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Experimental Investigation on Effect of the Zirconium + Magnesium Coating of the Piston and Valve of the Single-Cylinder Diesel Engine to the Engine Performance and Emission

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Abstract**—**The four-stroke single cylinder diesel engine has been used in this study, the pistons and valves of the engine have been stabilized, the aluminum oxide (Al_2O_3) in different ratios has been added in the power of zirconium (ZrO_2) magnesium oxide (MgO), and has been coated with the plasma spray method. The pistons and valves of the combustion chamber of the engine are coated with 5 different (ZrO_2 + MgO), (ZrO_2 + MgO + 25% Al_2O_3), (ZrO_2 + MgO + 50% Al_2O_3), (ZrO_2 + MgO + 75% Al_2O_3), (Al_2O_3) sample. The material tests have been made for each of the coated engine parts with the scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) using Cu Kα radiation surface analysis methods. The engine tests have been repeated for each sample in any electric dynamometer in full power 1600 rpm, 2000 rpm, 2400 rpm and 2800 rpm engine speeds. The material analysis and engine tests have shown that the best performance has been performed with (ZrO_2 + MgO + 50% Al_2O_3). Thus, there is no significant change in HC and Smoke emissions, but NOx emission is increased, as the engine improves power, torque, specific fuel consumption and CO emissions in the tests made with sample A3.

Keywords**—**Ceramic coating, material characterization, engine performance, exhaust emissions.

I. Introduction

THE needs for high performance materials are further enhanced by rapidly developing technology. One of the areas where these high-performance materials are used is the internal combustion engines [1]. Motor vehicle is a professional unit showing the development with interdisciplinary studies of the technological sciences such as electrical, electronic, mechanical, automation and materials science. In recent years, the automotive sector is rapidly developing along with developments in the profession, as reflected in the automotive industry. In this sense, materials science is the basis of motor vehicles. Today's such durable materials enable the production and development of high speed and durable vehicles. The technology transferred from the Formula 1 track at which high competition has been experienced is the basis of today's motor vehicles. When considered that the first composite material was used in Formula 1 cars and the first light and highly durable engine materials were used in this type of racing vehicles, it is more clearly emerging how materials science has the great importance. Coating technology is another focused important area of materials science which researchers works on it for many years. The coated solid materials production and improvement of the properties of the materials were made available in other materials [2], [3].

In today's engine design, the designers have focused on the following three points;

- Long-lasting engine component design
- Wear and corrosion resistant lightweight engine parts
- Low fuel consumption and emissions

In addition, these three points is an important selective factor for motor vehicle buyers [4], [5]. But the only way to collect these three points present in an engine is to use high-technologic methods. One of these methods that are used in advanced technology is a method to coat the materials with other materials. This method has been used to increase toughness of the metal casing of the space shuttle that is sent to the space first time. With this method, which is generally referred to as ceramic coating, the space shuttle has been withstood the abrasion and forming a heat barrier able to protect the space shuttle. At first, the ceramic coating, which is coated with a traditional method, is now professionalized and the coating process is simplified. The coating process may be prolonged life of the material in general, heat transmission is modified and friction properties are improved [6]. Moreover, some characteristics of the coating and the metal materials with different properties are also being equipped. Due to the reduced cost of the coating process, many areas are used today. Because of these recent developments in metal coating technology, the costs are also diminished and the application fields of the coating technology is expanding [7], [8].

Despite the many aspects of change and renewal from the date that the internal combustion engine was first discovered to present day, we have advanced less to obtain useful work from engine fuel. The useful work is measured by the work obtained over the engine flywheel in internal combustion engines. In many studies, it is known that some part of the fuels taken inside cylinder has been discharged by irradiation, the engine cooling system and the exhaust gases from the

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exhaust. For this reason, one of the major issues studied the internal combustion engine is to increase efficiency of the engine and ensure the longevity of the engine. Here technology that combines these two elements is coating technology [9].

Many parts of the internal combustion engine work in harmony with each other, and this can generate power at the end. Even the fuel getting into the cylinder has a different way to ignite in gasoline and diesel engines, it is working according to the principle that the basic pushing of the piston with the burning fuel. The vehicles are moved by being pushed by the piston or pistons to the crankshaft. The pistons are the leading materials of engine having direct contact with the burnt fuels. In addition to this, pistons must be lightweight to bring motor cycle up to desired point. The lightweight and durable pistons have important role in increasing more than 6000 rpm engine power at present. The other engine parts exposed to the burnt fuel are valves. The valves are like guardians of two gates opened inside cylinders mounted on the door of the cylinder. Two valves are available for each cylinder. One of them provides air or air-fuel mixture, while the other exhausts the exhaust gas. The two engine parts are exposed to varying high pressure and burnt gases from the heat, as well as being subject to deformation due to many movement variations within the seconds. For this reason, the coating of that two engine parts have been targeted in this study [10].

In literature, it appears that many studies are available for the fuels and type of different coatings. We emphasize that many of these studies cause positive developments in emission and engine performance of the coatings.

In the study, we have examined the effect of the various amounts of Al_2O_3 and TiO_2 coating with plasma spraying method and piston in a single cylinder diesel engine to the engine performance and emission. The engine performance increases with the piston and ceramic coating of the cylinder, and improvements appear in the consumption of fuel. In addition, there is decrease in the other exhaust gasses except for the NOx emissions in terms of the engine emission [6], [11]-[14]. In [15], Kumar et al. coated the parts of the single-cylinder diesel engine with the lanthanum zirconate, used the pinnata oil to run the engine, and measured engine performance and exhaust emissions. At the end of the study, they have found increase in engine performance, decrease in specific fuel consumption, and improvement in exhaust emissions [15].

In this study, the piston and valves of the air-cooled single-cylinder diesel engine has been coated, and its effect on engine performance and emission has been examined. Engine pistons and valves were coated with various ratios coating materials to find the engine performance and exhaust emission test results. Each sample is metallographically tested and compared with the engine test results to find out relationships between them [1].

II. Material and Method

A. Coating Material

In these experimental interdisciplinary studies, metallurgy and automotive engineering are combined and the engine in which the motor characterization and the emission can be studied is determined [1]. The necessary information has been given in Table I with regard to the engine used in tests.

TABLE I
TECHNICAL FEATURE OF THE TEST ENGINE

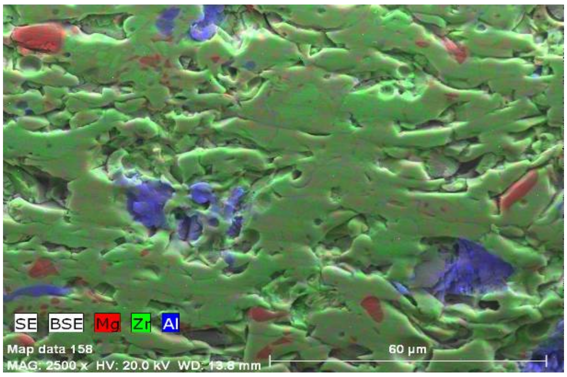
Model	4-stroke, direct injection diesel engine
Number of cylinder	1
Diameter of cylinder	78 mm
Stroke	62 mm
Compression ratio	18 /1
Valve arrangement	Overhead cam, two-valve
Maximum engine speed	3000 1/min

The plasma spraying method is used for coating of the engine parts with ceramic. The metal powders that are used in coating are the zirconium (ZrO_2) and magnesium oxide (MgO) in 210 NS standards of the Sulzer Metco company, and the aluminum oxide (Al_2O_3) powder makes coating added in certain amounts to this powder. Any of this coating types created in this study has been coded as;

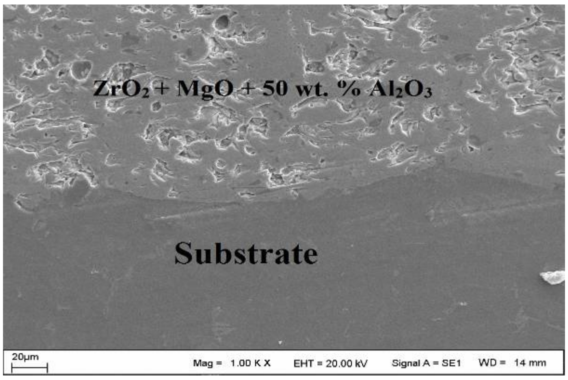
- For Standard Piston (AlSi12CuNi): A0
- For (ZrO_2 + MgO): A1
- For (ZrO_2 + MgO + % 25 Al_2O_3): A2
- For (ZrO_2 + MgO + % 50 Al_2O_3): A3
- For (ZrO_2 + MgO + % 75 Al_2O_3): A4
- For (Al_2O_3): A5.

The workshops of the Türk Hava Yolları Teknik A.Ş have been used for coating. The material tests of this coated 10 valves and 5 pistons have been made in the Malatya İnönü University, Scientific and Technologic Research Center. The SEM, EDX and XRD using Cu Kα radiation surface analysis methods have been applied to the coated materials to understand relations of material and coating surface with each other in detail.

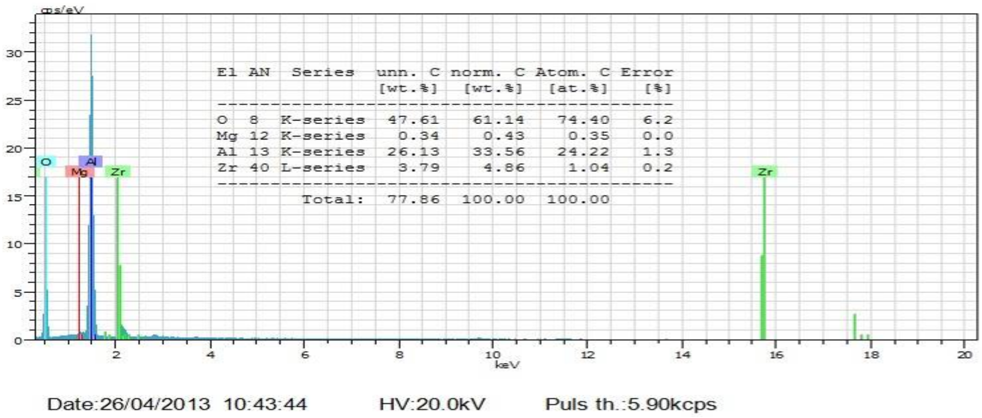
At the end of the metallographic examinations after coating of the piston and valve surfaces for each coating code given above, the coating has been examined at which defects are included in terms of composition phases of the material with chemical and structural feature of the geometric occurrence, order of compounds forming the material and microstructure. At the end of this examination, it has been found that less experienced samples at the defects is A3. The imaging made for sample code A3 is given in Fig. 1.



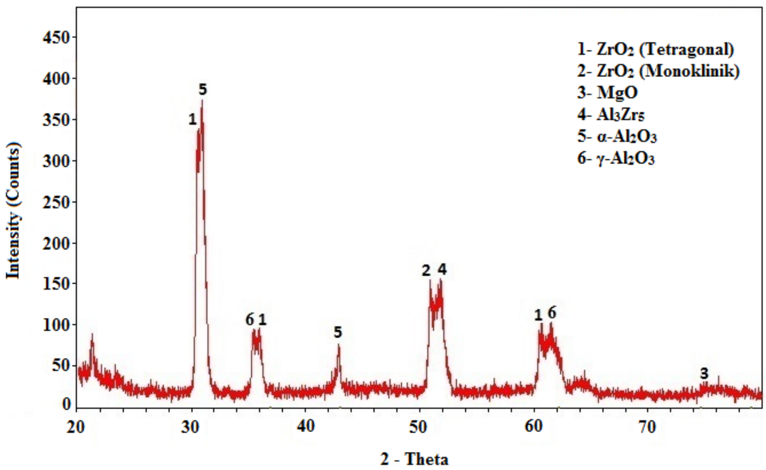
(a) SEM Coating Map



(b) SEM microscope view



(c) EDS analysis



(d) XRD analysis

Fig. 1 $ZrO_2 + MgO$ + 50 wt. % Al_2O_3 coatings without bond coat, SEM material map (a), SEM microscope view (b), EDS analysis (c), XRD analysis (d), results [16]

B. Engine Tests

Engine tests are carried out in the Karabuk University Automotive Laboratory. A schematic view of the test setup is given in Fig. 2. An electric dynamometer having 10 KW maximum holding power is used for the loading engine.

For the measurement of the force created by the test setup, an Esit brand SP100 model measuring cell is used. The exhaust gas temperature is determined by K-type thermocouple, it is instantaneously identified from a TES brand 1320 model reader. The fuel consumption is instantaneously measured with help of the Charles Sernard stop watch from the scales having precision of 0.1 g. The ITALO PLUS brand exhaust gas analyzer is used in measurement of the nature of the exhaust gas produced by the engine. The feature and measurement intervals of the exhaust gas analyzers are shown in Table II.

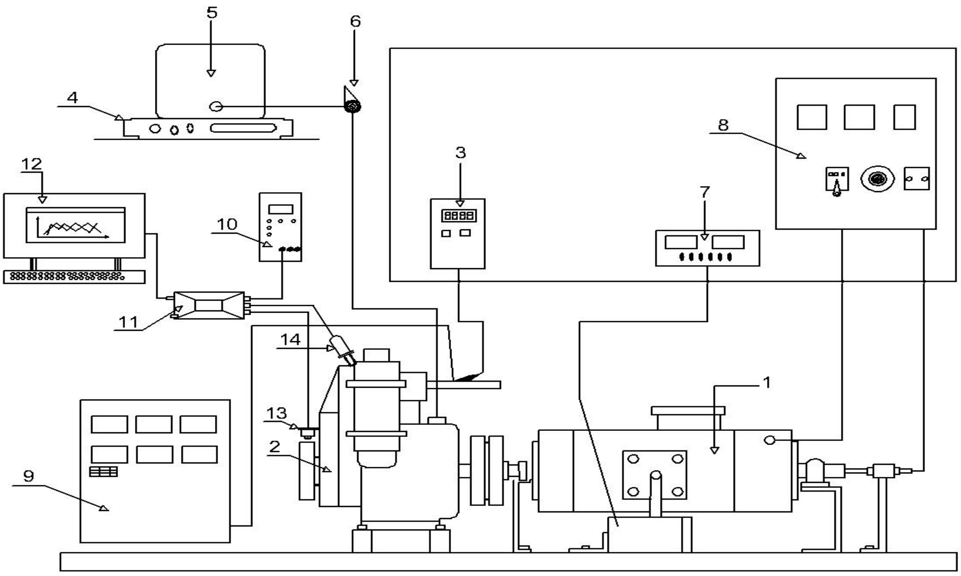


Fig. 2 A schematic view of the test setup 1- Dynamometer, 2- Diesel Engine, 3- Digital Thermometer, 4- Fuel Measuring Container, 5- Fuel Tank, 6- Fuel Flow Control Valve, 7- Load Cell Indicator, 8- Control Panel, 9- Exhaust Gas Analyzer, 10- Amplifier, 11- Oscilloscope, 12- Computer, 13- Position Sensor, 14- In-cylinder Pressure Sensor

TABLE II
ITALO PLUS EXHAUST GAS ANALYZER FEATURE

Measurement	Range	Precision
CO (% Vol.)	0-10,00	±0,06%
CO_2 (% Vol.)	0-20,00	±0,5%
NO_x (ppm)	0-2000	±5
HC (ppm)	0-50000 n-hexan	±12
O_2 (% Vol.)	0-21	±0,1

The Kistler brand 4065 A2 model pressure sensor and kistler brand 4618 type amplifier is used to determine the condition of the burning pressure in the cylinder. The operation interval of the sensor and amplifier is given in Table III. The data produced by the pressure sensor with the PICO brand ADC-212 model oscilloscope are recorded to the computer.

TABLE III
OPERATING RANGE OF THE KISTLER 4065 A2 MODEL PRESSURE SENSOR AND 4618 TYPE AMPLIFIERS

With Amplifier Type 4618	Type 4065	A200
Range	bar	0 ... 200
Overload	bar	300
Sensitivity (±0,5 % at 25 °C)	mV/bar	50
Natural frequency (sensor)	kHz	>40
Output signal (Pressure)	------	0 ... 10 V / 4 ... 20 mA
Output signal (Temperature)	mV/°C	10
Output impedance	Ω	10
Excitation (amplifier)	VDC	18 ... 30
End-point linearity	% FSO	<±1
Operating temperature range (sensor)	°C	20 ... 120
Operating temperature range (amplifier)	°C	0 ... 70

The engine tests are repeated for each sample in various engine speeds and fixed gas throttle position by using 5 pistons and 10 valves coated with the original piston and valves of the engine.

III. TEST RESULTS AND DISCUSSION

In the case of internal combustion engines, the factor that constitutes the engine power is measured by the useful work obtained as a result of combustion of the fuel taken into the cylinders. The useful work in the cylinders is calculated by the average rated pressure. As a result of the sudden combustion of fuel in the combustion chamber, the heat also suddenly increases and forms the pressure in the cylinder. Therefore, the internal combustion engine is defined as internal explosion engine in most of the resources [17]. The pressure formed at the end of compression of the piston in cylinders, acting on the piston, constitutes the engine torque and power. It is important to monitor the pressure in the cylinder for a better understanding of the combustion in cylinders. The pressures on the surface of the coatings in the cylinder were measured at 1600 l/min, 2000 l/min, 2400 l/min and 2800 l/min engine speeds.

In Fig. 3, the engine speed and the effect of the coated piston and valves on the pressure in the engine cylinder is observed. In Fig. 3, it appears that best pressure increase in various engine speeds is at the sample belonging to the coating no A3.

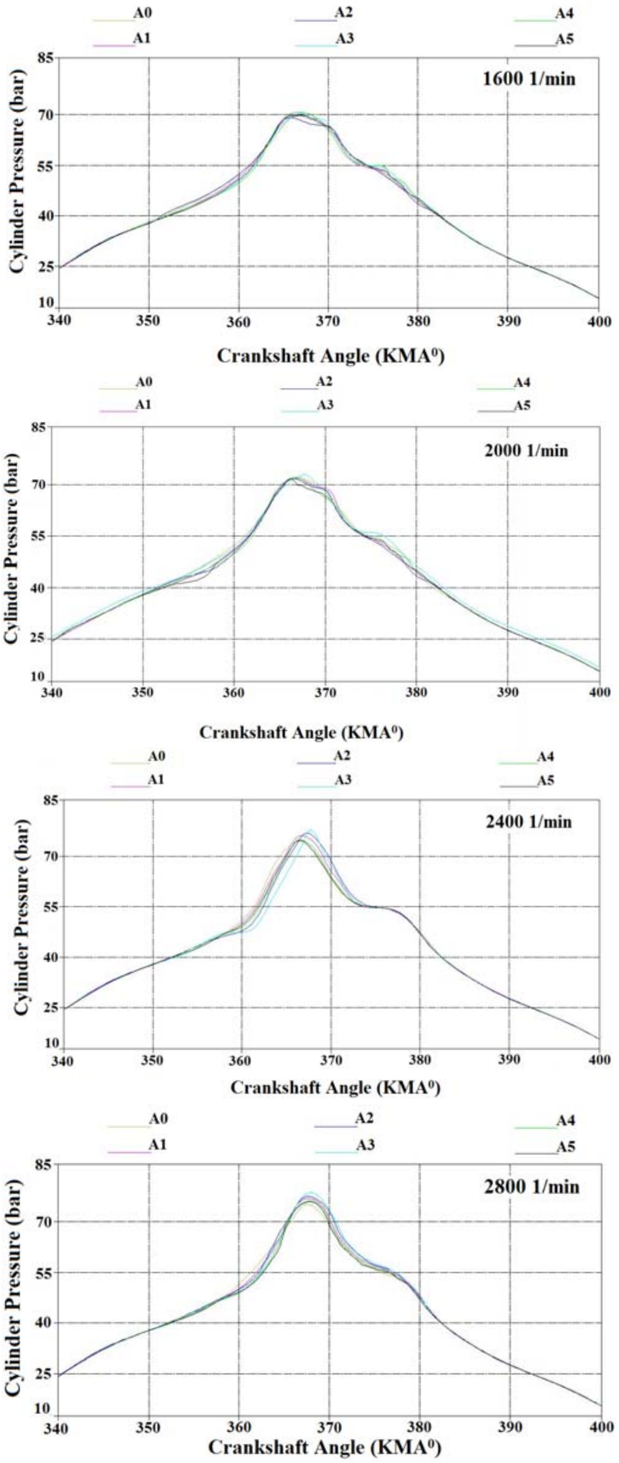


Fig. 3 Effect of engine speed and coated engine pistons on the cylinder pressure

Fig. 4 shows the effect of use of coated engine parts in a diesel engine on the engine torque. Factors that create the engine power in the internal combustion engine is measured by the useful work obtained in the combustion of fuel taken into cylinders. Useful work in cylinders is calculated with the mean indicated pressure. The pressure in the cylinder is formed as a result of the combustion of the fuel within the cylinder and the instantenous temperature increase in the cylinder. The useful work in the engine is measured with the help of the dynamometer connected to a flywheel [18]. Here, the force generated by the engine is converted to the engine torque with the calculations. As shown in Fig. 4, the 4.1% increase is provided in obtainment of the useful work in the engine's flywheel of the coated pistons. The engine torque and power is also increased parallel to the pressure rise in the combustion chamber. For each sample, at different engine speeds, the motor torque measured at the dynamometer load cell is shown in Fig. 4.

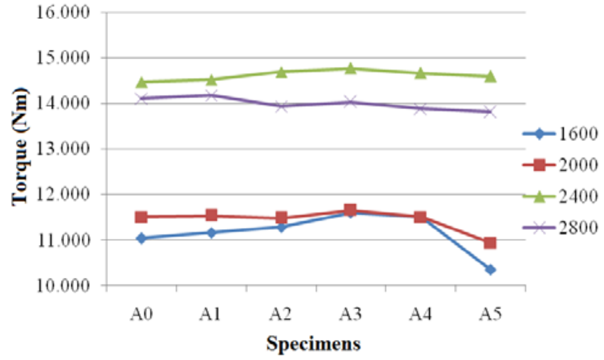


Fig. 4. The effect of the coated engine parts to the engine torque

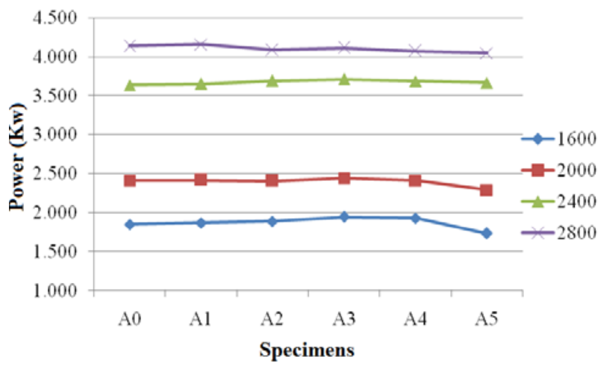


Fig. 5 Effect of the coated engine parts on the engine power

Fig. 5 shows the effect of the coated engine part for use in diesel engine to the motor power. It appears that the best performance increase is in the piston no A3 with the repeated work in different engine cycles. It has been found that there is increase on the engine power as a result of the obtained useful work (Fig. 5). The smaller amount of pores in the coating of the A3 coded sample results in a better thermal barrier coating. It is seen in Figs. 1 (a) and (b) that the porosity of the A3 coded sample is small. If the amount of pore is too large, there is an interstitial space in the material, which causes an acceleration in heat transfer. It is believed that the increase in heat transfer, together with the reduction in temperature in the cylinder, results in a decrease in pressure and moment. When comparing the standard engine (A0, non-cylinder coated engine) with A3, it was found that the engine torque (Fig. 4) and engine power (Fig. 5) increased 1.7% and 1.4% in sequence.

Fig. 6 shows the effect of use of the coated engine parts on a diesel engine to the specific fuel consumption. The specific fuel consumption is important comparison parameter showing the amount of fuel required to burn in one hour to obtain one kW power in the internal combustion engine. This parameter is found with the calculation. The increase of torque shown in Fig. 3 has been positively effected in fuel consumption of the engine. The useful work obtained from fuels positively reflected to the fuel consumption because it increases with help of coating.

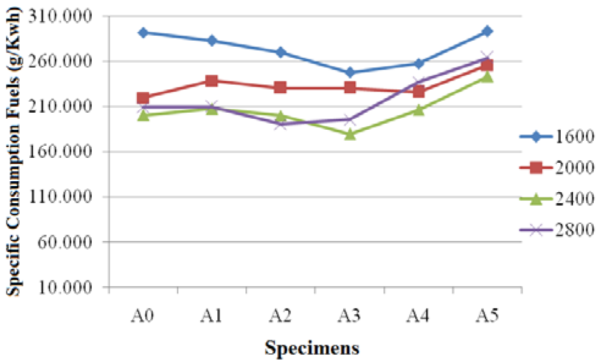


Fig. 6 Effect of the coated engine parts on the specific consumption fuels

Fig. 7 shows the effect of use of the coated engine parts on a diesel engine to the exhaust gas temperature. The burnt gasses created as a result of combustion of fuel on engine cylinders are discharged from the exhaust. As known, some part of the heating created in the cylinder with the gasses are thrown to the outside. As seen in Fig. 7, the coated pistons directly affect the exhaust gas temperature. The increase of temperature in the piston no A3 especially highly occurs. The highest increase in the exhaust gas temperature is calculated at the rate of 18,8% at the 2800 rpm.

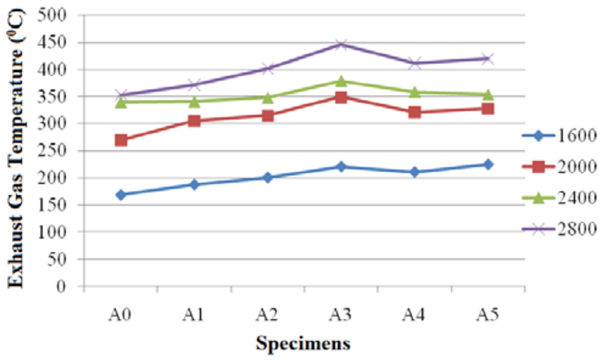


Fig. 7 The effect of the coated engine parts on the exhaust gas temperature (^{0}C)

Fig. 8 shows the effect of the use of the coated engine parts at the diesel engine on the hydrocarbon (HC) emissions. The HC emissions appear with the discharge of the unburnt fuels or burning of the lubricant oils in the diesel engine; the HC is unburnt fuel and oil waste. The presence of the HC carbon in the exhaust gases is failure to partially or wholly burn the fuel. The HC emissions appear from the fuel molecules occurred with incomplete burning as a result of very rich or pool H/Y mixture rates in some areas inside de the cylinder, and it is function of the temperature. The reason why the HC emissions increase in the diesel engine is that the fuel is removed in partial areas with the increase of the air rate in the poor mixture. In addition, the HC emission also increases with failure to burn the HC in the molecule core of the fuel with the dripping of remaining fuel at the endpiece of the injector at the moment of spraying fuel [19].

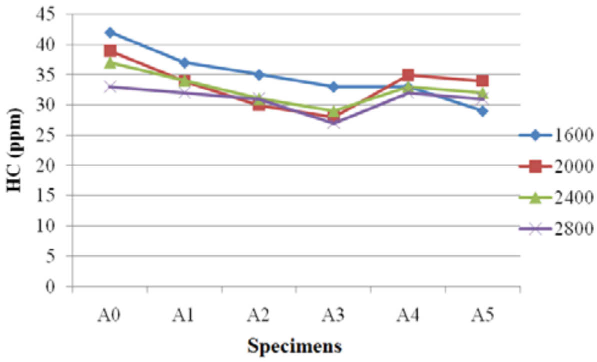


Fig. 8 The effect of the coated engine parts on the hydrocarbon (hc) emissions

As seen in Fig. 8, there is decrease in the HC emissions in all cycles of the diesel engine with the use of the coated pistons. As explained in Fig. 7, the temperature inside the cylinder increases with the coated pistons. This increase provides improvement of burning in the cylinder. Therefore, an improvement appears in the HC emissions. It has been found that the improvement is obtained at the rate 18.18% at 2800 rpm with the piston A3 in HC emissions.

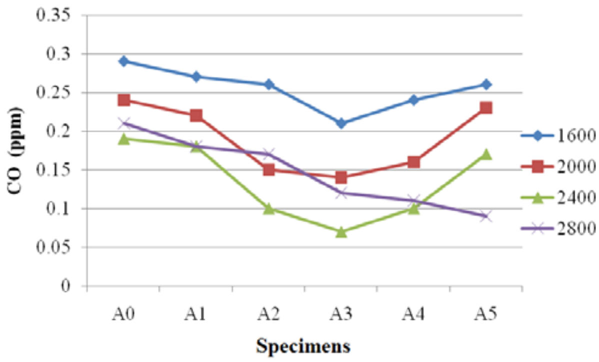


Fig. 9 Effect of the coated engine parts on the CO emissions

Fig. 9 shows the effect of use of the coated engine parts on the diesel engine to the Carbon monoxide (CO) emissions. The CO emissions increase because of failure to have complete burning in the cylinder in partial areas, and rich mixture in the cylinder. Because the diesel engine works with the high air overplus coefficient, the CO emissions are less. There are more air that is permanetly burnt in the cylinder. This is the factor that limits the CO emissions [19], [20]. In this study, there is decrease in the CO emissions in all cycle and coating. As seen in Fig. 8, it is thought that there is clean burning with the increase of the temperature in the cylinder. The increase of 63.15% has been found at the 2800 rpm with the sample A3 at the CO emission.

Fig. 10 shows the effect of the Nitrogen Oxide (NOx) for the use of coated engine parts on the diesel engine. The main reason of forming the NOx in diesel engine is to increase heat as a result of burning. The nitrogen oxide appears as a result of reaction of the nitrogen in the air with the oxygen in highest temperatures occurred as a result of burning (more than 1800 ºC). It is understood that the occurrence of the nitrogen oxide is considerably affected by the in-cylinder heat, and if the temperature increases, then NOx emissions rapidly increase [21]. As seen in Fig. 10, the NOx emissions increased in coated pistons. The main reason of this increase is that the end-of-combustion heat increases in the cylinder. The exhaust gas temperature is a function of the end-of-combustion temperature, and it is the parameter showing the amount of increase of burning in the cylinder. For this reason, it is sufficient to refer to Fig. 7 to understand the NOx emissions. Especially, the increase in the sample no A3 creates parallel situation with the exhaust gas temperature given in Fig. 7.

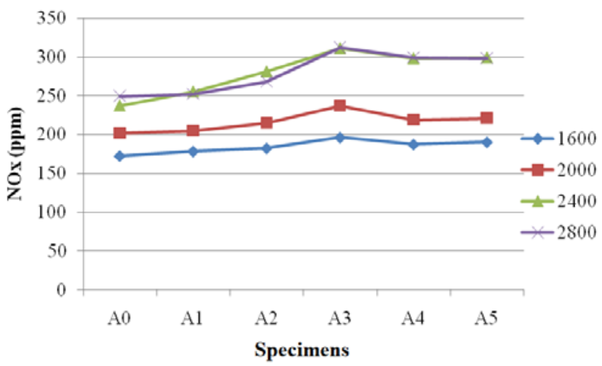


Fig. 10 The effect of the coated engine parts on the NOx emission

Fig. 11 shows the effect of use of the coated engine parts on the diesel engine on the fume emission. The hydrogen (H_2) molecules in the fuel dripping that is found as liquid in the cylinders of the diesel engines rapidly enter into reaction, and the remaining carbon (C) cannot burn when it cannot find sufficient oxygen (O_2), it is discharged in the form of fume particles. The main reason of the fume occurrence is that diesel fuel cannot find sufficient air in the cylinder, or it cannot mix with air on time, and it cannot evaporate [22]. As seen in Fig. 11, there is decrease in the fume emission in the coated pistons. The main reason of this fall is the increase of the end-of-combustion heat in the cylinder. At the end of the increased heat in the cylinder, the spraying fuel in the cylinder is evaporated well, and it provides good fuel/air (F/A) mixture. As seen in Fig. 11, it provides improvement of the emission. The best emission improvement is realized with the sample no A3.

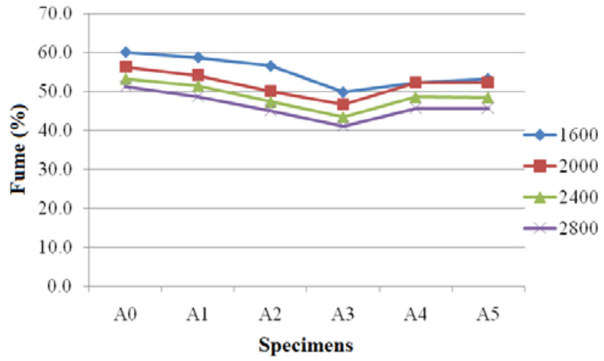


Fig. 11 Effect of the coated engine parts on the fume emission

IV. Results

When we look at the result of the material analysis made in the coated engine parts, it shows that the rate of pore increases in the Al_2O_3 added coating. At the end of material analysis, the best result in the ZrO_2+MgO added Al_2O_3 coating appears in the sample no A3 with addition of the 50% Al_2O_3. The reason of this can be explained that expansion coefficient of the ZrO_2+MgO is less than the expansion coefficient of the Al_2O_3. This difference affects the pore amount of the material, and it provides material more stable. The thermal conductivity of the coated engine parts is less than the thermal conductivity of the coated materials. Therefore, the end-of-combustion temperature is increased in the cylinder of the engine with the low thermal transmission, and more useful work has been obtained from the heat as a result of combustion.

With this study;

- There is improvement in the engine power, engine torque and specific fuel consumption.
- There are considerable improvements in the CO, HC, fume emissions.
- The increase of the NOx emissions appears as negative factor. However, some additional solution recommendations are available as a decrease of the NOx emissions. Some of them are spraying water in the cylinder, sending pure oxygen instead of the air in the cylinder, and additional catalytic convector connected to the exhaust system. All of these can create an additonal cost in addition to reduction of the NOx emissions.
- In addition, whole of the coated piston and valve samples as a result of material tests has more durability than the original piston and valves.

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