Changes in surface properties of engine cylinder bores due to laser treatment

Summary of the PhD thesis

Kornél Májlinger
MSc in mechanical engineering
IWE / EWE

Supervisor:
Péter János Szabó, PhD associate professor

Budapest University of Technology and Economics
Faculty of Mechanical Engineering
Department of Materials Science and Engineering

Budapest
2010

This dissertation, the comments of the reviewers and the log recorded on the defence are on show in the Dean's office of the Faculty of Mechanical Engineering of the Budapest University of Technology and Economics

Publications connected to the theses

In this section the publications published by myself are listed in cronological order (from the oldest to the newest).

[1] **Májlinger, K., Szabó, P.J.** Measuring the Effects of Some Laser Parameters on the Surface and Near Surface Region of Laser Treated Cast Iron Cylinder Bore. *Periodica Polytechnica Mech. Eng.* 2008/2., 52. pp.: 71-76.

[2] **Májlinger, K., Szabó, P.J.** Robbanómotor-hengerek futófelületének lézersugaras kezelése. Bányászati és Kohászati Lapok, Kohászat. 2009/2 142. pp.: 41-46.

[3] **Májlinger, K., Szabó, P.J.** The Effects of Some Laser Parameters on the Surface and Near Surface Region of Laser Treated Cast Iron Cylinder Bore. *Journal of Physics Conference Series.* 2010., 240. pp.:1-4. doi:10.1088/1742-6596/240/1/012169

[4] **Májlinger, K., Szabó, P.J.** Laser Treatment of Cast Iron Engine Cylinder Bore with Nanosecond Laser Pulses. *Materials Science Forum.* 659 (2010) pp.. 319-324. doi:10.4028/www.scientific.net/MSF.659.319

[5] **Májlinger, K., Szabó, P.J, Révész, Á.** Formation of Surface Layer due to Laser Treatment of cast iron. *Gépészet 2010, Proceedings of 7th International Conference on Mechanical Engineering 2010, (CD-ROM)* pp.: 42-47. (2010)

[6] **Bobor Kristóf, Májlinger Kornél**: Felületi réteg kialakulása öntöttvas motorblokkok hengerfuratának falán lézerkezelés hatására. *OGÉT 2010* conference paper, pp.: 283-286. (2010)

[7] **Bobor, K., Májlinger, K., Szabó, P.J.** Formation of Surface Layer on Cast Iron Cylinder Bore due to Nanosecond Laser Impulses. *Periodica Polytechnica Mech. Eng.* 2010/2 (accepted in the press)

Possible applications of the results

My research allows a better understanding of the laser treatment process of the engine-block processing for GJL-250 cast iron. The samples made by different laser types give comparable results so it is possible to change the excimer laser used in the serial production to a more efficient Yb-fiber laser. I determined the minimal laser energy density to produce adequate surface quality for engine operation.

With the examination of the limits of the different investigations techniques it was possible to compare the hardness of the surface layers and to image the structure of the molten layer.

With the developed of an image processing measurement method to determine GK the free graphite ratio after laser treatment it possible now to qualify the efficiency of the honing process and the following laser treatment.

All these results allow the improvement of the cylinder bore surface and the optimization of the production lines. They also can be good guidelines to further investigations in this area.

Introduction, industrial background of the research

The automotive engine development is defined by three main factors: first of all there is the need to make the engines more cost effective, the second is that the environmental regulations are becoming stricter, and thirdly the fuel prices are increasing. The economical requirement of the customers is that even by higher engine power the fuel and oil consumption should not increase, and beside this, engines should have a long lifetime. Accordingly to these requirements the main development trends are: reduction of the oil and fuel consumption and longer engine lifetime [Lindner 2003].

Both the consumption reduction and the power increase of Otto- or Diesel-engines cause higher pressures in the combustion space. The higher pressure forces the piston rings to the piston bore with higher pressure which results in higher tribological load and therefore in higher wear rate for both components. Increased wear reduces the lifetime of the engines and the gas and oil sealings between piston ring and piston bore becomes worse. This results in higher oil consumption and higher exhaust, which causes higher emission of pollution materials, decreasing efficiency and engine lifetime [Lindner 2003].

The environmental and pollution materials emission standards in Europe are going to be more and more strict. In order to keep the standards, a large European automotive manufacturer makes a laser treatment on the cast iron cylinder bores of the V-engine blocks.to alter the properties of the cylinder bores. This treatment allows higher load between cylinder bore and the piston rings, which results in an increased power output and reduced fuel and oil consumption and less emission. Due to the laser treatment, the near surface area of the cylinder bore becomes harder and more wear resistant, furthermore, due to the inhomogenity of the pearlitic matrix and carbon lamellae, oil reserving holes are formed [Lindner 2003], [Herbst 2004/2].

Since many years engine blocks serials have been produced with the laser surface treatment (but only V-engine blocks, except V8 and V10 Otto engines because they have aluminium blocks). The automotive factory wants to increase the production capacity and apply the laser treatment to other engine blocks types too. The factory also wants to replace the applied laser type to another one, so it is important to understand the mechanism during treatment and to have better knowledge about the influence of the different parameters.

At our department, and in our country there was no published premise of this research, but one of the main profiles of our department is materials research. Because of that and because of the engine production in our country, our department and myself were entrusted with this work.

The laser treatment of cast iron cylinder bore

To exploit the good properties of laser surface treatments one European automotive manufacturer makes a laser treatment on the honed surface of their cast iron engine cylinder bores as the finishing process. The aim of the laser treatment is to melt a thin surface layer. Simultaneously with the melting the laser induced plasma ablates the graphite lamellas. So these "holes" are practically non-communicating oil reservoirs during engine operation [Lindner 2003], [Herbst 2004/1], [Duffet 2003], [Queitsch 2004], [Herbst 2004/2], [Lindner 2006].

This treatment is patented, the patent number is: EP 1 738 859 A1 [Lindner 2006]. According to this the surface should be irradiated with a laser operating in the UV-wavelength range (like excimer lasers) to melt a thin surface layer. After the honing process the piston ring still can squeeze the oil by itself (*Figure 1.*), but after laser treatment the hone marks perish and the opened and out burned graphite holes function as non-communicating oil reservoirs (*Figure 2.*).

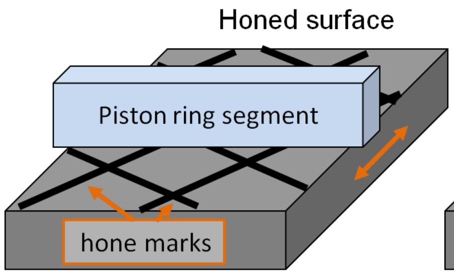

Figure 1. Schematic drawing of the surface after honing process [Herbst 2004/2]

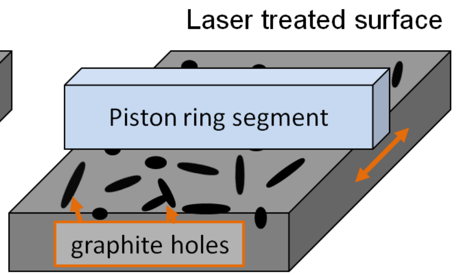

Figure 2. Schematic drawing of the surface after laser treatment [Herbst 2004/2]

The essence of the laser treating apparatus is the optic output system, the optic tube which lowered and rotated in the cylinder bores allowing to treat the surface with perpendicular laser beam, by different overlapping strate-

5. Thesis [6] [7]

I determined with finite element method simulations, that due to laser treatment of GJL-250 type grey cast iron in the 15,8-55,6 mJ/mm^2 laser energy density and 0,1129-1,3021 mJ/(mm^{2}ns) laser power density range, respectively, beneath the molten surface layer, there is a 3-8 μm deep layer where temperature exceeded the austenitisig temperature during laser treatment and was softened. This is supported by the hardness data measured perpendicular to the surface with relatively high penetration depth to the molten layer thickness, where the laser treated surface found to be softer than the honed one, but the hardness of the surface layers was determined by nanoindenter measurements and it states that the surfaces treated with higher than 17,5 mJ/mm^{2}ns laser energy density are harder than the honed surface. This is only possible if beneath the hard laser molten surface layer there is a softer one. Furthermore I determined with FIB images that the molten layer thickness is also in the simulated range.

6. Thesis [1] [2] [3] [4] [5]

I developed an image processing measurement method which allows the measurement of the free graphite ratio after laser treatment (GK). This is defined as $GK = \frac{G_{felület}}{G_{csiszolat}}$ free graphite ratio after laser treatment – where $G_{felület}$ is the measured graphite area ratio on the laser treated surface and $G_{csiszolat}$ is the measured graphite area ratio on the polished base material – this parameter describes reliably the effect of laser treatment of the ratio of oil reserving holes (graphite holes)

I proved that due to laser treatment with Yb-fiberlaser with 140 ns pulse length at the same base material, the value of GK increases monotonically with the higher laser power density in the 0,1129-0,2173 mJ/(mm^{2}ns) laser power density range.

New scientific results

The new scientific results of my PhD research program can be summarized in six theses.

1. Thesis [1] [2] [3] [4] [5] [6] [7]

I proved with SEM, TEM and FIB measurements that after laser treatment of the honed surface of GJL-250 type grey cast iron in the 15,8-55,6 mJ/mm^2 laser energy density and 0,1129-1,3021 mJ/(mm^{2}ns) laser power density, respectively, a layered surface is formed. The thickness of the outer molten layer varies from 0,5-2 µm in depth.

2. Thesis [5] [6]

I proved with nanoindenter measurements that due to the laser surface treatment of the honed surface of GL-250 type gray cast iron treated with Yb-fiberlaser with 140 ns pulse length, the hardness of the molten surface layer increases linear with the laser power density in the 0,1129-0,2173 mJ/(mm^{2}ns) power density range.

3. Thesis [3] [4] [5]

I proved with XPS and EDS measurements that due to the laser surface treatment of the honed surface of GL-250 type gray cast iron treated in the range of 15,8-30,4 mJ/mm^2 laser energy density and 0,1129-1,1 mJ/(mm^{2}ns) laser power density, respectively, no nitrided layer occurred, but the outer surface was oxidised. Furthermore I proved with Raman spectroscopy measurements that near the graphite lamellas there is a thin adherent carbon layer – brought up onto the surface due the high plasma pressure – which was identified as pyrolytic graphite and as DLC..

4. Thesis

I proved with EBSD measurements that due to the laser surface treatment of honed GL-250 type gray cast iron treated with Yb-fiberlaser with 140 ns pulse length with 30,4 mJ/mm^2 laser energy density concerning to the ferrite phase the following texture was formed: the [101] direction is parallel to the axis of the cylinder bore and in the direction of the honing and the laser treatment, respectively, [101] and [111] unidirectional texture was formed.

gies. The inventors suggest to irradiate the gray cast iron surface with 1,75-5 J/cm^2 laser energy density at 308 nm wavelength pulses.

References

[Lindner 2003] *UV-Laserbelichtung von Grauguß - Zylinderlaufbahnen von Verbrennungskraftmaschinen.* **Lindner, H, és mtsai.** Düsseldorf : VDI Verlag GmbH, 2003., VDI-Berichte, 1764. kötet, old.: 73-96. ISSN 0083-5560

[Herbst 2004/1] **Herbst, L, és mtsai.** Targeting diesel engine efficiency. *Industrial Laser Solutions for Manufacturing.* [Online] 2004. 10. 1. [Hivatkozva: 2007. 09. 15.] http://www.optoiq.com/index/lasers-for-manufacturing/display/ils-article-display/214247/articles/industrial-laser-solutions/volume-19/issue-10/features/targeting-diesel-engine-efficiency.html.

[Duffet 2003] *Improvement in friction by cw Nd:YAG laser surface treatment on cast iron cylinder bore.* **Duffet, G., Sallamand, P. és Vannes, A. B.** hely nélk. : Elsevier, 2003., 205. kötet, old.: 289-296.

[Queitsch 2004] **Queitsch, Robert és Lindner, Horst Joachim.** Deutscher Zukunftspreis. *Verschleiß- und ölverbrauchsarme Verbrennungsmotoren durch Werkstoffmodifikation von Zylinderlaufbahnen mit dem UV-Laser.* [Online] [Hivatkozva: 2008. 04. 15.] http://www.deutscher-zukunftspreis.de/nominierter/verschlei%C3%9F-und-%C3%B6lverbrauchsarme-verbrennungsmotoren-durch-werkstoffmodifikation-von-zyli?sec=2.

[Herbst 2004/2] **Herbst, Ludolf, Lindner, Horst és Hoult, Tony.** An important novel application for excimer lasers in the automotive industry. [Online] [Hivatkozva: 2007. 12. 22.] http://www.coherent.com/Downloads/ICAv2.pdf.

[Lindner 2006] **Lindener, Horst.** *Vorrichtung zur Laser-Belichtung von Zylinderlaufbahnen von Kolbenmaschinen mit mehreren voneinander beabstandete, höhenverstellbare und um eine rotationsachse drebare Optik-Einrichtungen; Verfahren zur Belichtung von Zylinderlaufbahnen von Kolbenmaschine. EP 1 738 859 A1* DE

Aim of the research

After reviewing the technical literature it is clear that there are a lot of processes available to enhance the properties (like: hardness, dry and lubricated sliding behavior) of metallic materials. Maybe the fastest developing of all is the laser materials processing techniques. A lot of publications are available about the different processes and the influence of the laser parameters on the wide scale of different laser processes.

After reviewing the literature it is clear that the process we investigated can be categorized as a laser surface structuring, laser surface hardening, laser surface melting and as laser surface alloying (in case of dissolution of the graphite lamella onto the surface).

The changes in the microstructure of the thin molten layer after laser surface structuring in the 15-55 mJ/mm^2 energy density range was not investigated yet. In the classic sense during the laser surface melting processes the molten layer is at least one or two order of magnitude thicker. The effects of laser treatments carried out in air atmosphere in the 1-50 mJ/mm^2 energy density range were only investigated for pure metals (in nitrogen atmosphere for some steels too).

In the literature I couldn't find papers (only from the inventors of this process for XeCl excimer laser treatment) in the 1-50 mJ/mm^2 energy density range and power density range, respectively, for laser treatment of industrial samples of honed gray cast iron (pearlitic matrix with graphite lamellas) surfaces irradiated in air atmosphere. But according to the literature non equilibrium crystallisation is to be expected.

The main factors – sideward the engine block – which influence the sliding behaviour of the piston in the cylinder bores (beside of the geometry of the bore) are the hardness of the surface and the opened graphite holes. So it is needed to determine which parameters influence the surface quality in focus of the laser treatment. So my aim was to determine about the laser treatment that:

- what kind of microstructural changes take place after the treatment
- which characteristic parameters are suitable to qualify the surface layer
- which values of the characteristic parameters give the best results especially for the surface hardness and oil reserving capacity

- what are the influences of the laser parameters in the industially applicable energy density range (with finite element method simulations).

Investigated materials and applied test methods

In this dissertation I investigated the surface of laser treated cylinder bores. The laser experiments were carried out on EN-JL1040 (EN-GJL-250) (according to EN 1561:1997 norm) cast iron, because that is the material the most engine blocks are produced of (in Hungary). The laser treatments were carried out on the honed engine cylinder bores. To study the surface treatment three different laser types were used: XeCl excimer laser, Nd:YAG laser and Yb-fiber laser which was a special point of interest, because a new production line is about to be equipped with these Yb-fiber laser.
The laser treated surface perpendicular to the surface and in cross section was investigated by different microscope techniques. The depth of the molten layer was measured by scanning electron microscope, transmissions electron microscope and focused ion beam (FIB) technique. The structure of the molten layer was also investigated with FIB.
The influence of the honing process and the laser treatment afterwards on the hardness of the surface and near surface layers was measured with different types of hardness measurements. The hardness of the cylinder bore surface layer was determined by nanoindenter measurements.
The phases after laser treatment were studied by X-ray diffraction. The chemical composition and binding state of the surface layer was investigated by X-ray photoelectron spectroscopy and energy dispersive X-ray spectroscopy.
The influence of the honing process and the laser treatment afterwards on the texture of the surface near regions was investigated with backscattered electron diffraction technique.
The effects of the laser parameters in the production applicable ranges were investigated also by finite element simulations.
After laser treatment the outburned graphite holes serve as oil reserving holes, so I defined a parameter *GK* – free graphite ratio after laser treatment (the graphite area ratio on the laser treated surface divided by the graphite area ratio on the polished base material sample), and I developed a measurement method to determine its value. With this parameter *GK* it is possible to qualify the efficiency of the honing process and the following laser treatment.