The effects of some laser parameters on the surface and near surface region of laser treated cast iron cylinder bore

K Májlinger and P J Szabó
Budapest University of Technology and Economics Department of Materials and Engineering, Goldmann György tér 3., Budapest 1111, Hungary
pmgpwo@hotmail.com

Abstract. 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. Samples of laser treated cast iron cylinder bore with lamellar graphite were investigated. Four samples were treated with Nd-YAG laser and Yb-fiber laser sources in three different configurations. Microhardness measurements were made to evaluate the hardness profile of the treated layer. In order to evaluate the microstructure and grain size of the laser treated layer, scanning electron microscopic (SEM) images were taken in cross section with a SEM/focused ion beam (FIB) dual beam electron microscope. The opened graphite area percent were also determined by image analysis method on the surface after laser treatment with a SEM in backscattered electron (BSE) mode, because the outburned graphite holes are the oil reservoirs for lubrication during operating conditions of the engine.

1. Introduction
The automotive engine development is defined by three main factors: (I) to make the engines more cost effective, (II) to keep the environmental regulations and (III) the increasing fuel prices, which means that by even higher engine power the fuel and oil consumption should not increase, and the engines should have a long lifetime [1]. Both the consumption reduction and the power increase of Otto- or Diesel-engines cause higher pressures in the combustion space resulting higher tribological load and wear rate for the piston rings and to the cylinder bore [1].

To improve mechanical and tribological properties of cast iron cylinder bores it is possible to use special mechanical [2] and laser structuring treatments [3], or – which is used by a large European automotive manufacturer – a special laser treatment on the V-block engines to alter the properties of the cylinder bores. Due to the laser treatment, the near surface area of the cylinder bore becomes harder and more wear resistant, furthermore, due to the inhomogeneity of the perlitic matrix and carbon lamellae, oil reserving holes are formed. This treatment results in an increased power output and reduced oil consumption [1, 4].

2. The Laser Treatment and Samples
The goal of the laser treatment is to melt a thin layer on the surface and at the same time the laser induced plasma over the surface evaporates the graphite lamellae, deeper than the metallic surface.
itself. So these “holes” are practically non-communicating oil reservoirs [1]. This treatment is patented, the patent number is: EP 1 738 859 A1.

Recently the cylinder bores in the mass-production are treated with a Xe-Cl excimer laser which works in the UV wavelength region (308 nm) at a repetition rate of 300 Hz. During treatment the workpiece is lasered with a rectangular laserspot with 4 times overlap in a definite raster. The adjustable parameters during the laser treatment are: (I) scale of the overlap (scanning grid), (II) mean laserpower on the surface and (III) the speed of the scanning.

There are further experiments to find alternative laser sources, because the excimer lasers have high maintenance requirements and the maintenance and servicing costs are higher than those of the solid states lasers. We investigated four samples, treated with Nd-YAG laser and Yb-fiber laser sources in three different configurations. The material of the samples is grey cast iron with lamellar graphite (GJL-250). The main laser parameters for the laser treatment are shown in table 1.

| Sample | Lasering strategy | Laser type | Wavelength | Pulse duration | Repetition frequency | Energy density on the surface |
|--------|------------------|------------|-------------|----------------|---------------------|-----------------------------|
| A      | 1x4 Nd-YAG       | 1064 nm    | 40 ns       | 6000 Hz        | 52 mJ/mm²           |
| B      | 2x2 Nd-YAG       | 1064 nm    | 40 ns       | 6000 Hz        | 52 mJ/mm²           |
| C      | 2x2 Nd-YAG       | 1064 nm    | 160 ns      | 6000 Hz        | 50 mJ/mm²           |
| D      | 2x2 Yb-Fiber     | 1065 nm    | 140 ns      | 12500 Hz       | 49 mJ/mm²           |

The only difference between sample A and B is just in the lasering strategy; sample A was treated with four times overlap of the laser spot (four laser pulses) during the insertion of the laser output tube into the cylinder bore. The samples B, C and D were treated with two times overlap during the insertion as well as during removal (also four laser pulses).

3. Experimental

The hardness profile of the surface and the near surface layer of the laser treated surface were measured with a Fisherscope® HM2000 XY microhardness measurement system which utilized the load-indentation depth method according to ISO 14577-1. The indenter was equipped with a Vickers pyramid. The hardness measurements were performed on the laser treated surface.

The FIB investigations were made by a FEI Nova Nanolab 600 SEM/FIB dual beam scanning electron microscope. Half of a regular cross section for TEM lamellae cutout were made and then images were taken – with lowered ion current – of the wall of the obtained cavity (figure 3). Because the outburned graphite holes are the oil reservoirs for lubrication during operating conditions of the engine [1, 4, 5]; it is important to know how many free graphite holes are going to influence the sliding behaviour. The graphite area of the base material and the laser treated surface were determined by Image Pro Plus software on SEM images in BSE mode. Twenty images were pasted together to cover a 1900×1860 µm² area approximately.

4. Results

Figure 1 and 2 shows the hardness vs. indentation depth curves of the four samples. Every curve is the mean value of seven separate measured curves on the same sample. The curves start at 0.1 µm indentation depth, because at the first 100 nm of the indentation – most likely because of the surface roughness of the treated surface – curves have a standard deviation of many order of magnitude. The standard deviation of the mean curves (for every sample) is approx. ± 500 N/mm².

The hardness profiles obtained by 150 mN load (figure 1) show that sample A was much harder then the other samples until 400 nm of depth. The hardness values decrease continuously until that point, than tend to the value of approx. 3700 HM. Samples B and D are actually very similar, the “softest” hardness profile was obtained for sample C.
The hardness profiles obtained by 1000 mN load (figure 2) shows that the hardness values also decrease continuously until 400 nm of depth and samples B and D are actually very similar, but the “softest” hardness profile – unlike with 150 mN load – was obtained for sample A.

![Figure 1. Hardness profiles by 150 mN load](image1)

![Figure 2. Hardness profiles by 1000 mN load](image2)

On the FIB cross section image (figure 3) and on the transmission electron microscope (TEM) image (figure 4) it is well seen that the laser treated layer is ultra fine grained. Below that the base material of perlitic cast iron has many larger grains. The ultra fine grained structure was most likely formed due to the large heat gradient during solidification of the molten surface.

![Figure 3. FIB image of the cross section of sample “B” and the mechanically heavily deformed grains near the surface](image3)

![Figure 4. TEM image of the laser treated surface of sample “C” and the mechanically heavily deformed near surface layer](image4)

**Table 2.** Thickness (R) and grain size (d) of the laser treated layer of the cylinder bores measured on FIB, TEM and SEM images

| Sample | Thickness of the laser treated layer | d_FIB (nm) | d_TEM (nm) |
|--------|--------------------------------------|------------|------------|
| A      | 0.76 - 0.93 0.52 - 1.26              | ---        | 386        | 150-560    |
| B      | 0.65 - 0.71 0.57 - 1.01              | 0.5        | 179        | 160-360    |
| C      | 0.85 - 1.18 0.65 - 1.19              | 1.1        | 222        | 100-400    |
| D      | 0.53 - 1.00                     ---   | 0.5 - 0.8  | 250        | ---        |

The thickness of the laser treated layers on the FIB images (R_{FIB}) was determined with Image Pro Plus image analysis software. The thickness values were measured also by SEM (R_{SEM}) on cross section samples prepared by conventional mechanical way, and on TEM (R_{TEM}) samples prepared by
FIB and classical TEM sample preparation. The layer thicknesses obtained by different methods are listed in table 2. To determine the average grain size several FIB images were pasted together, so the pasted images covered an area of approx. 20x7 \( \mu \text{m}^2 \). The average grain sizes (\( d_{\text{FIB}} \)) and the maximal and minimal values of grain sizes (\( d_{\text{TEM}} \)) measured from TEM images with Image Pro Plus program are also listed in table 2.

After mechanical finishing ( honing), a part of the graphite lamellae on the bore surface are buried by a thin ferrite smear of the base material. After laser treatment a part of these lamellae will be opened. The ratio between graphite area percent of the base material (\( G_{\text{BaseMat.}} \)) and the graphite area percent of the opened graphite lamellae on the treated surface (\( G_{\text{LaseredSurf.}} \)) defines an effectivity (\( \text{GOpening} \)) of the laser process. The graphite area ratios are listed in table 3 which indicates that the lasering strategy and the repetition frequency have a great effect on the graphite opening.

| Sample | \( G_{\text{BaseMat.}} \) (%) | \( G_{\text{LaseredSurf.}} \) (%) | \( \text{GOpening} \) (%) |
|--------|-------------------------------|-------------------------------|-------------------|
| A      | 10.53                         | 6.75                          | 64.1              |
| B      | 8.92                          | 4.98                          | 55.8              |
| C      | 9.33                          | 4.97                          | 53.2              |
| D      | 8.60                          | 6.70                          | 77.9              |

Additional x-ray diffraction measurements were made on samples treated with Yb-fiber laser and Xe-Cl excimer laser. The measurements showed that after laser treatment retained austenite was formed in every sample, as it has been reported in many other cases and for different laser types [6-9]. Additional x-ray photoelectron spectroscopy measurements indicated nitrogen incorporation of about 1.5 at\% in the laser treated surface and after Ar-ion bombardement at 25nm depth of the samples. Nitrogen solution into metallic surfaces is not unusual even in case of other laser sources induced plasma [9-12].

5. Conclusions
Due to the laser treatment on the cylinder bore the top layer of the surface was molten and at the place of outburned and opened graphite lamellae oil reserving holes were formed. The top layer showed considerably increased hardness which is most likely caused by the ultra fine grained surface layer and the nitrogen incorporation into the surface. Retained austenite was also found in the treated layer.

References
[1] Lindner H, Bergmann H W, Brandenstein C, Lang R, Queitsch A, Reichstein S and Stengel E 2003 *VDI-Berichte* 1764 73
[2] Knoll G, Lagemann V, Lechtape-Grüter R, Robota A Schleerege F 2003 *VDI-Berichte* 1764 63
[3] Andersson P, Koskinen J, Varjus S, Gerbig Y, Haefke H, Georgiou S, Zhmudd B and Buss W 2007 *Wear* 262 369
[4] Herbst L, Lindner H, Heglin M and Hoult T 2004 Targeting diesel engine efficiency, *Industrial Laser Solutions for Manufacturing* CDT (2004)
[5] Duffet G, Sallamand P and Vannes A B 2003 *Applied Surface Science* 205 289
[6] Benyounis K Y, Fakron O M A, Abboud J H, Olabi A G and Hashmi M J S 2005 Surface *Journal of Materials Processing Technology* 170 127
[7] Alabeedi K F, Abbouda J H and Benyounisb K Y 2009 *Wear* 266 925
[8] Lian S and Chenglao L 1991 *Wear* 147 195
[9] Schaa P 2002 *Progress in Materials Science* 47 1
[10] Carpene E, Landry F, Han M, Lieb K P and Schaa P 2002 *Hyperfine Interactions* 139/140 355
[11] Carpene E and Schaa P 2002 *Applied Surface Science* 186 100
[12] Höche D, Rapin G, Kaspar J, Shinn M and Schaa P 2007 *Applied Surface Science* 253 8041