Arab J Sci Eng (2015) 40:3329–3335
DOI 10.1007/s13369-015-1807-6

RESEARCH ARTICLE - MECHANICAL ENGINEERING

Effects of Borided Cylinder Liner on Engine Performance in a Firing Diesel Engine

Mehmet Cakir[1] · **İsmail Hakkı Akcay**[2]

Received: 25 January 2015 / Accepted: 23 July 2015 / Published online: 8 August 2015
© King Fahd University of Petroleum & Minerals 2015

Abstract The correlations between engine performance and the borided cylinder liner have been investigated experimentally on firing diesel engine. The inner surface of cast iron cylinder liners of the engine was boronized using powder box-boronizing technique at 780 °C for 4 h. The boronizing thickness was approximately 25 µm at the cross section of cast iron cylinder liner after boronizing process. Diesel engine was operated with original cylinder liner and borided cylinder liner. Engine performance data were measured with the help of a hydraulic dynamometer. Indicated mean effective pressure was measured through the in-cylinder pressure detector. Indicated and brake parameters were compared for both motors. Borided engine liner temperature was measured as higher than that of original engine. Similar measurements were seen in the exhaust temperatures. Mechanical efficiency is improved about 6 % with cylinder liner boronizing.

Keywords Piston–cylinder friction · Engine tribology · Boronizing

1 Introduction

In internal combustion engine, only 25 % of the total power obtained from the fuel is converted to useful energy. The rest of the energy from combustion of the fuel goes into 30 % cooling, 30 % exhaust, 15 % pumping, and mechanical losses [1]. The friction between the piston assembly and cylinder liner is the single largest contributor, virtually amounting to 50 % of the total mechanical losses [2,3].

In the tribological system, the piston assembly plays a very important role in ensuring performance and endurance of the engine [4,5]. The frictional behaviors of the piston rings and cylinder liner are very important in terms of fuel consumption, emissions, and mechanical efficiency in engine. Many researchers have made a great effort to understand the tribological phenomena and reduce the frictional losses of the piston assembly [6–12].

The reduction in fuel consumption and the increase in effective efficiency of engines have been investigated by engine manufacturers and researchers. Best method for increasing the efficiency of engine is reducing the mechanical losses in engine. Mechanical loss determination in engine is quite complex. The combination of several physical mechanisms is associated with different positions in the engine. Mechanical frictional losses can be measured both in motored engine tests and in engine tests that include combustion. However, the true exhibition of frictional losses can only be obtained by using a fired engine [13].

Engine performance measurement is a method for computation of mechanical friction losses in engines. Firing engine is compared in terms of P–V diagrams or brake-specific fuel consumption. P–V diagrams are widely used in engine performance measures [14]. The mechanical friction that is the difference between the indicated work and the brake work reduces the indicated work of engine [15]. The mechanical frictional energy loss is called friction mean effective pressure (fmep), and it is difference between the net indicated mean effective pressure (nimep) and brake mean effective pressure (bmep) [14]:

$$\text{fmep} = \text{nimep} - \text{bmep} \quad (1)$$

✉ Mehmet Cakir
mecakir@yildiz.edu.tr

[1] Department of Marine Engineering Operations, Yildiz Technical University, Besiktas 34349 Istanbul, Turkey

[2] Department of Machine Engineering, Süleyman Demirel University, 32100 Isparta, Turkey

Measure cylinder pressure is required for the determination of fmep. The indicated work per cycle is obtained by the cylinder pressure and combustion by integrating the pressure–volume (P–V) diagram as follows [13]:

$$\text{nimep} = \frac{1}{v_h} \int P \cdot dv \tag{2}$$

The indicated power equation is computed from nimep given below:

$$N_i = \frac{W_i \cdot n \cdot z \cdot f}{60} W \tag{3}$$

Here, W_i is indicated work and is a product of nimep and stroke volume. n is the engine speed, z is the cylinder number, and f is the number of cycles per revolution.

The determination brake mean effective pressure is given below [13,14]:

$$\text{bmep} = \frac{N_e \cdot n_C}{V_h \cdot \text{rpm}} \tag{4}$$

Here, n_C is number of revolutions per cycle (two for four-stroke cycles; one for two-stroke cycles). Brake power (N_e) given as follow [16]:

$$N_e = \frac{\text{rpm} \cdot M_d}{954{,}958} \tag{5}$$

By using Eqs. (2)–(4) and reordering the Eq. 1 are written as following:

$$\text{fmep} = \text{nimep} - \text{bmep} = \frac{1}{v_h}\left[\left(\int P \cdot dv\right) - \frac{M_d \cdot n_C}{954{,}958}\right] \tag{6}$$

Also, mechanical efficiency is given as follow:

$$\eta_M = \frac{\text{bmep}}{\text{nimep}} = \frac{M_d \cdot n_C}{954{,}958} \cdot \frac{1}{\int P \cdot dv} \tag{7}$$

The main purpose of the present research is to evaluate the variation of engine performance using borided cylinder liner in a firing diesel engine. Therefore, the inner surface of engine cylinder liner was borided with pack-boronizing method. Diesel engine was operated with original cylinder liner (original C. L.) and borided cylinder liner (borided C. L.). Engine performances were measured with the help of a hydraulic dynamometer. Indicated pressure of engine was measured through the in-cylinder pressure detector. Indicated and brake parameters were compared for both motors. Eventually, owing to boriding of cast iron cylinder liner in a diesel engine, the mechanical friction power is reduced by 6 % boron coating, and an increase in mechanical efficiency has been observed when the engine load is increased. Also, this process is projected to increase engine life.

2 Experimental Procedure

The experimental work was conducted in a single-cylinder, air-cooled, and four-stroke diesel engine. The engine specifications are given in Table 1. Cylinder liner of engine was boronized with pack-boronizing method using commercial Ekabor® 2 powder. The chemical composition of the cylinder liner used in the experiments is given in Table 2. The boronizing treatment was carried out in a furnace at 780 °C for 4 h. Then, borided C. L. is mounted to the engine. Original C. L. and borided C. L. were tested at different conditions in standard bench tests (1200–1600–2000–2400 rpm speed and 10, 20 Nm load). The average working time of engine was obtained as 200 h. Experimental setup is given in Fig. 1 [16].

Measure of cylinder pressure is important for the nimep calculation. Indicated mean effective pressure have been measured on both engines using a piezoelectric-type transducer mounted as shown Fig. 2. In addition to pressure measurement, a crank shaft encoder was used to trigger the acquisition of the pressure signal and also to provide crank positional information. Cylinder pressure data were recorded as 100 cycles with reference to the literature [17–20]. By measuring nimep and the bmep, the fmep could be calculated. K-type thermocouples were used for measuring the engine block and exhaust gas temperatures. All of the data were recorded to a computer through data collection card. So, the indicated and brake engine parameters were computed from the Eqs. 3 and 5. Afterward, original and borided cylinder liner engine data were compared with graphics.

Table 1 Engine specifications

Type	Diesel, air cooled, four stroke
Cylinder number	1
Bore × Stroke	102, 5 mm × 100 mm
Displacement	825 cc
Compression ratio	17:1
Engine speed max.	3000 rpm
Engine power max.	17 hp

Table 2 The chemical composition of the cylinder liner %

C	Si	S	P	Mn	Ni	Cr	Mo	Cu	Fe
3.22	1.87	0.03	0.24	0.75	0.03	0.2	0.005	0.49	93.17

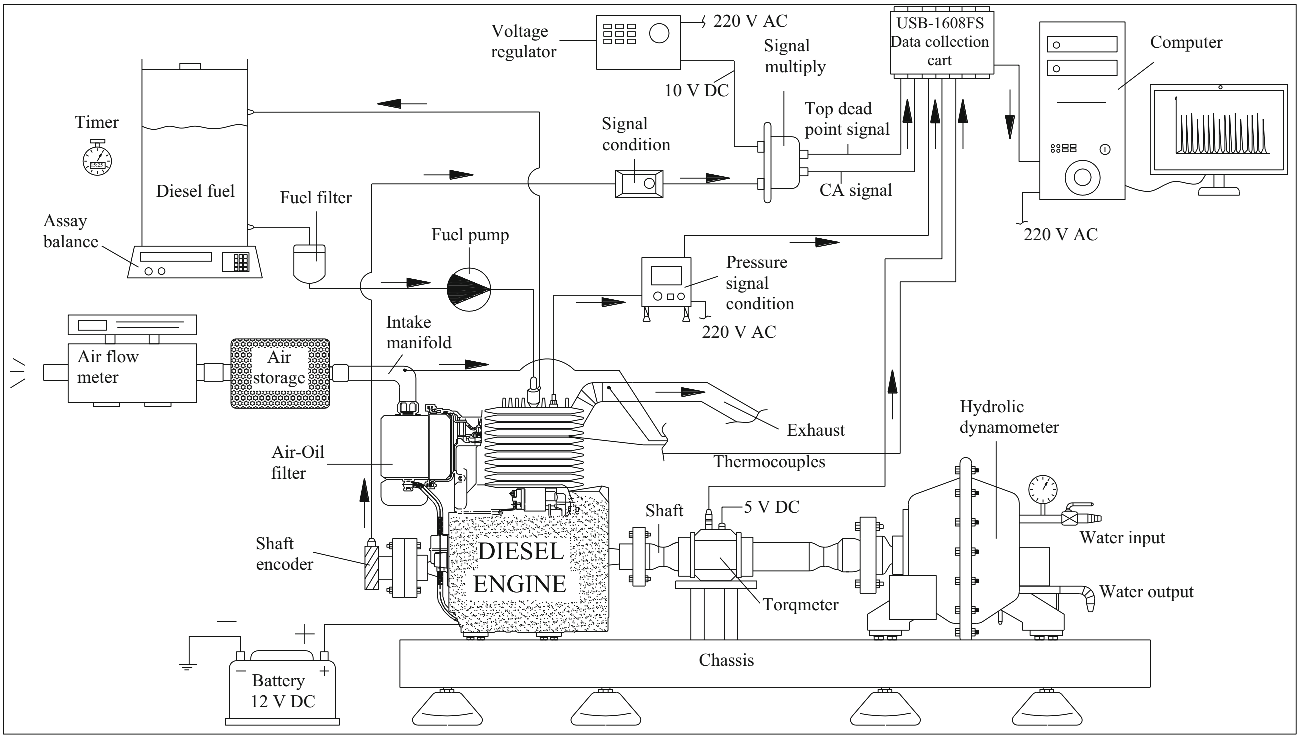


Fig. 1 Experimental set up

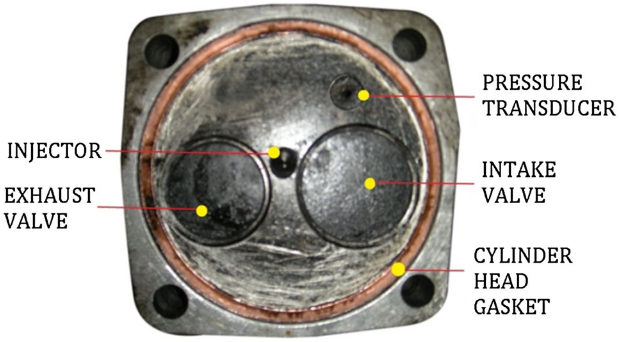


Fig. 2 Installation position of the pressure transducer

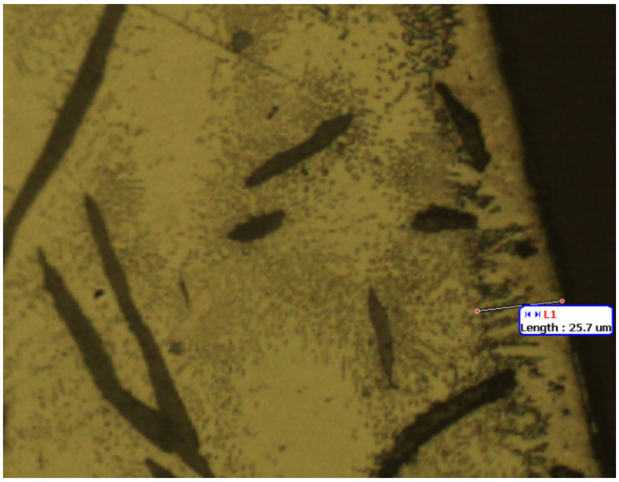


Fig. 3 Microstructure of borided cast iron cylinder liner

3 Results and Discussion

The mechanical losses were calculated experimentally on diesel engine test. The test equipment enables the measuring of in-cylinder pressure, the rotational speed, brake torque, exhaust gas, and engine block temperatures. Engine performance was compared with these parameters. Results of engine performance were determined for the original and borided cylinder liner.

Microstructure of the base metal and borided zone of cast iron are shown in Fig. 3. Here, the metallurgical structure of boronized cylinder liner has been determined; the boride layer has tooth-shaped structure. Alike, Sahin and Meric reported tooth-shaped structure in their cast iron boronizing tests [21]. With boronizing of cast iron cylinder liner, the topography of original and borided liner surface and SEM analysis are presented in Fig. 4.

Figure 3 shows that the boronizing thickness was approximately 25 μm at the cross section of iron cast cylinder liner after boronizing process. The iron-boride phases are formed at the material surface. In Fig. 4, when topographic surface was observed at the end of the borided process, very upright distinction vanished for the roughness of the surface which was observed to increase. Fe_2B spherical particles

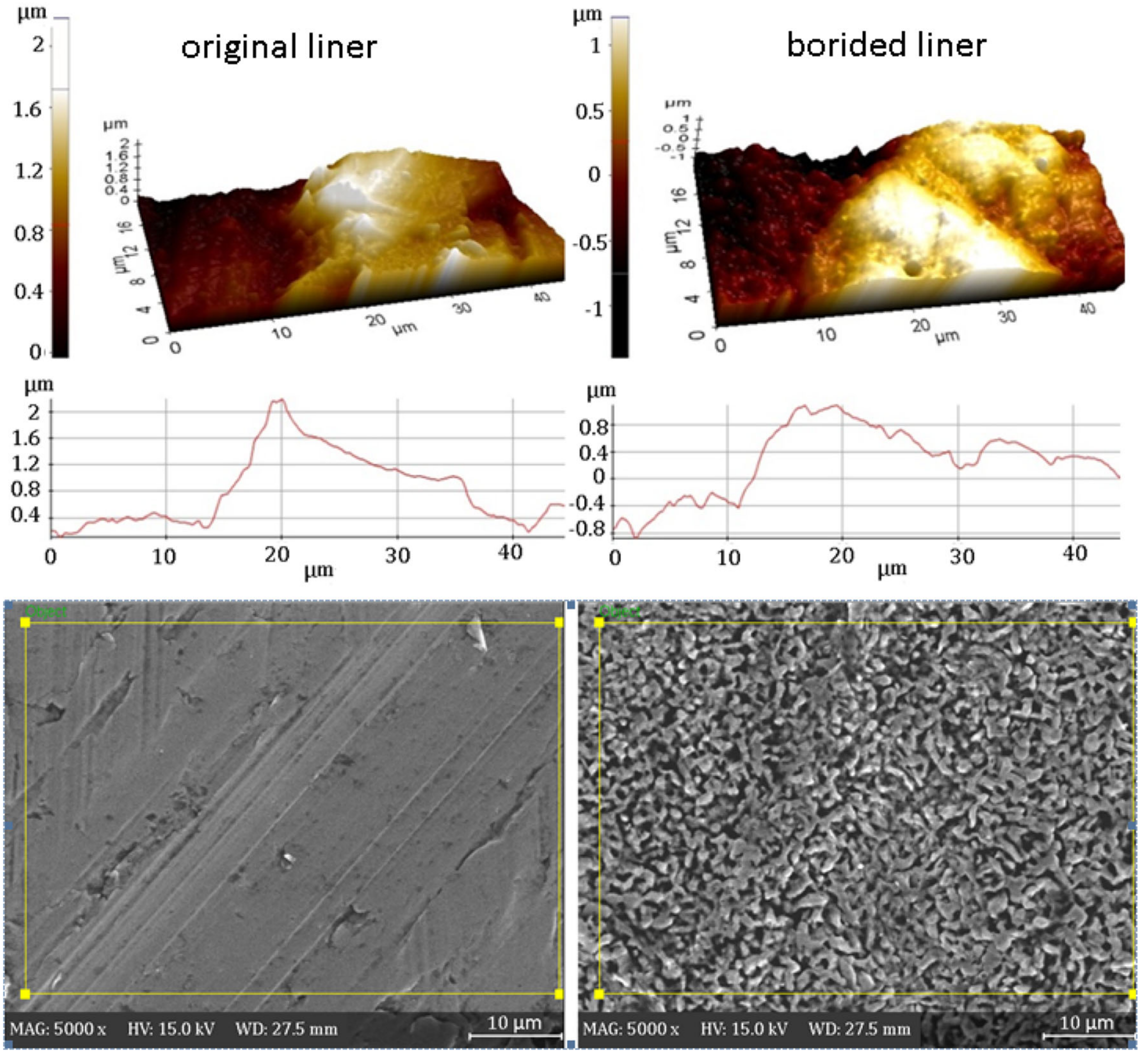


Fig. 4 Surface topography and SEM analysis original and borided cast iron cylinder liner

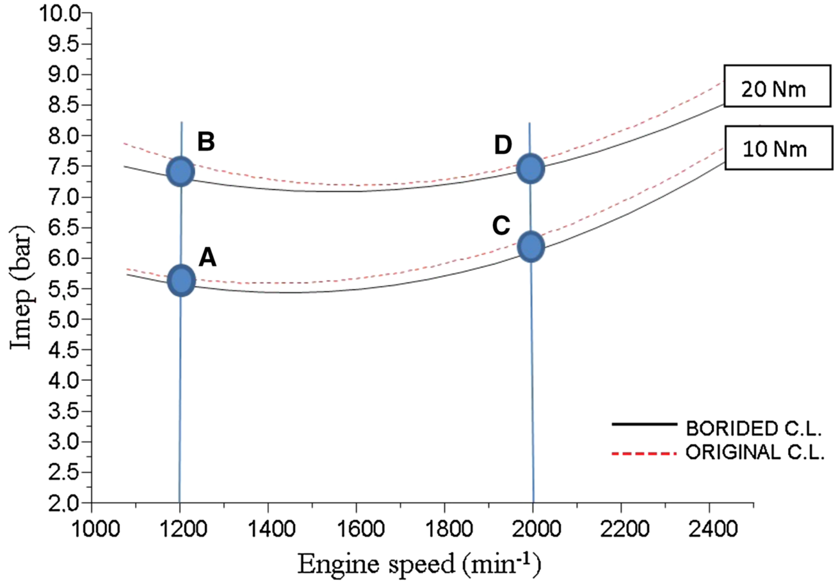
were formed on the surface and the surface turned into topography porous surface. After boronizing process, the borided cylinder liner was mounted to engine. The engine test was performed in different toques for both engines, and engine performance was illustrated with graphics. Figure 5 presents the dependence of nimep on rotational speed for both baseline engine and the modified one. By the comparison between original and borided cylinder liner, measured in-cylinder pressure is presented in Fig. 6.

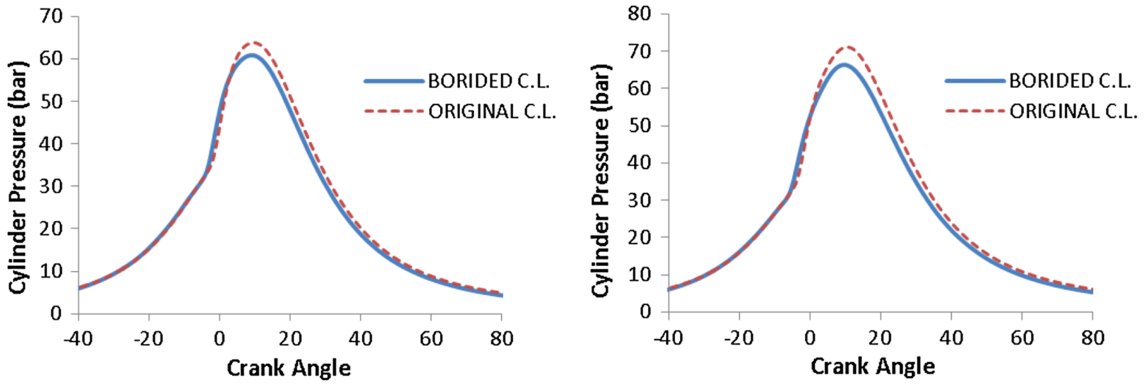
Figure 5 indicates the impact of engine torque on the indicated mean effective pressure (imep). Imep values increases with the increase in the engine torque for both engines. Also, imep values of original engine are higher from borided engine under equal effective engine torques. Cylinder pressure curves of imep values in A, B, C, and D points on the Fig. 5 were compared to both engine conditions in Fig. 6. Whereby, different analysis of study conditions is more clearly understood.

Figure 6 shows the instantaneous cylinder pressures as functions of crank angle for imep values given in Fig. 5. Maximum peak cylinder pressures of original engine are higher than that of borided engine values. Cylinder pressure data are the average of 100 cycles. While the difference between the peak cylinder pressures is about 3 bar under 10 Nm torque at 2000 min^{-1}, it was measured about 5 bar under 20 Nm torque at 2000 min^{-1}. Similarly, when the engine load was raised at 1200 min^{-1}, the difference between the cylinder peak pressures increased about from 2 to 4 bars for original and borided cylinder liner engines. The variation of mechanical efficiency on the engine speed at different torques for both engines is shown in Fig. 7.

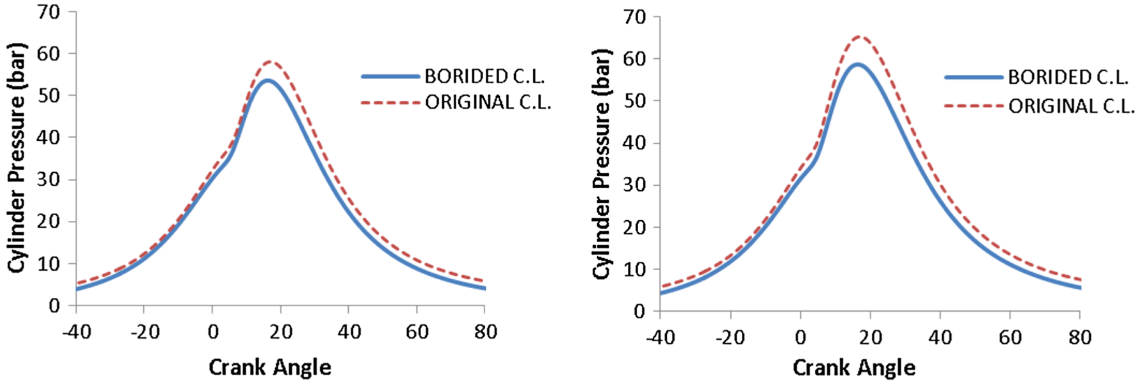
The friction within the engine has the greatest effect on mechanical efficiency. Figure 7 illustrates that the mechanical efficiency curves of the borided liner engine are higher than the mechanical efficiency curves of original liner engine under 10 and 20 Nm load. Mechanical efficiency increases as

Fig. 5 Comparison of nimep for engines with original and borided cylinder liners different torques over a range of engine speeds





A (1200 min^{-1}, 10 Nm) **B** (1200 min^{-1}, 20 Nm)



C (2000 min^{-1}, 10 Nm) **D** (2000 min^{-1}, 20 Nm)

Fig. 6 The comparison of cylinder pressures for A, B, C and D points on Fig. 5

the load increases. While the mechanical efficiency of original liner engine is 75 % under 10 Nm load at 1800 min^{-1} that is average speed for engine, this value is about 77 % for borided liner engine. Similarly, while the mechanical efficiency of original liner engine under 20 Nm load at 1800 min^{-1} is about 81 %, the mechanical efficiency of borided liner engine is about 83 %.

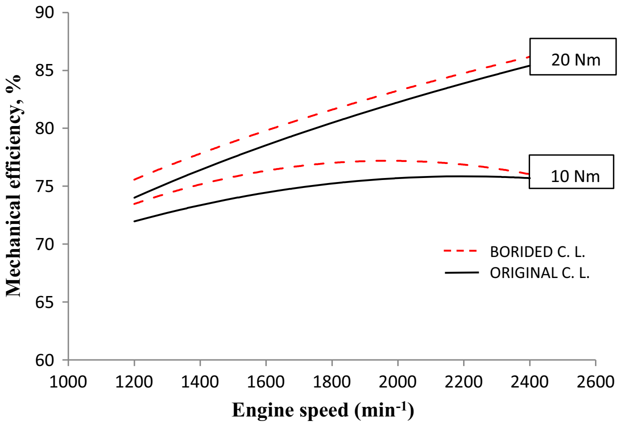


Fig. 7 Variation of mechanical efficiency with engine speed

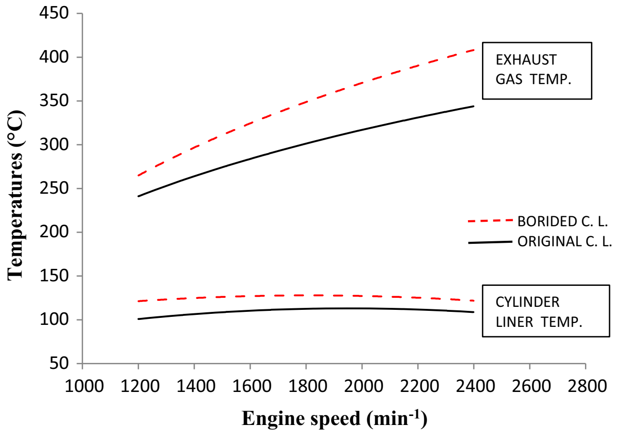


Fig. 9 Variation of temperature for engine with engine speed at 20 Nm load

Mechanical efficiency can be defined as the ratio of indicated power to the effective power out in internal combustion engines. Therefore, in Fig. 8 are given the indicated and effective power curves for both engines under 20 Nm load.

Figure 8 plots the indicated and effective power curves that vary with engine speed. The difference between curves of borided liner engine is less than difference between power curves of original liner engine. For example, the indicated and effective power values of borided liner engine at 1800 min^{-1} are about 5.1 and 4.2 kW, respectively. Total mechanical friction losses are about 0.9 kW value. The indicated and effective power values at the same engine speed on original liner engine are about 5.3 and 4.1 kW, respectively. Total mechanical losses for original liner engine are about 1.2 kW. Here is seen that original liner engine mechanical losses are higher than that of borided liner engine. Approximately, this value is about 6 % for medium engine speeds and load. Similarly, Howell-Smith et al. [22] have reported that cylinder liner surface-modifying features improve the engine's output power by as much as 4 % over that of the standard cylinder bore surface. To reduce wear and scuffing, particularly at the top dead center, hard coatings can also be used [22]. Also, Rahnejat et al. [23] have been informed that the smooth demand like coating surface should exhibit better frictional performance than the standard liner surface. Howell-Smith et al. have been stated to investigate the frictional performances of DLC (diamond-like carbon) coating with a range of lubricants investigated by Mistry, who determined that the coefficient of friction was reduced by nearly 30 % relative to an uncoated steel substrate [22].

The variations of cylinder liner and exhaust gas temperature for both engines are displayed in Fig. 9 with variation on engine speed from 1200 to 2400 min^{-1}. The exhaust gas temperature varies of borided C. L. engine more being higher than that of original C. L. engine. In a similar manner, this situation is shown for cylinder liner temperature variation. The average exhaust gas temperature difference is 45 °C at 20 Nm load.

4 Conclusions

This study investigated experimentally the correlations between engine performance and the borided cylinder liner in a diesel engine. Therefore, the gray cast iron cylinder liner

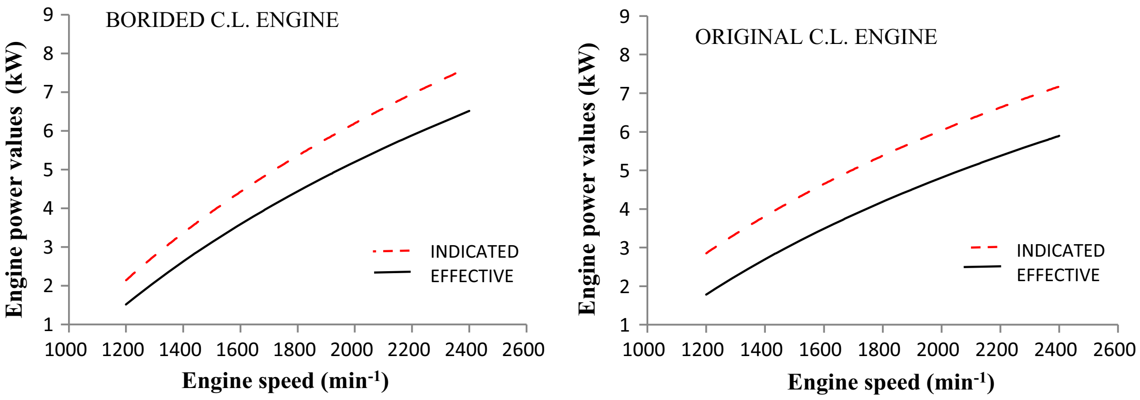


Fig. 8 The *curves* of the indicated and effective power for original and borided liner engine at 20 Nm torque

of a diesel engine was borided, and boriding parameters are determined with SEM analyses. Subsequently, diesel engine was operated with original and borided liners. The engine performances were measured. The indicated power, effective power, cylinder liner, and exhaust gas temperatures are compared to both engines. Eventually, the following points have been reached:

1. The gray cast iron liner successfully was borided about 25 μm thickness, and cylinder liner was mounted to engine for collecting engine performance data.
2. It was seen that imep data of original engine are higher than that of borided engine under equal effective engine torques. Similarly, the borided liner engine cylinder peak pressure data are lower than that of original engine at same engine load. On account of, the borided liner engine produces lower indicated power under equal torque.
3. The mechanical efficiency curves of the borided liner engine are higher than that of original engine under same loads. When the mechanical losses are compared, it seen that the borided liner engine losses are less than that of original engine. Mechanical efficiency is improved about 6 % with cylinder liner boronizing.
4. When the liner temperatures versus engine speed are compared, borided liner engine temperature is higher than that of original engine. Similarly, this situation is valid for exhaust temperatures and in terms of heat transfer should be investigated. The boron coating layer could be an adiabatic effect. As a result of, the combustion chamber rate of heat transfer could be decreased. This conclusion can be investigated in subsequent studies, such as, boriding layer heat transfer coefficient measurement and the heat transfer effects of layer thickness.

Acknowledgments This study was supported by Unit of Scientific Research Projects of Süleyman Demirel University (Project Number: 2667-D-11).

References

1. Kim, M.: Friction force measurement and analysis of the rotating liner engine. The University of Texas, Thesis of Doctorate, 196, Austin (2005)
2. Dimkovski, Z.; Anderberg, C.; Ohlsson, R.; Rosén, B.G.: Characterization of worn cylinder liner surfaces by segmentation of honing and wear scratches. Wear **271**, 548–552 (2011)
3. Johansson, S.; Nilssona, P.H.; Ohlssonb, R.; Rosénc, B.G.: Experimental friction evaluation of cylinder liner/piston ring contact. Wear **271**, 625–633 (2011)
4. Shuster, M.; Mahler, F.: Metallurgical and metrological examinations of the cylinder liner-piston ring surfaces after heavy duty diesel engine testing. Tribol. Trans. **42**(1), 116–125 (1999)
5. Peragon, F.C.; Polamar, J.M.; Diaz, F.A.; Espadafor, F.J.J.: Fast on-line identification of instantaneous mechanical losses in internal combustion engines. Mech. Syst. Signal Process. **24**, 267–280 (2010)
6. Akalın, Ö.: Tribological performance of plasma spray coated cylinder bores in IC engines. Mühendis ve Makina **486**, 30–33 (2000)
7. Radil, K.C.: Test method to evaluate cylinder liner-piston ring coating for advanced heat engines. NASA Center for Aerospace Information, NASA TM-107526 ARL-MR-362 (1997)
8. Wang, H.S.; Chao, G.Y.; Xiang, X.H.; Dao, W.J.; Mzhong, Z.: Distributed law of hydrodynamic lubrication of a cylinder liner of an internal combustion engine. Tribol. Trans. **41**(4), 610–614 (1998)
9. Stolarski, T.A.; Zhou, Q.: Temperature–friction characteristics of used lubricant from two-stroke cross-head marine diesel engines. Wear **252**, 300–305 (2002)
10. Ma, Y.; Li, S.; Jin, Y.: Impacts of friction-modified fully formulated engine oils on tribological performance of nitrided piston rings sliding against cast iron cylinder bores. Tribol. Trans. **47**, 421–429 (2004)
11. Tamminen, J.; Sandstroma, C.E.; Andersson, P.: Influence of load on the tribological conditions in piston ring and cylinder liner contacts in a medium-speed diesel engine. Tribol. Int. **39**, 1643–1652 (2006)
12. Bolander, N.W.; Sadeghi, F.: Deterministic modeling of honed cylinder liner friction. Tribol. Trans. **50**, 248–256 (2007)
13. Heywood, J.B.: Internal Combustion Engine Fundamentals. 1 McGraw-Hill, New York, 808 p. (1988)
14. Richardson, D.E.: Review of power cylinder friction for diesel engines. J. Eng. Gas Turbines Power **22**, 506–519 (2000)
15. Ferguson, C.R.; Kirkpatrick, A.T.: Internal Combustion Engines Applied Thermosciences, 2nd edn. Wiley, New York, 370 p. (2001)
16. Çakır, M.: Tek Silindirli Hava Soğutmalı Bir Motorda Borlanmış Dökme Demir Gömleğin Motor Performans Değerleri Üzerindeki Etkilerinin Deneysel Araştırılması. Süleyman Demirel Üniversitesi, Fen Bilimleri Enstitüsü; Doktora Tezi; 121; Isparta (2013)
17. Bueno, A.V.; Velasquez, J.A.; Milanez, L.F.: A new engine indicating measurement procedure for combustion heat release analysis. Appl. Therm. Eng. **29**, 1657–1675 (2009)
18. Lamaris, V.T.; Hountalas, D.T.: A general purpose diagnostic technique for marine diesel engines—application on the main propulsion and auxiliary diesel units of a marine vessel. Energy Convers. Manag. **51**, 740–753 (2010)
19. Luján, J.M.; Bermudez, V.; Guardiola, C.; Abbad, A.: A methodology for combustion detection in diesel engines through in-cylinder pressure derivative signal. Mech. Syst. Signal Process. (2010). doi:10.1016/j.ymssp.2009.12.012
20. Payri, F.; Luján, J.M.; Martin, J.; Abbad, A.: Digital signal processing of incylinder pressure for combustion diagnosis of internal combustion engines. Mech. Syst. Signal Process. (2010) doi:10.1016/j.ymssp.2009.12.011
21. Sahin, S.; Meric, C.: Investigation of the effect of boronizing on cast irons. Mater. Res. Bull. **37**, 971–979 (2002)
22. Howell-Smith, S.; Rahnejat, H.; King, P.D.; Dowson, D.: Reducing in-cylinder parasitic losses through surface modification and coating. Proc. IMechE D J. Automob. Eng. **228**(4), 391–402 (2014)
23. Rahnejat, H; Balakrishnan, S.; King, P.D.; Howell-Smith, S.: In-cylinder friction reduction using a surface finish optimization technique. Proc. Inst. Mech. Eng. D J. Automob. Eng. **220**(9), 1309–1318 (2006)