Effect of thermo-chemical treatment on tribological features on crankshaft journals of combustion engines

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Abstract. The article presents research on the wear between the bearing and journal surfaces. The investigation was done for two types of layers obtained by: laser drilling of EN-GJS-600 ductile cast iron and gas nitriding of 38 HMJ steel. Wear rates were defined on the base of comparison of surface layer profiles before and after the wear test. Comparing test results it was found that the biggest differences of the surface roughness parameter were obtained for gas nitrided specimens (ε + γ’+ α) while the smallest differences for the laser drilled ones. Moreover the surface layer of specimens was evaluated with the usage of microhardness measurements. The surface of the drilled specimens was characterized with the constant value for the melt layer. At the end of the paper findings of the research were summarized and the conclusions were drawn.

1. Introduction

Cast iron invented in the fifth century BC by the Chinese, is still very popular casting alloy. The low price of raw materials, low cost of manufacturing, the simplicity of equipment for melting and beneficial properties of casting and mechanical properties of cast iron have been the reason for the popularity of the material [1,2].

There has been observed worldwide increasing demand for ductile cast iron and one of the most dynamically developing constructional alloys is ductile cast iron ADI. It seems that the share of production of cast iron in the total cast iron alloy castings is now an indicator of the novelty in foundry and industries for which these castings are important elements of products, which is machine-building industry or the automotive industry. Countries with a modern structure of the economy produce about 50% of ductile cast iron including ADI in the total mass-produced cast iron. In Poland, the ratio has not exceeded 12% [2].

Gray cast iron with flake graphite is the most widely used not only in the design of motor vehicles. The mentioned cast iron is used in the agricultural machinery building industry i.e. in order to design various wheels (gears, pulleys, chains, road), brackets, grinders covers, seeders or harvesters.

Flake cast iron is a basic material used in the production of cylindrical sleeves for various combustion engines. Good tribological and technological properties suggest that this cast iron will be used for such designs for a long time. In order to ensure maximum durability and reliability of the connection ring - cylinder sleeve there are used proper alloy additives or the wide range of surface treatment tools.
The use of suitable alloying additives may contribute to a significant reduction in the intensity of wear or improvement of scuffing resistance. However, sometimes wrong conclusions can be drawn on the base of our own knowledge or literature review. Research carried by the authors of the article [3], did not confirm literature review findings on the beneficial effects of boron on mechanical properties of iron ZICu1.4PVB. The situation was explained by different interaction of boron with alloying elements and their cumulative effect on the properties of cast iron. The authors also found that theoretically better ZICu1.4PVB cast iron containing boron is characterized by worse plasticity properties than ZICu1.4PV cast iron what may result in greater susceptibility to cracking of such a sleeve. The authors also pointed that cast iron containing boron was characterized by greater resistance to wear but in cooperation with a counterspecimen of insufficient hardness it caused accelerated wear. Cast iron ZICu1.4PVB is currently used as a material for cylindrical sleeves of marine engines manufactured by Sulzer license [3]. Despite many advantages of flake gray cast iron or even malleable cast iron as a constructional material, it has been observed that it is being replaced by modern foundry material, which is ductile cast iron. Its good mechanical and plastic properties, even better than malleable cast iron with less energy consumption for production, determine the growing use of the material in the automotive engineering. Changing the form of flake graphite on modular graphite created wide opportunities to improve the mechanical properties and performance of cast iron. The technology for producing ductile iron was developed after World War II, although there were cases of casting applications with the ductile cast iron structure made in China approx. 500 years BC. Nowadays, the share of ductile cast iron in the entire production of castings is constantly growing, especially in highly developed countries. Much attention in the literature is devoted to the huge advancement in the development of a completely new ductile and vermicular cast iron. These materials subjected to hardening with the isothermal transformation are called cast iron ADI (the abbreviation stands for Austempered Ductile Iron) and AVCI (the abbreviation stands for Austempered Vermicular Cast Iron), respectively. Ductile cast iron ADI in matrix contains ferrite and austenite, called ausferrite. Tensile strength of the material is twice as high compared to the ductile cast iron, showing at the same time much better plastic properties than ductile cast iron. Its strength is comparable to the one of wrought and heat treated steel. Elements of ductile iron are characterized by excellent resistance to abrasive wear (due to the hard matrix and the lubricating effect of the graphite) and high fatigue life and also the ability to hardening due to cold work. Advantageous thermal conductivity and much better ability to damping capacity in comparison to the steel are also distinctive features [4,5,6,7,8,9,10].

In engines made of ductile cast iron for the needs of the automobile market there can be found piston rings, engine timing gears, camshafts and connecting-rods also valves and crankshafts. In principle cast iron pistons are not applicable due to their heavy weight, the known application is for example the compression ignition engine of the Robur car. Cast crankshafts due to good strength properties, high fatigue resistance and good damping of torsional vibrations can be found in engines of such vehicles as the BMW 318, VW Golf 1.4, Peugeot 405 1.9/R4 [11,12].

Journals of various shafts (eg. crankshaft or camshaft) are often subjected to conventional nitriding, carburizing, carbonitriding or surface hardening. Abrasion research of the camshaft model made of ductile cast iron EN-GJS-500, treated by drilling diffusion, cooperating with the steel structure shows [13] that there can observed positive effects of this process (even in comparison to hardening) on wear of such a tribological node. The mentioned research revealed that the wear resistance of specimens treated by drilling diffusion was twice as high compared to hardened specimens (heated to temperature of 930 °C and cooled in a salt bath up to 180 °C). The authors stated that elements with drilled layers can be extremely resistant to abrasion and adhesion due to their high hardness (1600 HV).

In addition to conventional surface treatments in many different scientific studies, new and more favourable solutions for constituting the surface layer are sought. As a consequence many studies have been carried out in relation to the shaping element layer also cast iron using fascicular techniques. Due to recognition of the advantages of the concentrated beam of photons, what not only shatters the material but can also quickly favourably change (eg. for operational reasons) the structure of the surface layer in
selected parts of the element. Information on the increase in wear resistance of the surface layers obtained on iron cast elements as a result of the laser treatment can be found in papers [14,15].

The beneficial effect of boron on the wear process (also at elevated temperature) may also be used for cast iron components by laser alloying that can increase the wear resistance of such elements. Therefore, it seems appropriate to undertake the research in order to verify the method with reference to conventional surface treatment methods.

2. Research methodology
Researchers decided to prepare two types of layers on the cylindrical surface by laser boronizing (non-conventional thermo-chemical treatment) of EN-GJS-600 ductile cast iron in ferrite-pearlite matrix and by gas nitriding (conventional thermo-chemical treatment) of 38 HMJ steel. It was determined to make sleeves (specimens) having an outer diameter of 44 mm and a length of 60 mm.

The sleeves were subjected to laser heat treatment with continuous heating to achieve melting of coverage and the substrate. For this purpose, the molecular CO$_2$ laser manufactured by TRUMPF with maximum power of 2600 W and mode TEM$_{01}$ located at the Laboratory for Laser Technology at Poznan University of Technology was used. The treatment parameters of the laser are the laser beam power $P = 600$ W, the linear velocity of the beam in relation to the workpiece $v=3$ mm/s, the exposure time $t=2$ s. The applied feed of the laser beam along the axis of the shafts subjected to the laser treatment was $f=2$ mm/rev.

The laser drilled surface layer was obtained by melting of alloying element with substrate along the helical of sleeve what in the area of cooperation of sleeve with the semi-setting allowed when overlaying following areas to obtain perpetual surface layer. Parameters of the laser treatment applied during forming of the surface layer were obtained during preliminary studies that allowed selection of parameters to achieve a continuous layer with optimal thickness, microhardness, or roughness. After the laser treatment layer of sleeve was grinded on grinding machine removing the layer not exceeding 0.01 mm.

For specimens with the nitrided surface layer the process of gas nitriding was carried out in such a way to obtain the layer with $(\gamma' + \alpha)$ and $(\gamma' + \varepsilon + \alpha)$ phases, respectively. The main parameters applied during gas nitriding of tested specimens are listed in Table 1.

| Layer type   | Temperature $T$ $^\circ$C | Time $t$ h |
|--------------|--------------------------|------------|
| $\varepsilon + \gamma'$ | 550                      | 26         |
| $\varepsilon + \gamma' + \alpha$ | 550                      | 18         |

In the study, thick-walled sleeves were defined as specimens as their goal was to model a crankshaft main bearing journal of combustion engine. Evaluating manufactured layers specimens were tested on friction machine, where a semi-setting manufactured by Glyco with a width of 19.1 mm was a counterspecimen. The tribological node has been subjected to gravitational lubrication with usage of engine mineral oil Lotus SAE 15W40.

Wear tests were carried out on the ZPG-IV stand for accelerated tribological tests. The station's instrumentation allows for wear tests in conditions similar to operating ones.

Through cooperation of machine with a logger and a computer, there is possibility to measure and record such values as the driving torque of shaft in station M Nm; shaft rotational speed n rev./min; the pressure in the hydraulic load system p bar pressure corresponding to the calculated value of the thrust of shaft on setting MPa; the temperature in the direct area under the setting $T ^\circ$C; resistance in the contact zone of journal and setting $R$ kΩ (what may be a measure of the presence of the oil film).

The wear research included changes of surface pressure resulting from pressure changes in the hydraulic load system in the range of 0 - 25 MPa. Changes in pressure appeared every 15 minutes by approximately 2 MPa until 25 MPa then were reduced to 0 MPa. Constant rotational speed was used
with the value of 1000 rev/min. The test lasted 6 hours. As initial tests showed the measurement uncertainty of the moment on the shaft (moment of friction) was about 1.5 Nm as a result of resistance generated by shaft’s rolling bearings mounted in station. Before each test measurements were taken in order to deduct clearance between a journal and a semissetting, which oscillated in the range between 0.03 - 0.09 mm for nitrided and laser drilled specimens. Taken measurements of run-out showed that run-out of drilled journals had maximum value of 0.05 mm while for nitrided journals maximum value was 0.01 mm.

The authors assumed to determine the wear rate by making (in contact places of journals and bearing shells) profiles of surface referring them to surface areas that were not subjected to wear process. Profilograms of journals and settings surfaces before and after wear test were made with profilografometr manufactured by Jena Carl Zeiss with Sajda software. For microstructure analysis there was used the Zeiss Epiquant microscope coupled with a CCD camera, and for measurement of the microhardness there was used the 3212 microhardness tester manufactured by ZWICK using Vicars method with 100 g load.

3. Test results and analysis

Carried out surface treatment by laser alloying required melting of the surface layer of processed sleeve, resulting in the occurrence of surface corrugation. In addition, laser processing in a helical pattern using raster method increased effect of corrugation, what was also visible visually during preliminary tests (Figure 1). Preliminary test were taken in order to properly select the drilling parameters to obtain a surface layer of thickness about 0.3 mm and to minimize the corrugation and porosity of surface. Parameters defined in the chapter "research methodology" for laser boronizing allowed to achieve the desired effect and reduce surfaces corrugation of processed cast iron sleeves. Distinct traces of the accivity and hollows of the surface layer are shown in Figure 2 on the example of roughness profile of surface along with its basic parameters. The prepared surface profiles of laser drilled specimens with optimum processing parameters revealed that from the point of view of corrugation of surface it is necessary to remove the layer of material with a minimum thickness of 40 μm. The value of Ra before grinding of the surface was in this case up to 3.02 μm.

Figure 1. View of the laser boronized sleeve : a - during laser heating b - after laser heating
It should be noted that the grinding of laser processed area provides significantly less surface roughness, even in comparison with the same material which was not laser processed, and grinded. In this case, the parameter Ra was up 0.09 μm (Figure 3) (average value of Ra = 0.137±0.012 μm).

It suggests that the surface layer formed with similar roughness to semi-setting roughness (0.102 ± 0.070 μm) in a short time it will undergo lapping (Figure 4).

Measurements of run-out of shafts that did not exceed 0.05 mm did not indicate deformation of sleeve what may not cause its damage due to the heating process during melting by laser beam.

Gas nitriding process allowing to obtain nitrided layer (γ ' + α) caused the parameter Ra reached an average value of 0.320 ± 0.030 μm. In the case of the sleeve where nitrided layer was formed (ε + γ ' + α) it was observed that, for example Ra parameter averaged in the range of 0.350 ± 0.030 μm. It means that the manufactured surface layer has a higher surface roughness of not only for the nitrided layer (γ ' + α), but also for the laser drilled layer.

It should be added that specimens before gas nitriding had value about 0.30 μm for the Ra parameter.
Conducting the assessment of the state of the surface layer of laser drilled and gas nitrided specimens there were also made microhardness measurements from the surface into the material using the Vickers and Knoop method. The microhardness measurements clearly indicated the different nature of the course of microhardness changes on the cross-section of the surface layer formed with melting and without melting of the processed material. Laser boronizing clearly revealed constant microhardness in the melted zone to a depth of about 0.3 mm which then gently decreased gradually in the hardening zone from the solid state (Figure 5).
Figure 5. Changes of microhardness into the surface layer obtained by laser boronizing. Confidence limits for the mean are given at significance level of 0.1.

The reason for the growth of microroughness (for one of the specimens 1298 HV0,1±58) in melted area was inserted boron and probably manufactured softer iron borides Fe₂B. Microscopic examination revealed also creation of dendritic structure in the melted zone with axes of dendrites set in direction of heat abstraction. However, in the hardened area the martensitic structure was observed.

Gas nitrided layers were characterized by rather even decrease of the microhardness from surface until the microhardness of the core was reached (Figure 6).

Figure 6. Changes of microhardness into the nitrided layer (γ' + α) and the nitrided layer (ε + γ' + α) obtained by gas nitriding of steel 38 HMJ.

The maximum value of the microhardness for nitrided layer (γ' + α) was 1050 HK 0.1 and was higher than the microhardness obtained for the nitrided layer (ε + γ' + α), which was 950 HK 0.1. The thicknesses of nitrided layers was estimated to be about 0.4 mm. In order to evaluate the wear resistance of the prepared journals cooperating with half-shell bearings on the friction machine there were made profiles in the area of cooperation between half-shell bearings and journals and partly outside it. The
profile shape thus illustrated the amount of wear of the tested element. The profiles obtained on the laser drilled surfaces after operation on the friction machine showed the wear rate equal to 0.56±0.05 μm. One of the exemplary profiles is shown in Figure 7.

Figure 7. Surface profile of the laser drilled shaft after the wear test

However, the surface profiles subjected to gas nitriding showed higher wear in relation to the laser drilled ones, for specimens with the gas nitrided layer (γ’ + α) 1.32±0.82μm and for the ones with the gas nitrided layer (ε + γ’ + α) 1.92±0.62μm respectively.

4. Conclusions
As a result of carried out tests it was found that:

- it is possible to produce a surface layer of 0.3 mm thickness by drilling EN-GJS-600 ductile cast iron with the usage of the raster method on sleeve representing the shaft neck,
- the melted area is characterized by even distribution of microhardness on a cross section and in the hardened area there can be observed gradual reduction of microhardness,
- laser boronizing of ductile cast iron allows to obtain microhardness of the surface layer even equal to 1298HV0.1 ±58
- there is distinctly different course of changes in microhardness on the section of the layer obtained by laser boronizing and gas nitriding,
- roughness of the sleeve surface grinded after the laser treatment is very similar to roughness of half-shell bearings cooperating with this surface what can significantly reduce the lapping time of the tribological node.

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