Research Article

Taguchi method for investigation of the effect of TBC coatings on NiCr bond-coated diesel engine on exhaust gas emissions

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ARTICLE INFO	ABSTRACT
	The NiCr bond coated piston and valve surfaces were coated with Cr_2O_3, Cr_2O_3 + 50% Al_2O_3, Cr_2O_3 + 75% Al_2O_3 powders by thermal barrier coating (TBC). The influence of the coating layers on CO, CO_2, HC and NOx was examined both statistically and experimentally. The statistical investigation was carried out by using Taguchi analysis. According to the experimental test results obtained at different engine speeds, the sample with the highest CO_2 value was found at 2600 rpm in the Cr_2O_3 + 75% Al_2O_3 coated diesel engine and the sample with the lowest CO value was found at 2600 rpm in the Cr_2O_3 + 75% Al_2O_3 coated diesel engine. Also, the sample with the lowest NO_x value was found at 1400 rpm in the standard diesel engine and the sample with the lowest HC value was found at 2600 rpm in the Cr_2O_3 + 75% Al_2O_3 coated diesel engine. Experimental results were analyzed by Taguchi optimization method according to L16 (4^2) orthogonal array. According to the statistical results obtained from ANOVA test, factor levels affecting the exhaust emission values best were found. In general, better emission values have been determined in diesel engines with bond coated ceramic layers.

1. Introduction

In internal combustion engines, deformation and chemical wear on the piston surfaces decrease the service life of the material after a while, resulting in a gradual decrease in performance, an increase in fuel consumption and an increase in emission values. Preventing these surface deformations, which are likely to occur, can be achieved by preventing the high temperature, pressure and chemical wear (corrosion) occurring during the combustion event from directly touching the main material surface. One of the most suitable methods to provide this protection is to cover the surface of the material with a ceramic material, that is, to create a thermal and physical interface on the main material. By coating the combustion chamber elements with ceramic material, temperatures in the cylinders rise and play a vital role in reducing emissions while improving engine efficiency, heat emission rate, specific fuel consumption [1-3].

The combustion chamber is the place where power and energy occur in internal combustion engines. Fuel burning in the combustion chamber causes sudden temperature and pressure changes in the cylinders. Piston is the most exposed part to these suddenly changing loads. During that the engine is operating, the piston's pressure can get to 8 MPa, while the gas temperature is up to 2500 ^{0}C [4].

Thermal barrier coatings (TBCs) are implemented on the surface of these parts to increase the reliability, durability and engine performance of metal parts operating in hot regions in advanced engines [5].

There are some benefits of utilizing TBC in engines working with diesel fuel. Firstly, heat can be kept inside the engine. Secondly, thermal shocks and fatigue can be prevented. Thirdly, it can decrease hydrocarbon and carbon monoxide emission levels. Moreover, in the case of using low quality fuels, TBC engines have the ability to retain heat within the engine although fuel quality is low [6].

Taguchi analysis is a successful method used in the solution of optimization problems with less cost and fewer experiments. Applying the analysis, the quantity of tests is significantly reduced, thus saving time and money spent on experiments. Moreover, the Taguchi method helps the development of high-quality processes and products in every respect. It has minimum sensitivity against uncontrollable factors that may occur in products and production conditions. For this reason, the costs that may arise due to the necessary tolerances can be reduced and the quality process can have a new understanding with the help of the Taguchi loss function [7-9]. Taguchi analysis has been previously applied in various studies regarding the design of experiments [10-13].

In this work, the bond-coated (NiCr) piston and valve surfaces in the internal combustion engine were coated with Cr_2O_3, $Cr_2O_3 + 50\%$ Al_2O_3, $Cr_2O_3 + 75\%$ Al_2O_3 powders by thermal barrier coating (TBC) method, and the influence of the coating layer on CO, CO_2, HC and NOx emissions was optimized by the Taguchi analysis.

2. Material and Method

2.1 Coating Materials

Coating materials and NiCr bond-coated layer were covered with plasma spray method on the piston and valve. The ceramic coating powders and substrates used are given in Table 1. To compare and better understand the results of these three different ceramic powders, measurements were also obtained from a standard diesel engine.

2.2 Engine Tests Method

The combustion chamber elements (piston and valve) of the single-cylinder, four-stroke air-cooled diesel engine were coated with NiCr bond-coated layer and Cr_2O_3, $Cr_2O_3 + 50\%$ Al_2O_3, $Cr_2O_3 + 75\%$ Al_2O_3 powders using the plasma spray coating method. Emission measurement values of standard engine and coated engines were measured with the test setup shown in Figure 1 in the experimental setup. The test engine's technical characteristics used in the experimental setup are given in Table 2.

There was not any modification to the original injection system of the test engine, the engine was operated at the original injection advance of 31 CA and the original injection pressure of 200 bar. The engine was run for 10 minutes for engine test measurements and the engine was brought to operating temperature. Engine test measurements were performed at 4 different engine speeds (1400rpm, 2000rpm, 2600rpm and 3200rpm) at the engine full throttle position.

Table 1. Coating materials used on NiCr bond-coated valve and piston surfaces

Coating Material	Substrates
Standard Engine	Valve and Piston
Cr_2O_3	
$Cr_2O_3 + 50\%$ Al_2O_3	
$Cr_2O_3 + 75\%$ Al_2O_3	

1. Diesel Test Engine   3. Diesel Fuel Tank   5. Control Panel Recording Computer NF Software
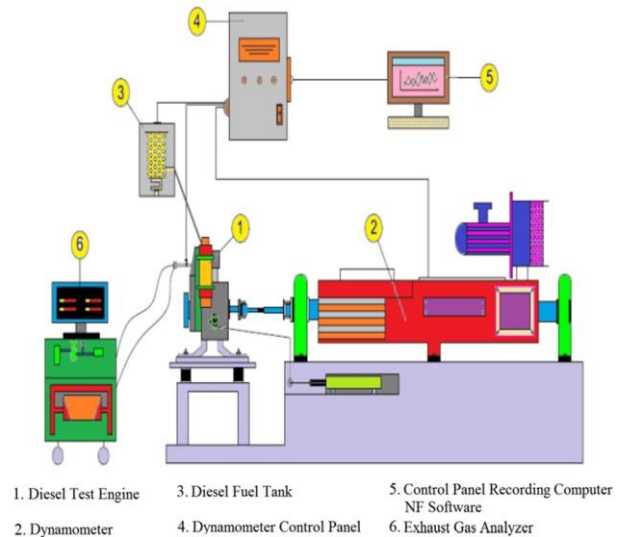2. Dynamometer   4. Dynamometer Control Panel   6. Exhaust Gas Analyzer

Figure 1. Schematic representation of the test setup.

Table 2. The test engine's technical features.

Features	Values
Number of Cylinders	1
Cylinder diameter (mm)	78
Stroke (mm)	62
Cylinder Volume (cc)	296
Compression Ratio	20/1
Maximum power (kW)	4.0
Maximum Engine Speed (rpm)	3600
Tank Volume (L)	3.5
Fuel consumption ratio (g (ml) /kW.h)	3600rpm:285(339)
Crank Angle (CA)	31^0
Injection Pressure (bar)	200

2.3 Statistical Method

The Taguchi analysis is beneficial way of the design of experiments. The results of experimental studies can be achieved utilizing the signal to noise ratio (S/N) [14, 15]. Concepts that can be used to analyze data in a Taguchi study;

- Larger is better
- Nominal is better
- Smaller is better

The information of each parameter used in the experiment can be accessed by performing variance analysis (ANOVA) [14].

This analysis uses L_{16} (4^2) orthogonal array to make the design of the experiments robust. Parameters that might affect the gas emissions are ''engine speed'' and ''coating material''. Table 3 gives the control parameters and levels of 1400 rpm, 2000 rpm, 2600 rpm and 3200 rpm engine speeds with standard diesel engine, NiCr bond-coated diesel engines coated with Cr_2O_3, Cr_2O_3+ 50% Al_2O_3 ve Cr_2O_3+ 75% Al_2O_3 powders.

The models used in the experimental stage of this study are "smaller is better" for CO, HC and NOx emissions while it is "larger is better" for CO_2. The reason is that CO, HC, and NOx emissions are expected to decrease during the engine working, while CO_2 is to increase. Signal noise (S/N) ratios is found applying the formulas below.

''Larger is better'': $S/N = -10 \; x \; log_{10} \left(\frac{1}{n} \sum_{i-1}^{n} \frac{1}{Y_i^2} \right)$ (1)

''Nominal is better'': $S/N = -10 \; x \; log_{10} (s\textasciicircum2)$ (2)

''Smaller is better'': $S/N = -10 \; x \; log_{10} \left(\frac{1}{n} \sum_{i-1}^{n} Y_i^2 \right)$ (3)

S/N: Signal to noise ratio, Y_i : Result of experiment, i = The quantity of repeats

3. Experimental and Statistical Findings

3.1 Analysis of Test Outcomes

In Figure 2, graphs of the rates of CO, CO_2, HC and NOx gases in different speeds of diesel engines coated with different powders and uncoated diesel engine are given.

In Figure 2.a., Changes in carbon monoxide (CO) value are given according to the engine speed obtained from experimental data. When the graphic is analyzed, it is seen that the CO values obtained from the standard diesel engine are at higher rates than all the coated engines. The engine with the lowest CO emission is observed to be Cr_2O_3 + 75% Al_2O_3 coated engine. Another remarkable factor in this graph is that while all the speeds, there is a downward release of CO gas, the rate of CO increases in all engines at 3200 rpm. This may be the reason for the high frequency of closing of the valves at high speeds and the insufficient amount of air entering the engine [16].

Table 3. Levels and control parameters.

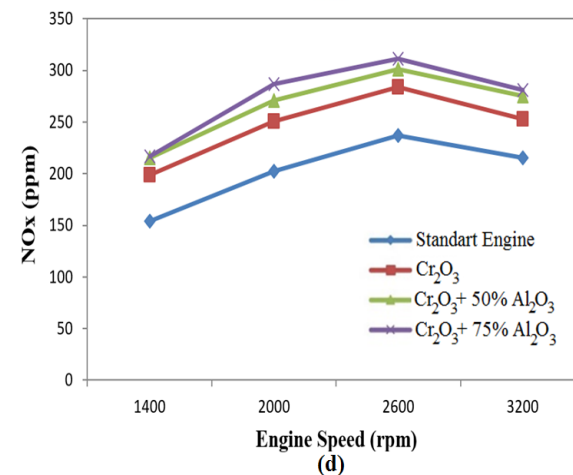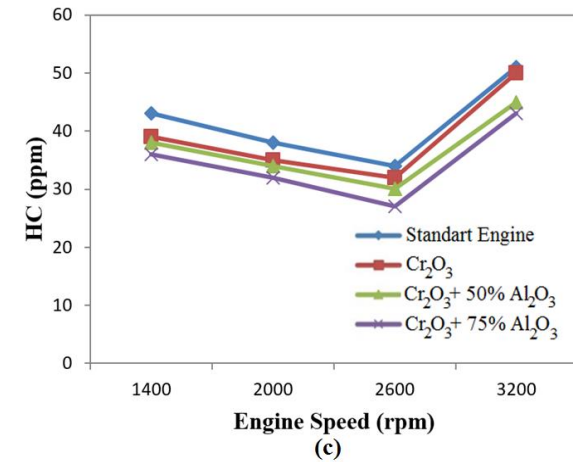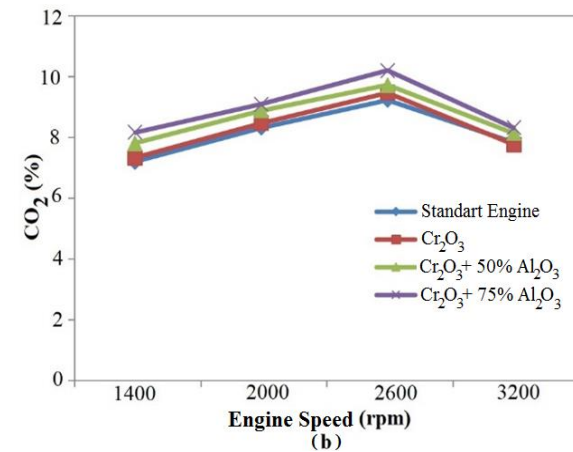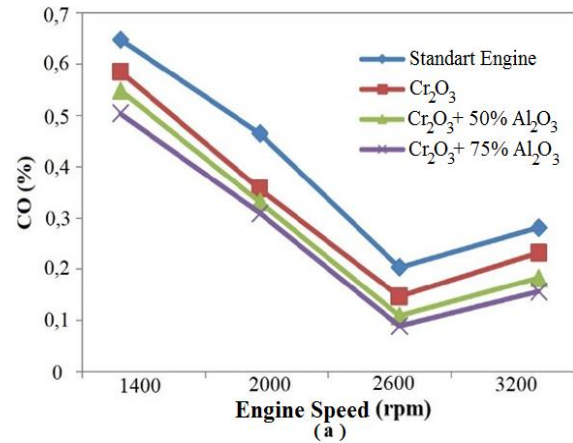| Control parameters	Level 1	Level 2	Level 3	Level 4
Coating Material	Standard engine	Cr_2O_3	Cr_2O_3+ 50% Al_2O_3	Cr_2O_3+ 75% Al_2O_3
Engine Speed	1400 rpm	2000 rpm	2600 rpm	3200 rpm

Figure 2. Exhaust emission values

In Figure 2.b., changes in carbon dioxide (CO_2) value are given according to the engine speed obtained from experimental data. In this graph, it is seen that CO_2 emission has the highest value in engines coated with Cr_2O_3 + 75% Al_2O_3 powders and the lowest value in standard diesel engines. It is also seen that CO_2 emissions increase at 1400 rpm, 2000 rpm and 2600 rpm speeds, but CO_2 rate decreases from 2600 rpm to 3200 rpm. When the speed is low, the CO_2 ratio is lower than the fuel, but when the speed is increased, the momentum increases to the maximum point and improves combustion. In addition, the increase in the amount of fuel and the reduction of the combustion time due to the increase in the engine speed at higher revs can not fully perform the combustion process and this causes the CO_2 emission to decrease [17-18].

A striking situation revealed by both the CO and CO_2 graphs is that the proportions of these gases are almost opposite, meaning that CO_2 emissions are decreasing while CO_2 emissions are decreasing or vice versa [19-20].

In Figure 2.c, the graph shows the change of Hydrocarbon (HC) emissions according to engine speed. It is the main component of hydrogen and carbon fuels. Hydrocarbon emissions are the amount of unburned fuel as a result of partial combustion in the combustion chamber [21]. With ceramic coated engines, there has been a decrease in HC emissions in all engine speeds compared to the standard engine. The main source of HC formation is around the reaction zone where the mixture in the combustion chamber is too poor to ignite. It is thought that, with the increase of the end–burn temperature in coated engines, there is a better combustion in the cylinder and it causes a decrease in HC emissions, as well as the decrease in ignition delay time with the increase in the temperature of the cylinder, and the shortening of the ignition delay, causing the fuel to emerge with the sudden combustion of the fuel.

In Figure 2.d, the graph shows the change of Nitrogen Oxide (NOx) emissions by engine speed. Factors affecting NOx emission in diesel engines are end of combustion temperature, reaction temperature, heat dissipation rate, stoichiometric combustion, ignition delay time, mixture from previous engine cycles and excess oxygen rate. The increase of NOx emission depends on the temperatures inside the cylinder and increases in direct proportion to the temperature increase. With the use of coated pistons, the end of combustion temperature obtained in the cylinder increases. Because the heat generated at the end of combustion by coating the piston surface remains in the cylinder. Thus, the temperature value at the end of combustion increases partially. This situation causes a good combustion start

with the increase of the temperature of the gas in the cylinder in each cycle.

Since the thermal conductivity coefficients of Cr_2O_3 and Al_2O_3 materials are lower than that of AlSi, which is the coating material of the standard combustion chamber of the engine, the temperatures inside the cylinder are trapped, and hence, the end-burn temperature in the cylinder increases [22]. All ceramic coated engines show higher NOx emissions than the standard engine. Ceramic-coated engines create a better thermal barrier coating, thereby raising the temperature inside the cylinder, thus increasing NOx emissions.

3.2 Statistical Results and Taguchi Analysis

The experimental results mentioned in the previous section will also be interpreted in this section with the Taguchi and ANOVA test results.

In this part of the study, emission values of CO, CO_2, HC and NOx exhaust gases will be analyzed. It is desired that the ratios of CO, HC and NOx are minimum since these emissions are toxic and dangerous. Although CO_2 emission is actually dangerous, it is desired to be maximum in this study. The reason for this is that, as mentioned in section 3.1, CO_2 has the opposite action with CO, HC, and NOx. During the experimental design phase, CO, HC, and NOx were evaluated as "smaller is better" but CO_2 as "larger is better".

3.2.1 Carbon monoxide (CO)

Table 4 gives the S/N ratios of CO obtained by using control parameters. These values are expressed graphically in Figure 3. Also, in Table 5, there is a statistical analysis (ANOVA) of S/N ratios obtained as a result of Taguchi analysis using experimental results.

The two parameters are statistically significant on CO values since P values in Table 5 are less than 0.05.

When the values given in Table 4 and Figure 3 are evaluated together, coating material parameter gives S/N ratios minimizing CO ratios in Level 4 and engine speed parameter Level 3.

3.2.2 Carbon dioxide (CO_2)

S/N ratios of CO_2 are given in Table 6. In Figure 4, there is a graphic obtained using these values. In Table 7, there is a statistical analysis (ANOVA) of S/N ratios obtained as a result of the Taguchi analysis using experimental results.

According to the statistical data in Table 7, it can be concluded that independent parameters are statistically significant in explaining CO_2 values since the P value is less than 0.05.

When the values given in Table 6 and Figure 4 are evaluated together, it is seen that the coating material

parameter at the 4th level and the engine speed parameter at the 3rd level make the CO_2 ratios maximum.

Table 4. CO Signal to Noise ratios.

Control Parameters	CO			
	Level 1	Level 2	Level 3	Level 4
Coating Material	7,8	9,223	10,188	10,889*
Engine Speed	4,714	7,962	13,965*	11,459

* Levels that minimize results

Table 5. Variance analysis of CO S/N ratios (ANOVA)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating Material	3	21,458	21,458	7,1526	29,92	0
Engine Speed	3	196,18	196,18	65,393	273,6	0
Residual Error	9	2,151	2,151	0,2390		
Total	15	219,79				

Table 6. CO_2 Signal to Noise ratios.

Control Parameters	CO_2			
	Level 1	Level 2	Level 3	Level 4
Coating Material	7,8	9,223	10,188	10,889*
Engine Speed	4,714	7,962	13,965*	11,459

Table 7. Variance analysis of CO_2 S/N ratios (ANOVA)

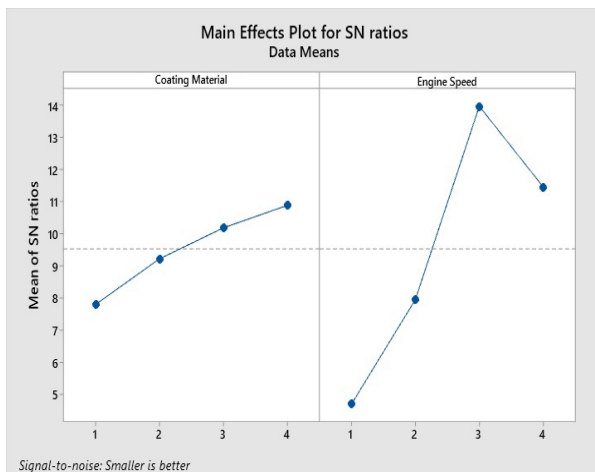| Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating Material	3	21,458	21,458	7,1526	29,92	0
Engine Speed	3	196,179	196,18	65,393	273,6	0
Residual Error	9	2,151	2,151	0,2390		
Total	15	219,788				

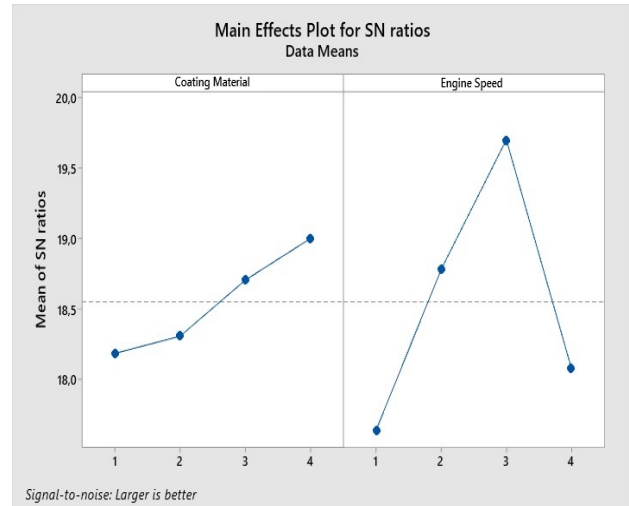Figure 3. CO Signal to Noise graphic

Figure 4. CO_2 Signal to Noise graphic

3.2.3 Nitrogen Oxide (NOx)

Table 8 gives the Signal / Noise (S/N) ratios of NOx obtained using the control parameters mentioned earlier. The values in this table represent the values that give the effect of test parameters on the results. In addition, these values are reflected graphically in Figure 5 to show the effects of coating material and engine speeds on NOx.

These parameters are statistically significant on NOx values according to the statistical results (P <0.05) in Table 9 obtained by using the independent coating materials and engine speeds.

Table 8. NOx Signal to Noise ratios

Control Parameters	NOx			
	Level 1	Level 2	Level 3	Level 4
Coating Material	**-46.00***	-47.77	-48.42	-48.68
Engine Speed	**-45.78***	-47.98	-49.00	-48.12

* Levels that minimize results

Table 9. Variance analysis of NOx S/N ratios (ANOVA)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating Material	3	17,4612	17,4612	5,82039	138,5	0
Engine Speed	3	22,5361	22,5361	7,51205	178,75	0
Residual Error	9	0,3782	0,3782	0,04203		
Total	15	40,3755				

S / N ratios of NOx are given in Table 8, and they are also graphical in Figure 5. Accordingly, both Coating Material and Engine Speed parameters have the highest values in Level 1. The lowest values are at Level 4 in Coating Material parameter, while at Level 3 in Engine Speed parameter.

3.2.4 Hydrocarbon (HC)

In this section, S / N ratios of HC gas are given in Table 10 and Figure 6. In Table 11, there are statistical data of Coating Material and Engine Speed parameters on HC gas ratios.

When Table 11 is examined, it is seen that both Coating Material data and Engine Speed data are statistically significant on HC data (P <0.05).

Based on the data in Table 10 and the graph in Figure 6, it is seen that the values that minimize the results are at Level 4 of the Coating Material parameter and Level 3 of the Engine Speed parameter.

Table 10. HC Signal to Noise ratios

Control Parameters	HC			
	Level 1	Level 2	Level 3	Level 4
Coating Material	-32,26	-31,70	-31,21	**-30,63***
Engine Speed	-31,80	-30,80	**-29,73***	-33,47

* Levels that minimize results

Table 11. Variance analysis of HC S/N ratios (ANOVA)

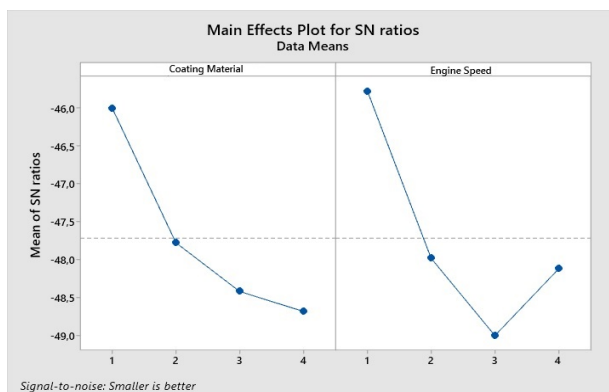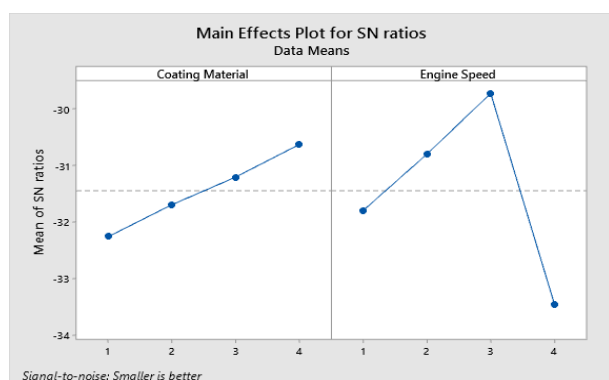| Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating Material	3	5,7913	5,7913	1,9304	50,47	0
Engine Speed	3	30,3296	30,3296	10,1099	264,29	0
Residual Error	9	0,3443	0,3443	0,0383		
Total	15	36,4652				

Figure 5. NOx Signal to Noise graphic

Figure 6. HC Signal to Noise graphic

4. Conclusion

The following results were obtained by looking at the experimental, statistical and Taguchi analysis results.

- While carbon monoxide (CO) and hydrocarbon (HC) emissions are lower in Cr_2O_3, Cr_2O_3 + 50% Al_2O_3 and Cr_2O_3 + 75% Al_2O_3 ceramic coated diesel engines compared to standard diesel engine, nitrogen oxide (NOx) emission is lower in standard diesel engine compared to the other coated diesel engines.
- Carbon dioxide (CO_2) emission is higher in Cr_2O_3, Cr_2O_3 + 50% Al_2O_3 ve Cr_2O_3 + 75% Al_2O_3 ceramic coated diesel engines compared to standard diesel engines.
- The control parameters give statistically significant results (P <0.05) on CO, CO_2, HC and NO_x results.
- While the Taguchi analysis of CO, CO_2 and HC gives the best results in Cr_2O_3 + 75% Al_2O_3 coated diesel engine at 2600 rpm, that of NO_x is best in standard diesel engine at the 1400 rpm.
- According to the experimental and taguchi analyses, CO, CO_2 and HC emissions in ceramic coated diesel engines with NiCr bond-coated layer have better performance than standard diesel engine although standard engine is the best for NO_x emission.

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

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References

1. Masera, K., A.K. Hossain, *Biofuels and thermal barrier: A review on compression ignition engine performance, combustion and exhaust gas emission*, Journal of the Energy Institute, 2019. **92**(3): p. 783-801.

2. Karthikayan, S., S. Ganesan, P. Vasanthakumar, G. Sankaranarayanan, M. Dinakar., *Innovative Research Trends in the Application of Thermal Barrier Metal Coating in Internal Combustion Engines*, Materials Today: Proceedings, 2017. **4**(8): p. 9004-9012.

3. Çolak N.Y. ve D. Şimşek, *Emisyon Kontrol Uygulamalarında Saf Ponza Taşı Kullanılabilirliğini Deneysel Olarak Araştırılması*, Bitlis Eren Üniversitesi Fen Bilimleri Dergisi, 2017. **6**(1): p. 31-41.

4. Heywood, J.B., *Internal Combustion Engine Fundamentals. 1988*, USA:McGraw-Hill Education.

5. Zhou, H., D. Yi, Z. Yu, L. Xiao, *Preparation and thermophysical properties of CeO2 doped La2Zr2O7 ceramic for thermal barrier coatings*, Journal of Alloys Compounds, 2007. **438**: p.217–221.

6. Özel, S., E. Vural, M. Binici, *Optimization of effect of thermal barrier coating (TBC) on diesel engine torque by taguchi method*, in FCE2019: Antalya. p. 393-399.

7. Şirin, E., Ş. Şirin, Y. Turgut, and İ. Korkut, *Optimization of surface roughness using the Taguchi method in milling of AISI D2 cold work tool steel*, Düzce Üniversitesi Bilim ve Teknoloji Dergisi, 2015. **3**(1): p. 132-144.

8. Naik, A.B. and A. C. Reddy, *Optimization of tensile strength in TIG welding using the Taguchi method and analysis of variance (ANOVA)*, Thermal Science and Engineering Progress, 2018. **8**: p. 327-339.

9. Özel, S., H. Turhan, and E. Gönel, *Optimization of effect of production parameters on wear resistance of coated layer on the surface of copper alloy by taguchi method*, Internation Journal of Advance Research and Innovative Ideas in Education, 2017. **3**(4): p. 1517-1523.

10. Park, I. C. and S. J. Kim, *Cavitation erosion behavior in seawater of electroless Ni-P coating and process optimization using Taguchi method*, Applied Surface Science, 2018. **477**: p. 37-43.

11. Tabaraki, R. and A. Nateghi, *Application of taguchi L16 orthogonal array design to optimize hydrazine biosorption by Sargassum ilicifolium*, Environmental Progress & Sustainable Energy, 2016. **35**(5): p. 1450-1457.

12. Moganapriya, C., R. Rajasekar, K. Ponappa, R. Venkatesh and S. Jerome, *Influence of coating material and cutting parameters on surface roughness and material removal rate in turning process using taguchi method*, Materials Today: Proceedings, 2018. **5** (2): p. 8532-8538.

13. Trivedi, H.K. and D.V. Bhatt, *An experimental investigation on friction and wear test parameters of cylinder liner and piston ring pair using Taguchi technique*, Industrial Lubrication and Tribology, 2018. **70**(9): p. 1721-1728.

14. Montgomery, D.C., *Design and Analysis of Experiments. 2017*, USA: John Wiley & Sons, Inc.

15. Maghsoodloo, S., G. Ozdemir, V. Jordan, and C. H. Huang, *Strengths and limitations of Taguchi's contributions to quality, manufacturing, and process engineering*, Journal of Manufacturing systems, 2004. **23**(2): p. 73-126.

16. Ciniviz, M., *Türboşarjlı bir dizel motorunun yanma odasi yüzeylerinin Y2O3 – ZrO2 ile kaplanmasının performans ve emisyonlara etkileri*, in *Mechanical Engineering* 2005, Selçuk University:Turkey.

17. Vural, E., and S. Özel, *Dizel Bir Motorda Al2O3 İlaveli Cr2O3 Termal Bariyer Kaplamaların Egzoz Emisyonlarına Etkisi*, Bitlis Eren Üniversitesi Fen Bilimleri Dergisi, 2019. **8**(1): p. 308-318.

18. Akçay M. And S. Özer, *Experimental investigation on performance and emission characteristics of a CI diesel engine fueled with fusel oil/diesel fuel blends*, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2019. Published online, in press.

19. Vural, E., S. Özel, *İçten yanmalı dizel motorda Cr2O3 termal bariyer kaplamaların motor performansı üzerine etkisi*, in INCOS2018: Karabük. p. 374-378.

20. Celik, M. B., *Experimental determination of suitable ethanol–gasoline blend rate at high compression ratio for gasoline engine*, Applied Thermal Engineering, 2008. **28**(5-6): p. 396-404.

21. Goga, G., B. S. Chauhan, S. K. Mahla, H. M. Cho, *Performance and emission characteristics of diesel engine fueled with rice bran biodiesel and n-butanol*, Energy Reports, 2019. **5**: p. 78–83.

22. Vural E. And S. Ozer, *Thermal Analysis of a Piston Coated with SiC and MgOZrO2 Thermal Barrier Materials,* International Journal of Scientific and Technological Research, 2015. **1**(7): p. 43-51.