [mm]. Other process parameters were maintained constant throughout such as powder feeding rate of 25 mm per minute and the pressures of fuel, oxygen and air as 0.4 MPa, 0.5 MPa, and 0.3 MPa. The thickness of coatings were made around 150 μm each.

Feasible process parameter selection

By studying previous literatures, and by trial and error experiments, the HVOF process parameters were evaluated. It was found that within oxygen flow rate, *O*, between 200 L/m and 260 L/m, fuel flow rate, *F*, between 45 L/m and 55 L/m, and spray distance, *D*, between 180 mm and 220 mm, the coatings were found to be of good quality. The values of the feasible limits have been given in tab. 1.

Table 1. Feasible limits of HVOF process parameters

Parameter		Levels				
		–1.68	–1	0	1	+1.68
Oxygen flow rate [Lm^{-1}]	*O*	200	212	230	247	260
Fuel flow rate [Lm^{-1}]	*F*	45	47	50	52	55
Spraying distance [mm]	*D*	180	188	200	211	220

By fluctuating the HVOF process parameters, the experiments were conducted. After coating, the IC engine was run with constant load conditions, at constant brake power of 3 kW and by using an exhaust gas analyzer, the smoke density and NO_x content present in the exhaust gas were found.

Development of central composite model

Using a central composite design model, the HVOF process parameters for 20 different experiments were set. With 8 design, 6 star, and 6 central points, the model was developed having the process parameter values ranging from -1.68 to +1.68. The intermediate values were obtained by using the relationship that was developed by Montogomery DC [11]:

$$B_\mathrm{i} = 1.682 \frac{2B - (B_\mathrm{max} + B_\mathrm{min})}{(B_\mathrm{max} + B_\mathrm{min})} \tag{1}$$

The intermediate values for the HVOF process parameters were obtained and indicated in tab. 1. The conditions for 20 sets of experiments is given in tab. 2. With the given process parameter values ZrO_2 and Al_2O_3 were coated over the aluminum piston. Then, the IC set-up was run using constant load conditions and the exhaust gas was analyzed. For each set of coating on the piston by using the HVOF process parameter values indicated in tab. 2, combustion experiments were conducted and the responses in the form of smoke density in HSU and NO_x content in ppm were found from exhaust gas analysis and the observations were tabulated in tab. 2.

Results and discussion

Empirical relations development

Empirical relationships were developed between the HVOF thermal spray process parameters and the responses, in the form of smoke density (*SD*) and NO_x (*N*) content. As per the relationship developed by Paventhan *et al.* [12] the equations have been developed:

$$SD = f(O, F, D) \tag{2}$$

$$N = f(O, F, D) \tag{3}$$

Table 2. Range of central composite design model

Run	Coded factor value			Actual factor value			Smoke Density HSU	NO_x [ppm]
	O [Lm^{-1}]	F [Lm^{-1}]	D [mm]	O [Lm^{-1}]	F [Lm^{-1}]	D [mm]		
1	–1.68	0	0	200	50.00	200.00	54.2932	435.051
2	0	0	0	230.00	50.00	200.00	29.7843	238.661
3	0	0	1.68	230.00	50.00	220.00	59.3064	475.221
4	1	1	1	247.84	52.97	211.89	63.7626	510.929
5	0	1.68	0	230.00	55.00	200.00	43.1528	345.783
6	0	0	–1.68	230.00	50.00	180.00	39.8106	319.002
7	1	1	–1	247.84	52.97	188.11	39.2536	314.539
8	1	–1	1	247.84	47.03	211.89	62.0915	497.538
9	0	0	0	230.00	50.00	200.00	30.3413	243.124
10	1.68	0	0	260.00	50.00	200.00	59.8634	479.685
11	–1	–1	–1	212.16	47.03	188.11	61.5345	493.075
12	1	–1	–1	247.84	47.03	188.11	51.5081	412.734
13	–1	1	1	212.16	52.97	211.89	48.7459	390.6
14	–1	1	–1	212.16	52.97	188.11	40.9247	327.929
15	0	–1.68	0	230.00	45.00	200.00	54.8174	439.251
16	0	0	0	230.00	50.00	200.00	30.8983	247.588
17	0	0	0	230.00	50.00	200.00	26.9991	216.344
18	0	0	0	230.00	50.00	200.00	28.1132	225.271
19	–1	–1	1	212.16	47.03	211.89	53.1791	426.124
20	0	0	0	230.00	50.00	200.00	31.4553	252.051

The response surface, J, of the SD and NO_x content of the exhaust gas from the IC engine are represented by using a polynomial regression equation of second order:

$$J = g_0 + \Sigma g_i x_i + \Sigma g_{i1} x_{i2} + \Sigma g_{ij} x_i x_j \tag{4}$$

From analysis of variance, other than O and D in SD model and other than O and $O \times F$ in NO_x model, other terms were within prob < 0.0001. This attributes to very minimal level of the variation left unexplained. High level of significance can be attributed as R^2 value was obtained near to 1, tab. 3.

Empirical optimization by using contours and 3-D surface plots

The fluctuations in dependent variables such as smoke density and NO_x were evaluated using response surface methodology:

$$U = \Phi(z_1, z_2 \ldots z_k) \pm er \tag{5}$$

Table 3. The ANOVA analysis of the developed models

SD model					NO_x model				
Source	SS	Df	F	Prob > *F*	Source	SS×10^3	Df	F	Prob > *F*
Model	3123	9	124	<0.0001	Model	2018	9	129	<0.0001
O	33.2	1	11	0.0063	*O*	2.2	1	13.01	0.0048
F	225	1	80	<0.0001	*F*	14.4	1	83.9	<0.0001
D	329	1	117	0.0135	*D*	21.4	1	124.4	<0.0001
O×*F*	25	1	8	<0.0001	*O*×*F*	1.6	1	9.3	0.0120
O×*D*	155	1	55	<0.0001	*O*×*D*	10.3	1	59.8	<0.0001
F×*D*	111	1	39	<0.0001	*F*×*D*	7.1	1	41.4	<0.0001
O^2	1322	1	473	<0.0001	O^2	85.1	1	493.6	<0.0001
F^2	650	1	232	<0.0001	F^2	4.1	1	243.1	<0.0001
D^2	690	1	247	<0.0001	D^2	4.4	1	258.1	<0.0001
Res	27	10			*O*	1.7	10		
LOF	13	5	0.9	0.5432	LOF	0.7	5	0.8	0.57
Std. dev 1.67		R^2		0.9911	Std. dev 13.1		R^2		0.9915
Mean 45.4		Adj		0.9831	Mean 364		Adj		0.9839
C.V. % 3.6		Pred		0.9609	C.V. % 3.6		Pred		0.9638
Press 123		Adeq Pres		30.061	Press 7378		Adeq Pres		30.8

The response is indicated by *U* and the factors in qualitative nature are indicated by z_1, $z_2 \ldots z_k$, while *er* is the error function. Using circle geometry, the dependence between the dependent and independent variables were attributed. Under constant loading conditions, the input variables such as oxygen flow rate and spraying distance were fluctuated to predict the least possible emission of smoke density and NO_x content. Also the complexity of the developed contours were found to increase with increase in order of the models. From contours and surface plots, the optimal values were obtained. Aavudaiappan *et al.* [13] and Dinesh *et al.* [14] developed empirical models for predicting the responses using RSM, ANOVA, and neural network modelling.

The surface and contour plots for smoke density model with *F vs. O* is shown in figs. 2(a) and 2(b). Similarly, for *S vs. F* and *S vs. O* is shown in figs. 2(c)-2(f). For NO_x model, *F vs. O*, *S vs. O*, and *S vs. F* has been shown in figs. 2(g)-2(l). From the optimization model the optimized values for the HVOF proces parameters were found to be oxygen flow rate of 229 L/m, fuel flow rate of 51.2 L/m and spray distance of 194 mm, to attain minimum smoke density of 27.7 HSU and minimum NO_x emission of 220.8 ppm. For validation, the piston was coated with ZrO_2 and $Al_2O_3$with optimized HVOF process parameters and the combustion experiments were conducted to evaluate the emissions. Under three consecutive validation experiments, the error between the predicted and obtained smoke density and NO_x content was less the 4% which proved that the model was developed with good predictability.

Evaluation of coating composition

Using XRD analysis, the coating which was sprayed under optimized conditions were evaluated further. For evaluation purpose, Al_2O_3 was coated directly over the piston and its XRD is shown in fig. 3(a). Post ZrO_2 coating on piston, the XRD peaks are indicated in fig. 3(b). The XRD coating of Al_2O_3 over ZrO_2 coating is shown in fig. 3(c), indicating the combination of both.

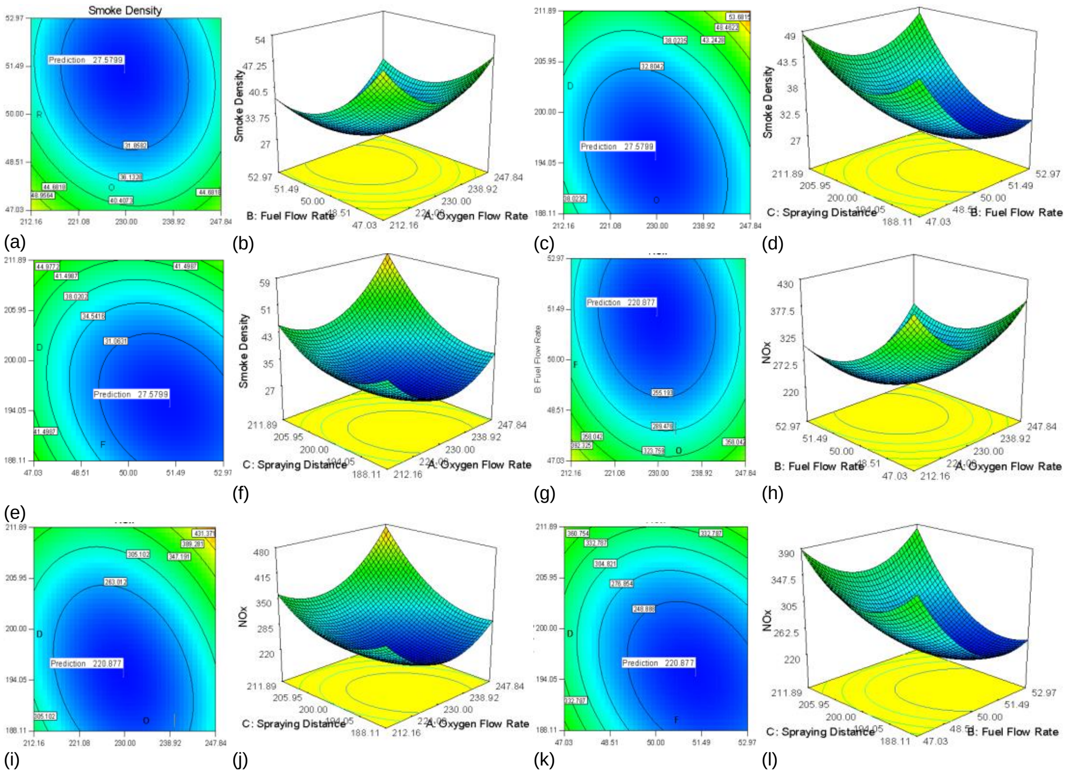

Figure 2. Surface and contour plots (*for color image see journal web site*)

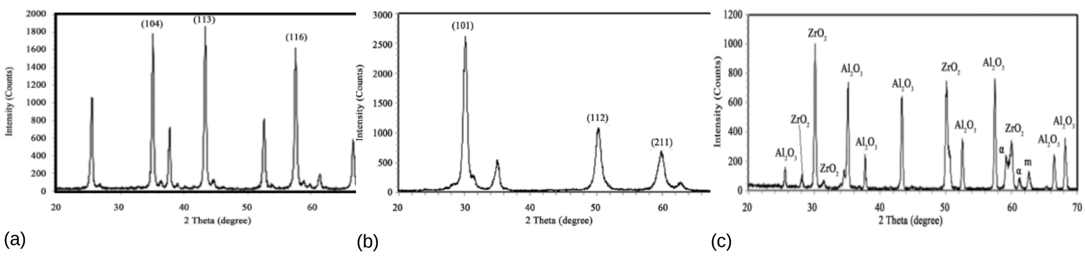

Figure 3. The XRD evaluation

Conclusion

Thus in this paper, an attempt has been made to control emission in IC engines by using thermal coatings of Al_2O_3 over ZrO_2 on the piston by using HVOF thermal spray method. Using a central composite design model, empirical relationships were developed between HVOF process parameters and IC engine emissions such as smoke density and NO_x, which was validated using analysis of variance. At optimized oxygen flow rate of 229 L/m, fuel flow rate of 51.2 L/m and spray distance of 194 mm, minimum smoke density of 27.7 HSU and minimum NO_x emission of 220.8 ppm was predicted which was validated to high accuracy. The XRD evaluation revealed peaks consisting of both ZrO_2 and Al_2O_3 peaks on the coated surface.

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