COATING OF DIESEL ENGINE WITH NEW GENERATION CERAMIC MATERIAL TO IMPROVE COMBUSTION AND PERFORMANCE

by

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In this study, piston and valve surfaces of a Diesel engine to improve exhaust emission and engine performance values, NiCr with bond coat and without bond coat with Cr_2O_3, Al_2O_3+13%TiO_2, Cr_2O_3+25%Al_2O_3 coatings were coated using plasma spray method. By examining the micro-structures of the coating materials, it was observed that a good coating bond is formed. In this study, unlike other coating applications, two different and proportions of specific ceramic powders were coated on the combustion chamber elements, mounted on a Diesel engine, and their effects on engine performance and emissions were tested on the engine dynamometer. For this purpose, the internal combustion engine was operated at 1400, 1700, 2000, 2300, 2600, 2900, and 3200 rpm engine speeds and engine power, engine torque, in-cylinder pressure changes and heat release rate values were recorded. In this study, the that results were obtained by comparing thermal barrier coated engine with standard engine. An increase of 14.92% in maximum engine power, 12.35% in engine torque, 13% in-cylinder pressure, heat release rate by 4.5%, and brake thermal efficiency by 10.17% was detected, while brake specific fuel consumption decreased by 14.96%.

Key words: *Diesel engine, performance, combustion, plasma spray coating, bond coat NiCr*

Introduction

Heat loss in Diesel engines is an important variable in determining the total performance and size of Diesel engines. In Diesel engines, only 1/3 of the total energy obtained due to energy losses caused by cooling water, exhaust, heat transfer, and mechanical friction is used as useful energy [1]. Therefore, heat losses must be reduced to improve engine efficiency. The efficiency and overall performance of the Diesel engine can be increased by using these temperatures and converted into useful work. It is emphasized that the piston, cylinder head, combustion chamber and valve surfaces can be achieved using thermal barrier coating (TBC) technology to minimize heat transfer [2-4]. The TBC is the coating of combustion chamber elements of internal combustion engines with ceramic materials with low thermal conductivity coefficient.

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In these engines, the insulation of combustion chamber elements reduces the heat transfer between the gas and cylinder liners inside the cylinder, preventing the heat from the combustion chamber from going to the cooler and keeping it under control and saving the energy from the combustion chamber in a useful way [5]. Each TBC material has its own characteristics and it is very important to select and cover the TBC material correctly for the application areas. The most common method is plasma spray coating in the selection of ceramic materials in the surface modification of combustion chamber elements in internal combustion engines with low thermal conductivity, and in the coating of these materials in a substrate material, low cost, and ease of applicability [5-10]. Ceramics, with their ability to resist wear and corrosion, low thermal conductivity and light mass, are among the important research topics of automotive design engineers, so currently, research on ceramic coated engines continues. Omar *et al.* [11], covered the piston of a single-cylinder, air-cooled, 4-stroke and direct injection Diesel engine with lanthanum zirconated ($La_2Zr_2O_7$) by plasma spray coating method in their study. In the results of the experiment, they reported that engine torque increased by 3%, cylinder pressures increased by 8.8%, and specific fuel consumption decreased by 1.26-2.6%. Mohamed *et al.* [12] in their study, they covered the piston surface of a single-cylinder, water-cooled, four-stroke diesel engine with intermediate (Ni-Al)PSZ/Al_2O_3 powders with plasma spray method and performed engine performance analysis decoyer: As a result of the experiments, they found that the pressure in the cylinder increased by up to 72 bar, the thermal efficiency of thermal efficiency increased by about 4.6% compared to the coated engines, and the exhaust gas temperature increased by 12.6%. The TBC materials inside the cylinder in diesel vehicles are used to increase the reliability, durability, engine efficiency and performance of the hot parts of the metal components in the engine. For this reason, TBC materials of the combustion chamber elements of diesel vehicles are constantly being researched and the search for new materials is increasing day by day [8]. A literature review shows that the application of TBC has been widely used to improve engine performance and has become an important issue in recent years. In the studies of the researchers, there is not much study on TBC applications of Cr_2O_3 and Al_2O_3 + 13% TiO_2 ceramic powder mixtures in engines. In previous studies, engine performance experiments of Cr_2O_3 and Al_2O_3 + 13% TiO_2 coatings to a Diesel engine were not examined in detail. In this study, the piston and valve surfaces of a Diesel engine were covered with NiCr bond layer and without bond layer Cr_2O_3, Al_2O_3 + 13% TiO_2, Cr_2O_3 + 25% Al_2O_3 powders using plasma spray method and engine combustion and performance were investigated in detail.

Materials and methods

In the experiments, single-cylinder, the 4-stroke, air cooled, direct injection Diesel engine was used. The technical specifications of the test engine are given in tab. 1. Pistons and valves of test engine with plasma spray coating method with NiCr bond coat and without bond coat Cr_2O_3, Al_2O_3 + 13% TiO_2, Cr_2O_3 + 25% Al_2O_3 were coated powder. Samples were subjected to surface roughening using Al_2O_3 under 60 psi pressure in order to ensure surface roughness. Plasma spray coating processes were carried out with a 3 MB plasma gun in the coating unit. The schematic picture of the coated piston is given in fig. 1. The powder and ratios to be coated on the surface and specimen codes are given in tab. 2. In order to keep the compression ratio of the standard engine constant with the value in the catalog, the chip has been removed from the piston and valve surfaces as much as the coating thickness. For pistons and valves (suction, exhaust), 200-300 μm thick coatings were obtained in CE1, CE2, and CE3 samples. The surface of CE4, CE5, and CE6 samples were coated with 350-450 μm thick coatings (80-150 μm thick for NiCr bond coat).

Table 1. Technical feature of the test engine

Engine type	Single cylinder, 4-stroke, air-cooled, direct injection, Diesel engine
Bore stroke [mm(in)]	78 × 62(3.07 × 2.44)
Displacement [ml(cu.in)]	296(18.06)
Engine speed (rpm)	3600
Compression ratio	20:1
Rated output power [kW(hp)/rpm]	4.0(5.44)/3600
Fuel tank volume [L(gal.)]	3.5(0.77)
Fuel consumption rate [g(ml)/kW.h]	3600 rpm: 285(339)
Crank agle [°]	310
Injection pressure [bar]	200

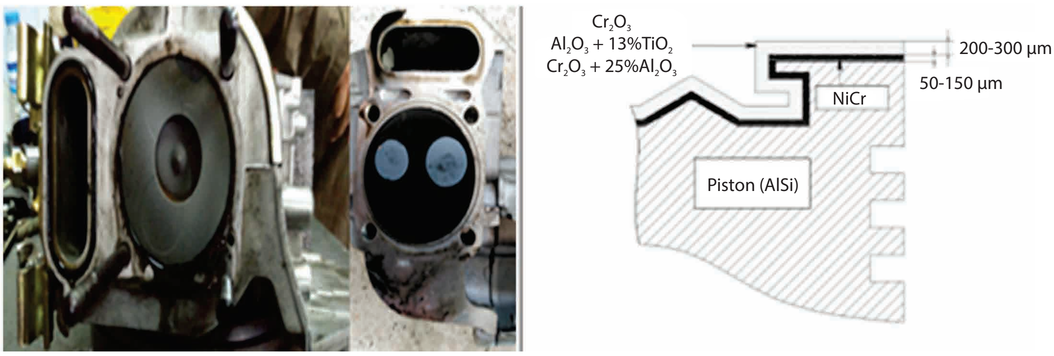

Figure 1. Coated piston valve images and schematic drawing

Table 2. Powder and proportions that will be coated on the surface

Specimens	Coating materials	Boand coat	Coating layer thicknesses [µm]
CE0	Standart engine	–	–
CE1	Cr_2O_3	–	200-300
CE2	Al_2O_3 + 13% TiO_2	–	200-300
CE3	Cr_2O_3 + 25% Al_2O_3	–	200-300
CE4	Cr_2O_3	NiCr	300-450
CE5	Al_2O_3 + 13% TiO_2	NiCr	300-450
CE6	Cr_2O_3 + 25% Al_2O_3	NiCr	300-450

In the experiments, diesel fuel which is given in tab. 3 is used. Diesel fuel meets EN590 standards. For the measurement of internal combustion engine speed, torque, power, and specific fuel consumption and exhaust gas temperature in experiments Netfren brand, 26 kW power based on the principle of the Fottinger hydrodynamic dynamometer was used Netfren brand software automatically calculates the measured data and is saved to the computer in real time. There was not any modification 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. During the experiments, the in-cylinder pressures were carried out with a piozza Electric Pressure sensor from Kistler brand 4065A and a 4618a amplifier compatible with the sensor. An Opkon optical encoder is attached to the crankshaft to determine the change of cylinder pressures with the crankshaft angle. In-cylinder pressure values are recorded to the computer in such a way that a value at 0.25 CA° is recorded. A Pico brand oscilloscope and computer were used to record the data. One pressure cycle was calculated by taking the average of 50 cycles.

Table 3. Diesel fuel properties

Fuel specification	Diesel
Chemical structure	$C_{13}H_{28}$
Lower heating value [kJkg^{-1}]	42500
Autoignition temperature [°C]	240
Boiling point [°C]	160-370
Cetane index	52
Viscosity-kinematic at 40 °C	3
Density (15 °C) [kgL^{-1}]	0.83
Latent heat of evaporation [MJkg^{-1}]	0.260
Carbon/hydrogen ratio (C/H)	~0.47
Complies with EN590 standards	

Heat release rate (HRR) of thermodynamics eq. (1) by applying the law, equality was calculated with the help of 1. Considering wall heat loss when calculating heat dissipation have not been taken. In *e.g.* 1, k is the constant polytrophic exponent, and this is the study was taken as 1.35 [13]:

$$\frac{\mathrm{d}Qn}{\mathrm{d}\theta}=\frac{k}{k-1}p\frac{\mathrm{d}V}{\mathrm{d}\theta}+\frac{1}{k-1}V\frac{\mathrm{d}P}{\mathrm{d}\theta} \tag{1}$$

Engine test measurements were performed at seven different engine speeds (1400, 1700, 2000, 2300, 2600, and 3200 rpm) at the engine full throttle position. It was thought that the engine had reached operating temperature at the point where the temperature remained constant and then the measurement parameters were started to be taken. The experiments were repeated three times and were used to transfer the average to the graphs. A schematic picture of the experimental set-up was given in fig. 2.

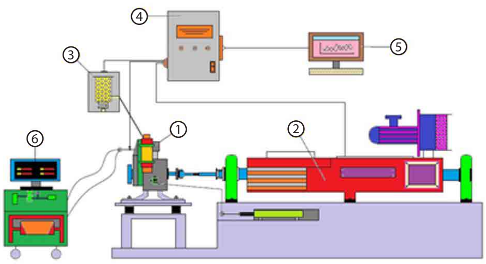

Figure 2. Engine test mechanism schematic view: *1 – diesel test engine, 2 – dynamometar, 3 – diesel fuel tank, 4 – dynamometar control panel, 5 – control panel recording computer NF software, 6 – exhaust gas analyzer*

Results and discussion

The coating layer

The SEM photos of samples CE2 and CE5 are shown in fig. 3. Figure 3 shows that there is no gap between the coating layer and the substrate material. For micro-structure images of other samples, the literature study of [14] can be examined.

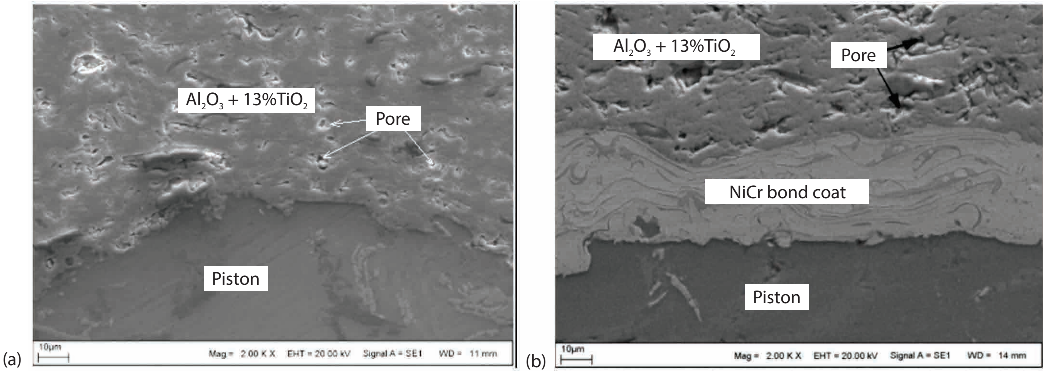

Figure 3. (a) The CE2 and (b) SEM micro-structure appearance of samples CE5

The thermal conductivity of Al_2O_3 + 13% TiO_2 ceramic material is low [15]. In the samples CE2 and CE5, it was observed that the porosity was less. For this reason, thermal barrier properties are thought to yield higher results than other samples. The amount of pore in plasma spray coatings affects thermal conduction coefficient [16].

Engine performance

Figure 4 shows the effect of coatings on engine power, fig. 4(a), and torque, fig 4(b). In internal combustion engines, the engine power of the active cylinder is obtained as a result of burning of the fuel in the unit time is useful work. The combustion reaction in Diesel engines starts with the spraying of the fuel. The fuel must reach the ignition temperature in order to burn. The duration of fuel injection from the injector to the combustion reaction of the fuel is slow and full of fuel for it to burn in the first place, it must undergo a certain period of time. For this reason, Diesel engines are given the advance of ignition, so during the delay of ignition is more fuel consumption into the cylinders. Therefore, the temperature of the fuel and ignition advance in the cylinder, it is observed that ignition temperature is an important parameter [17, 18]. Fuel consumption in the range of the most efficient burning of both fuel consumption, according to the unit fuel consumption is thought to be maximum engine power. The results obtained in figs. 4(a) and fig. 5 show that it supports this situation. Figure 4(a) shows that engine power increases with increasing engine speed for all coating types. Depending on the number of cycles, the number of cycles in the unit time has also increased. With the increase in the number of cycles, the air-flow in the cylinder at absorption time by affecting the air-fuel ratio mixture has increased homogeneity. Engine power up to 2600 rpm as quickly as, and then slowly increased. This is because the engine speed is too high, so there is not enough time to burn the whole of the fuel that is sprayed into the cylinder. When the increase in engine power was examined for all test engines, it was observed that the thermal barrier effect resulting from ceramic coating improved combustion efficiency and the coated engine work produced better engine power in the same conditions as the non-coated Diesel engine. Since the fuel that creates the pressure inside the cylinder is caused by the end of combustion temperature and the sudden increase in temperature inside the cylinder, it is thought that the ceramic coated engines increase the power by creating higher temperatures in the combustion chamber. The highest engine power in standard and coated engines was found to be at 3200 rpm. This is due to the increase in engine speed, the amount of fuel increases, so the increased fuel density causes the engine power to increase [19]. Thermal barrier coated engine increased engine power by 1.72%

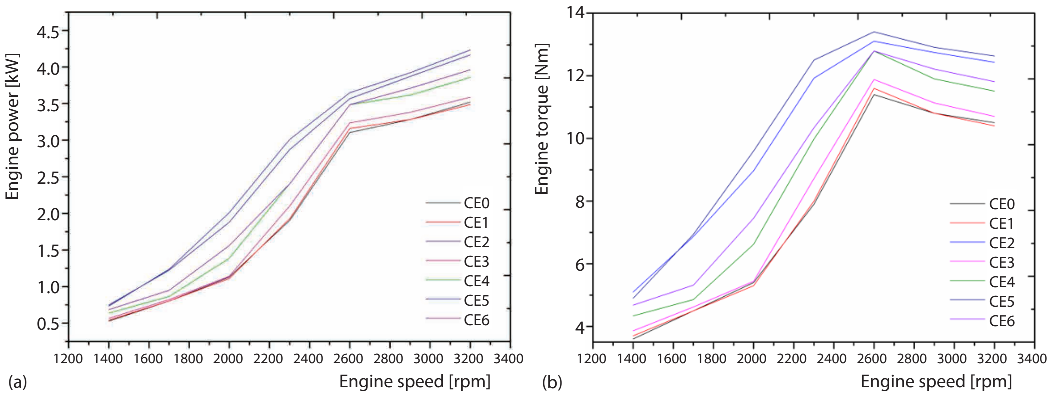

Figure 4. Changes under different speed; (a) engine power and (b) torque

in CE1 sample, 4.84% in CE3 sample, 10.86% in CE4 and CE6 samples, 12.97% in CE2 and 14.92% in CE5 sample when compared to standard engine.

Figure 4 (b) shows the effect of coatings on the engine torque. In internal combustion engines, torque can be called the rotational force from the cylinder arm as a result of the pressure obtained at the end of the combustion of the fuel inside the cylinder affects the piston surface. Torque is an important measure of the engines ability to do work, but its size depends on the characteristics of the engine [20].

As the engine speed increases in internal combustion engines, the increase in engine torque is seen, and this increase is seen again by-passing a maximum point [21]. The increase in torque with increased engine speed, after 2600 rpm, is thought to reduce engine torque due to the increase in cylinder walls and gas temperatures resulting from the increase in volume efficiency and increased friction losses at high speeds as a result of TBC. Thermal barrier coated engines are known to have high combustion end temperature. As we mentioned earlier, the reaction time decreases with the injection of fuel into the cylinders, so the ignition time decreases [17]. However, the air/fuel ratio is fully met with each other and has formed a homogeneous mixture because the spraying time is reduced. Thus, volumetric efficiency is increased, so it is thought to increase the torque of the engine. In addition, increasing the temperature in the cylinder causes the pressure coming to the piston surface to increase. Therefore, all thermal barrier coated engines have increased torque compared to the standard engine. Thermal barrier coated engines increased by 1.52% in CE1 sample, 3.63% in CE3 sample, 8.61% in CE4 and CE6 sample, 10.73% in CE2 and 12.35% in CE5 sample when compared to standard engine. In internal combustion engines, torque and power are terms that change in connection with each other. The net torque generated by combustion can be increased by increasing the average effective pressure or by decreasing the losses in the cylinder block. Figure 5 shows that the torque obtained from the engine is increased due to the increased engine speed. The heat losses in the cylinder block in the engine operated by thermal coating were reduced and more of the heat energy resulting from combustion was converted into mechanical energy. This has led to higher engine torque in the coated engine compared to the without bond coat standard engine. However, the engine torque is a slight decrease as the high speed goes up. The reason for this is thought to be the negative effect of temperature rise in cylinder block and combustion gases on volumetric efficiency at high speeds.

Figure 5 shows the effect of coatings on brake specific fuel consumption (BSFC). It is known that more pressure is applied to the piston surface with the increase in combustion end temperature in coated engines [22]. This means more useful work with the same amount of fuel. In general, the thermal barrier coated engines have less fuel consumption than the standard engine [23, 24]. The reason for reduced BSFC values with the use of coated pistons is considered as a result of the increase in combustion temperature. The 2600 rpm, where specific fuel consumption is lowest, corresponds to engine speed with the highest engine torque. This is thought to be due to the high combustion temperature and the fact that the fuel/air mixture becomes much closer to the stoichiometric ratio. With the use of TBC engine, BSFC reduction has been determined in all engine revolutions compared to CE0 piston. Thermal barrier coated engines were found to have decreased by 1.07% in CE1 sample, 2.34% in CE3 sample, 2.82% in CE4 sample, 4.34% in CE6 sample, 11.82% in CE2 and 14.96% in CE5 sample compared to standard engine.

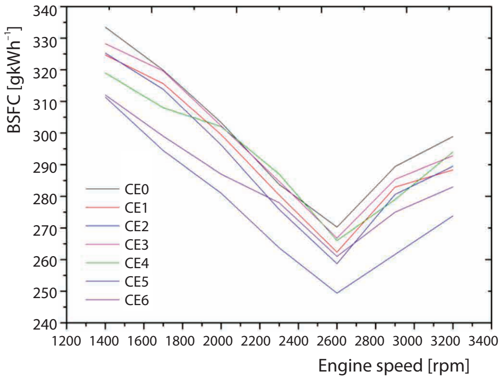

Figure 5. The BSFC changes under different speed

Figure 6(a) shows the effect of the coating on the in-cylinder pressure and fig. 6(b) HRR change for the 2600 rpm engine speed at which maximum torque is achieved. In internal combustion engines, the curves of the gas pressures in the cylinder according to the position of the crankshaft are expressed by the change of pressure in the cylinder. Here the state of combustion can be analysed better. It is observed that similar gas pressure profile is formed with the CE0 piston along with the coating. This suggests that similar critical mechanical loads, combined with the use of cladding at the engine speed at which maximum engine torque occurs. In addition, it is seen that the thermal barrier with the coating is effective and that the in-cylinder pressure values and combustion timing vary. Similar studies on coatings have also shown that thermal coating reduces the thermal conductivity and increases the pressure in the cylinder by storing more heat in the cylinder [24, 25]. In this study, like similar studies in the literature, it was observed that changes in cylinder pressures occur according to the quality of the thermal conductivity coefficients. As can be seen, coated engines also increase heat dissipation rates. The highest heat dissipation

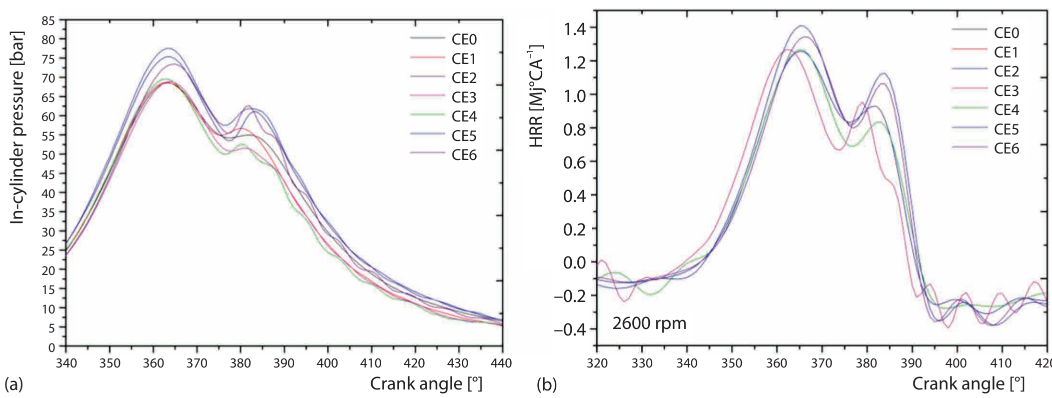

Figure 6. Changes at 2600 rpm; (a) in-cylinder pressure and (b) HRR

value is achieved with the CE5 coating, while the lowest heat dissipation rate is achieved with the uncoated engine. It is observed that the coating provides thermal insulation and increases engine power as well as increases the rate of heat dissipation.

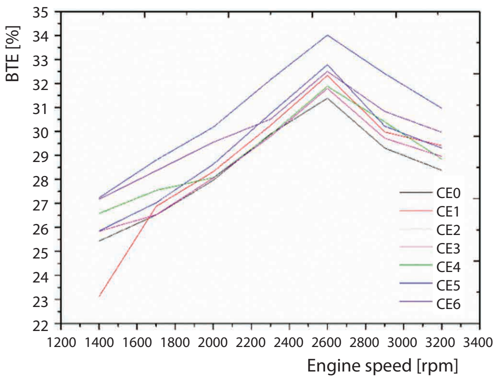

Figure 7. The BTE changes under different speed

In fig. 7, the brake thermal efficiency (BTE) change of the thermal barrier coated engines and the standard engine is given. It has been observed that BTE increases in engines covered with thermal barrier. Important parameters affecting the thermal efficiency of the brake ignition delay, combustion temperature, the chemical and physical properties of the fuel are. The increase in combustion temperature with TBC has been observed to increase the thermal efficiency of brake and it has been determined that this situation is in harmony with the literature [26].

The highest thermal efficiency was found in the CE5 coated engine. With the decrease in porosity in the coating, the coating formed a good thermal barrier to the pistons and valve surfaces, causing the BTE to increase. Thermal barrier coated engines have increased BTE by 0.89% in CE1 sample, 2.66% in CE3 sample, 3.39% in CE4 sample, 4.84% in CE6 sample, 8.73% in CE2 and 10.17% in CE5 sample compared to standard engine. With the increasing engine speed, BTE has also increased. This shows that a more efficient combustion occurs in the cylinder due to the increase in engine speed. However, in high engine speed, the combustion efficiency decreases with the shorter time required for combustion and the cooling of the engine block. In addition, the excessive temperature increase of combustion gases reduces volumetric efficiency and causes BTE to decrease. In general, thermal coatings at all engine speeds and better performance values were achieved in BTE compared to the standard diesel engine.

Conclusions

The results of the experimental study showed that when compared to standard engine and thermal barrier coated engines, engine power, engine torque, in-cylinder pressure, HRR and BTE increase and decrease in BSFC were observed in thermal barrier coated engines.

In this experimental study, by examining the micro-structures of the coating materials, it was observed that a good coating bond is formed, it was determined that ceramic powders can be easily coated on the piston surface by plasma spray coating method. The best results were obtained in the samples covered with bond coat and without bond coat Al_2O_3 + 13%TiO_2 powder. The samples covered with Al_2O_3 + 13% TiO_2 powder were observed to have at least porosity and to create the best thermal barrier. Also Al_2O_3 + 13% TiO_2 TBC thermal conductivity coefficient is lower than Cr_2O_3, and 25% Al_2O_3 powder in the Cr_2O_3 material has improved engine performance.

The TBC at all engine speeds the an increase of 1.72% to 14.92% in maximum engine power, 1.52-12.35% in engine torque, 0.33-13% in-cylinder pressure, HRR by 4.5% and BTE by 1.07-10.17% was detected, while BSFC decreased by 14.96%.

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