Improvement of tribological properties of bearings by laser processing of cast-iron shafts of heavy-duty diesel engines

Valery Alisin[1*]

[1]Mechanical Engineering Research Institute of the Russian Academy of Sciences, 4 Maly Kharitonyevsky Pereulok, 101990 Moscow, Russia

Abstract. The article discusses the tribological properties of plain bearing materials in heavy-duty diesel engines with a cast-iron crankshaft. The effectiveness of the influence of laser hardening of shaft necks on the tribological properties of main and connecting rod bearings in comparison with nitriding is substantiated. Simulation comparative tribological tests have been carried out on a laboratory friction machine on samples of materials of an insert made of bronze Br-30 and a shaft made of high-strength cast iron with nodular graphite under conditions of sliding friction with lubrication after laser treatment hardening and nitriding. The influence of hardening treatments of the shaft necks on the antifriction properties and wear resistance of friction couples materials is investigated. Particular attention is paid to the scuff resistance of friction couples. The assumption of a higher efficiency of laser hardening in comparison with nitriding based on the tribological properties of friction surfaces is substantiated. Based on the study, it is recommended to use laser hardening of the crankshaft necks to increase the service life of heavy-duty low-speed diesel engines.
Keywords: cast iron crankshafts, diesel connecting rod and main bearings, coefficient of friction, scuff resistance, plain bearing wear.

1 Introduction

In powerful automotive engineering, diesel locomotives, large ships, heavy-duty diesel engines are widely used, in which crankshafts made of high-strength cast iron with nodular graphite are of mass application. The manufacture of crankshafts from cast iron is due to a number of economic advantages. Particular attention is paid to the operation of bearings, connecting rod and main bearings. Cast iron is prone to brittle damage, so the areas of bearing assemblies, as stress concentrators, are the subject of research. The service life of the crankshaft depends on the wear resistance of the main and connecting rod bearings, especially when bronze inserts are used. Hardening treatments, such as nitriding, are used to increase the wear resistance of the pins. Much attention is paid to increasing the wear resistance of plain bearings. To improve the lubrication of the friction surface, the effect of recesses with different geometrical parameters on tribological characteristics was studied [1], and the effect of diamond polishing on the wear resistance of bearing bushings made of bronze was studied

* Corresponding author: vva-imash@yandex.ru

[2]. In [3], the influence of surface modification on the friction properties of plain bearings was studied, mainly by the geometric characteristics of the surface texture. In works [4 - 7], an analysis of failures of cast iron crankshafts of a diesel engine was performed. The hardness and microstructure results showed that both the connecting rod neck and the main bearing neck had no hardened surface layer. Recommendations are formulated to prevent premature failure of the engine. In [8], an analysis of the failure of the crankshaft of a diesel locomotive is presented. The study included testing methods and experimental process: selection of the crankshaft for study, visual inspection, non-destructive testing of the crankshaft, failure analysis, 3D modeling of the crankshaft, and finite element analysis. Recommendations have been developed to prevent the appearance and surface cracks on the connecting rod neck and the main neck bearing, which made it possible to significantly increase the service life of the locomotive crankshaft. Article [9] describes the failure analysis of the crankshaft of a diesel engine used in a truck, which is made of cast iron. The crankshaft has been induction hardened. The study included chemical analysis, microhardness measurement, tensile testing and metallographic examination. Article [10] presents an analysis of diesel engine crankshaft failures. Complicated dynamic loads are established due to rotational flexure combined with torsion on the main necks and alternating flexure on the connecting rod pins. Recommendations for improving the design of the engine are presented. In [11], based on field studies of bearings, an analysis was made of the main causes of engine bearing failures. The successful operation of a marine diesel engine is highly dependent on the design of the crankshaft. In the study [12], an analysis of the crankshafts operation life of marine engines and their maintenance was carried out, taking into account the improvement of the design over the past decades. In [13], a new composition of the material was recognized as promising as a material for the manufacture of inserts for plain bearings. One of the signs of a crankshaft malfunction is [14] the value of low pressure in the lubrication circuit, which can lead to its catastrophic failure of bearings and other parts. The crankshaft model was analyzed using the finite element method and a modification of the crankshaft geometry was proposed. Diagnostics of malfunctions of a marine diesel engine based on machine learning is recognized [15] as promising for improving engine reliability.

From the standpoint of new environmental regulations aimed at reducing gas emissions, a study was carried out [16] of operating parameters related to the tribological behavior of an internal combustion engine, mainly focused on the crankshaft and bearings. Laser hardening of cast irons is a promising hardening treatment, but its effectiveness in comparison with nitriding has not been studied enough.

The purpose of the work is to study the effectiveness of the effect of laser hardening of the necks of cast-iron crankshafts of heavy-duty diesel engines on the tribological properties of main and connecting rod bearings in comparison with nitriding.

2 Materials and research methods

The studies were carried out with samples of the crankshaft material - high-strength cast iron ВЧ 45-0 with nodular graphite, the disks were made with nitriding, without nitriding, with laser processing. The chemical composition of cast iron C (3.0 - 2.2); Si (1.8); Mn (0.6-0.8); P (0.2); Mg (0.04 - 0.8). Plain bearing inserts are made of bronze BrS30 composition P (0.1); Si (0.02); Ni (0.5); Fe (0.25); Cu (the rest).

The samples were made in the form of disks and pads (Fig. 1), the disk was 50 mm in diameter and 12 mm wide; the pad had a square shape with a side of 10 mm in cross section.

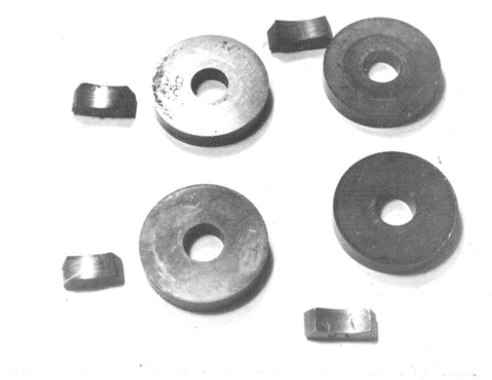


Fig. 1. General view of samples.

Tribological tests of materials used for the manufacture of crankshaft bearings for heavy diesel engines were carried out on friction machines ИИ-5018 according to the disk-pad scheme.

Laser hardening treatment was performed on a continuous CO_2 laser with a continuous output power of 1.5 kW.

X-ray phase analysis was performed on the "Dron" X-ray machine.

3 Results

The advantages of laser hardening are especially evident in such processing modes, when it is possible to maintain the original surface roughness, which is possible only when the surface is not melted. In most known calculation methods, a model of one-dimensional heating of a semi-infinite medium by an unlimited surface heat source with a constant intensity is considered, and the thermophysical characteristics of the material are considered independent of temperature. Laser hardening of the disk samples was carried out by applying annular reinforcing tracks with a step of 2 mm along the cylindrical surface according to the scheme shown in Fig. 2.

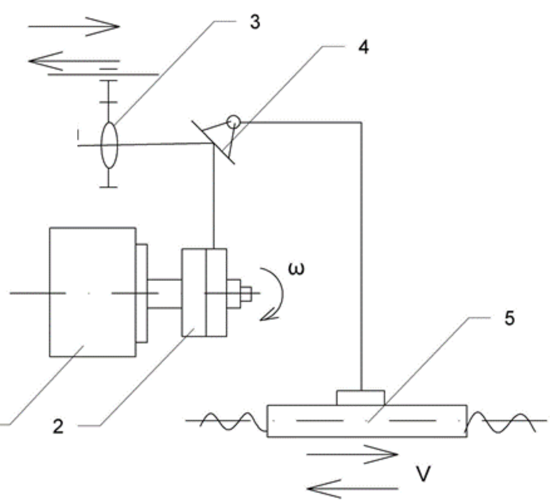
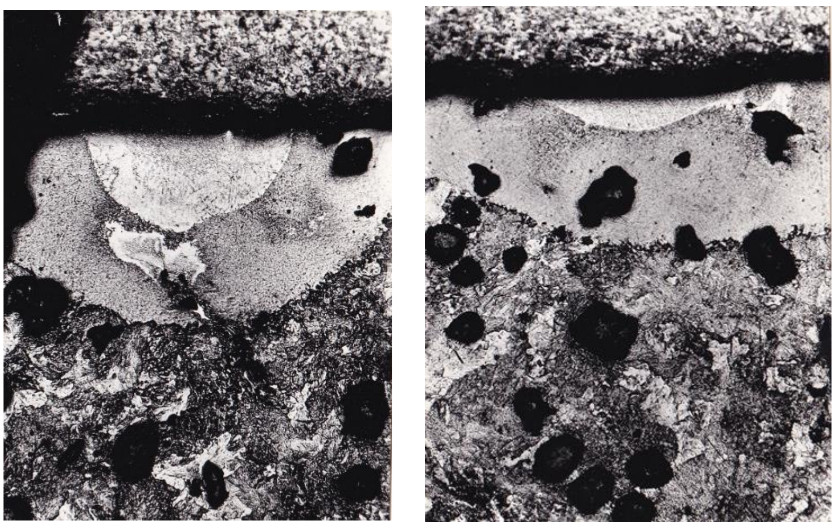


Fig. 2. Scheme of laser processing of disk samples.

A holder with a package of samples - disks 2 is installed in the cartridge 1. The laser beam passes through the focusing lens 3, falls on the rotary mirror 4, which is rigidly fixed on the support 5, and falls on the surface of the sample being processed. The specified diameter of the light spot is provided by moving the lens 3, and moving the spot over the surface - by moving the mirror 4. During laser processing, the cartridge rotates at a speed of 2 rpm, which ensures a linear processing speed v = 0/31 m/min.

The friction surface of specimens of ductile iron was processed by continuous laser radiation with a power of 1.5 kW. The optimal processing speed was determined experimentally based on the parameters of the zone of interaction between the laser beam and the surface. On fig. 3 shows the structure of the surface layer in the extreme limits. Photographs of microstructures were used to determine the dimensions of the laser impact zones: l_1 is the length of the hardening zone (μm); l_2 - melted zone length (μm); l_3 - maximum depth of the melted zone (μm); l_4 - maximum depth of the hardening zone (μm).



a) b)

Fig. 3. Microstructure of ductile iron with nodular graphite after laser hardening at different sizes of laser impact zones (magnification x100): a) l_1 = 1050, l_2 = 400, l_3 = 240, l_4 = 450; b) l_1 = 1200, l_2 = 400, l_3 = 100, l_4 =320.

Two zones can be distinguished: the first one crystallizes from a liquid state, has a dendritic structure and is a three-phase mixture of austenite, cementite, and ledeburite; in the second zone, phase transformations occur in the solid state. Microhardness in melted zones is determined quantitatively by the ratio of cementite and austenite, which depends on the chemical composition of cast iron and the rate of cooling of the liquid phase. In the melting zone, an austenite-cementite mixture with a hardness of H_{50} = 702 kgf/mm^2, in the heat-affected zone martensite H_{50} = 745 kgf/mm^2, the base is perlite with nodular graphite H_{50} = 341 kgf/mm^2.

Tribological tests were carried out after the samples were run in. In accordance with the test procedure, the experiments were carried out at a speed of 1.3 m/s. Before testing, the samples were washed in gasoline and rubbed. Then the samples were fixed, brought into contact and loaded with a normal load. Lubrication of the samples was carried out with a felt wick pressed against the surface of the sample-disk, M14Г oil was introduced periodically in the form of drops after 5–10 min.

The samples were run in for 3-5 hours at a load of 10 kg. The quality of running-in was judged by the formation of a contact area of at least 90% of the nominal area. Surface wear during running-in was not controlled, but selective measurements show that its linear value exceeds the value of the initial height of the roughness profile. Upon completion of the run-in, the samples were washed with gasoline and then rubbed with alcohol and weighed on an analytical balance. During the test, the moment of friction was recorded. The average duration of the test was 7 hours.

The scuff resistance of the bearing was determined from the dependence of the friction coefficient on the load. As the contact load increases, the process of scuffing of friction surfaces is characterized by a sharp increase in the friction coefficient. Figure 4 shows curves of the friction coefficient for nitrided and laser-treated samples.

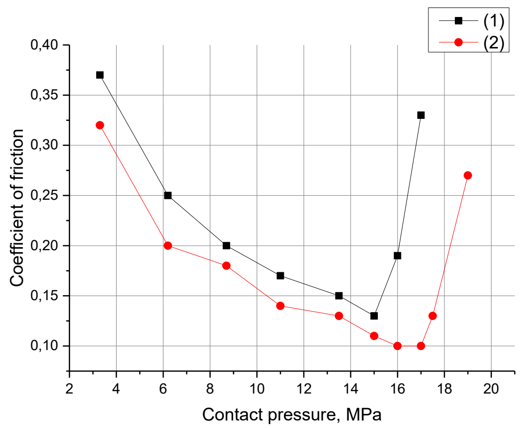


Fig. 4. Dependence of friction coefficient on pressure: 1 – nitriding; 2 - laser hardening.

It has been experimentally established that the scuff resistance of a bearing whose cast-iron shaft neck is treated with a laser is significantly higher than that of a nitrided one. Laser hardening of the shaft also significantly improves the anti-friction properties of the bearing compared to nitriding.

After the completion of the experiment, the samples were washed in gasoline, alcohol and weighed. The experimentally obtained weight loss of the samples was recalculated to the linear wear rate. Since the tested friction couples have undergone full running-in, the wear rate in this case is directly proportional to the nominal pressure. To compare the results of tests carried out at different pressures, it is convenient to introduce the reduced wear value I / p (mm^2 / kgf) as an indicator of surface wear resistance, where I is the wear rate, p is the contact pressure. In table. 1 shows the test results. Despite the significant spread in values of test results, which is typical for sliding friction due to the very nature of the problem (due to the influence of a very large number of factors), the main indicators of wear resistance make it possible to evaluate the effectiveness of surface treatment to increase wear resistance.

Table 1. The results of comparative tests of a bearing with a cast-iron shaft during friction on bronze BC-30.

Hardening treatment of cast iron sample	Load, kgf	Test duration, hour	Wear rate	
			Cast iron disc	Bronze pad
Nitriding	45	8	$2.36*10^{-9}$	$2.08*10^{-10}$
	45	8	$3.56*10^{-9}$	$3.47*10^{-10}$
	45	8	$3.34*10^{-9}$	$2.56*10^{-10}$
		average	$3.08*10^{-9}$	$2.70*10^{-10}$
Laser hardening	39	8	$3.41*10^{-10}$	$3.64*10^{-11}$
	39	12	$2.34*10^{-9}$	$2.33*10^{-10}$
		average	$1.34*10^{-9}$	$1.35*10^{-10}$

The wear resistance of bearings on a crankshaft made of laser-hardened ductile iron is significantly higher compared to a nitrided crankshaft.

4 Conclusions

1. It has been established by simulation experiments that laser hardening of the necks of cast-iron crankshafts, in comparison with nitriding, improves the antifriction properties of plain bearings with inserts made of БС-30 bronze, increases the scuff resistance and wear resistance of friction surfaces.
2. Laser hardening of crankshaft necks made of ductile iron is promising for increasing the service life of main and connecting rod bearings in heavy-duty low-speed diesel engines

References

1. Shaopeng Ding, Jia Xu, Pengfei Liu et al, Results in Engineering **9**, 100211 (2021) https://doi.org/10.1016/j.rineng.2021.100211
2. G.V. Duncheva, J.T. Maximov, A.P. Anchev et al, Wear **510–511**, 204491 (2022) https://doi.org/10.1016/j.wear.2022.204491
3. Guangqiang Shi, Xiaodong Yu, Hui Meng et al, Tribology International, 107937 (2022) https://doi.org/10.1016/j.triboint.2022.107937
4. K.Aliakbari, R. Masoudi Nejad, T. Akbarpour Mamaghani et al, Structures **36**, 482-492 (2022) https://doi.org/10.1016/j.istruc.2021.12.034
5. Nan Hou, Ning Ding, Shen Qu et al, Engineering Failure Analysis **136**, 106216 (2022) https://doi.org/10.1016/j.engfailanal.2022.106216
6. Sang Myung Chun, M.M. Khonsari, Tribology International **97**, 440-466 (2016) https://doi.org/10.1016/j.triboint.2016.01.042
7. Nan Hou, Ning Ding, Shen Qu et al, Engineering Failure Analysis **136**, 106216 (2022) https://doi.org/10.1016/j.engfailanal.2022.106216
8. T. Singh, Sh. Singh Sengar, Materials Today: Proceedings **44(6)**, 4369-4374 (2021) https://doi.org/10.1016/j.matpr.2020.10.564
9. O. Asi, Engineering Failure Analysis **13(8)**, 1260-1267 (2006) https://doi.org/10.1016/j.engfailanal.2005.11.005
10. M. Fonte, V. Anes, P. Duarte, L. Reis, M. Freitas, Engineering Failure Analysis **56**, 109-115 (2015) https://doi.org/10.1016/j.engfailanal.2015.03.014.
11. A. Vencl, A. Rac, Engineering Failure Analysis **44**, 217-228 (2014) https://doi.org/10.1016/j.engfailanal.2014.05.014
12. Fonte, P. Duarte, V. Anes, M. Freitas, L. Reis, Engineering Failure Analysis **56**, 51-57 (2015) https://doi.org/10.1016/j.engfailanal.2015.04.014
13. M. Nursoy, C. Öner, İ. Can, Materials & Design **29(10)**, 2047-2051 (2008)
14. J. Gomes, N. Gaivota, R.F. Martins, P. Pires Silva, Engineering Failure Analysis **92**, 466-479 (2018) https://doi.org/10.1016/j.engfailanal.2018.06.020
15. P. Narasimha Chandra, P.P.S. Reddy, K. Vinayak, S.R. Shukla, A.K. Prasada Rao, Biotribology **29**, 100205 (2022) https://doi.org/10.1016/j.biotri.2021.100205
16. N. Duarte Souza Alvarenga Santos, V. Rückert Roso, M. Tulio C. Faria, Engineering Failure Analysis **108**, 104344 (2020) https://doi.org/10.1016/j.engfailanal.2019.104344