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Implementation of the process of forming regular micro-reliefs on the working surfaces of connecting rod bearings

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Abstract

The article presents the results of designing a technological operation for the formation of a Type II regular mesh micro-relief with triangular grooves, performed using a vibration-free method in a single pass on the inner cylindrical surface of connecting rod bearings. The technological operation is implemented utilizing a specially designed tool by machining a pair of connecting rod bearings within a split holding fixture. The connecting rod body for the specified bearing size was used as the holding fixture. The required depth of the micro-relief grooves is achieved through a dimensional analysis of the developed special tool designed for the plastic deformation of the connecting rod bearing surface. Relative micro-relief areas of 14.9% and 28.5% were obtained by determining the appropriate feed rate and tool rotational speed. Experimental samples of connecting rod bearings for a Volvo V50 1.6 HDI vehicle, with the geometric parameters D_{ring} = 47.0 mm and B_{ring} = 16.9 mm, were produced with the formed regular micro-relief. The process was executed at an axial tool feed rate of f_{in} = 19.43 mm/rev (for the 28.5% area) and f_{in} = 39.56 mm/rev for the 14.9% area, utilizing a HAAS VF-B/40HE CNC vertical milling machine. It has been established that this technological operation can be performed either during the finishing stage of machining the copper-lead base of the bearing (which has a thickness of 250–400 μm) immediately prior to the application of protective metal layers of nickel, copper, and/or composite materials, or after the application of the protective coating. The creation of a regular micro-relief ensures high operational reliability, enhanced durability, and the stable performance of both the connecting rod bearings and the internal combustion engine as a whole.

Keywords: connecting rod bearings, technology, tool, parameters, formation modes, regular micro-relief

Introduction

Modern internal combustion engines (ICEs) are highly sophisticated mechanisms that convert thermal energy into mechanical energy. However, as their design becomes more complex, there is a noticeable trend towards a reduction in their operational lifespan. In contrast to the durable engines of previous decades, modern turbocharged engines (particularly low-displacement gasoline units subjected to high thermal loads) frequently exhaust their service life before reaching a mileage of 150,000 km. Stringent environmental standards also exert a negative impact on engine durability: in an effort to minimize toxic emissions and optimize combustion, manufacturers increase the compression ratio of the fuel-air mixture, thereby imposing additional loads on engine components. The scientific literature has already addressed a range of issues concerning the reliability, performance characteristics, and durability of ICE components [1]. To gain a profound understanding of the physical and mechanical processes occurring within friction zones, it is essential to systematically investigate the impact of operating conditions on the overall service life of the engine [2]. Consequently, the systematization and analysis of operational damage in automotive plain bearings (connecting rod bearings) remains a highly relevant objective in modern mechanical engineering [3–6]. Connecting rod bearings are among the most heavily loaded components of an ICE. Operating as plain bearings, they function under conditions of extreme temperatures and high specific pressures. Given that their working surfaces are continuously subjected to friction, the optimization of tribological conditions is a fundamental prerequisite for ensuring the reliable and uninterrupted operation of the engine.

Literature review

The mounting conditions and stiffness parameters of automotive plain bearings (particularly connecting rod bearings), which are among the most critical components of internal combustion engines (ICEs), are determining factors in the formation of their stress-strain state during operation. Based on the simulation of the technological operations of forming and fitting, the patterns of residual stress generation and their correlation with cyclic operational deformations induced by piston kinematics have been established [7, 8]. Furthermore, distinctions between hydrodynamic and elastohydrodynamic lubrication regimes have been identified, and the direct influence of bearing mounting parameters on the spatial distribution of hydrodynamic pressure has been demonstrated. Under normal operating conditions of modern ICEs, the thickness of the hydrodynamic lubricating film in plain bearings varies within the range of 1–20 μm (0.001–0.02 mm) [9–12].

At high rotational speeds and optimal lubricant viscosity, the film thickness can reach 15–20 μm, whereas at low speeds under increased load conditions, it is reduced to a few micrometers. A decrease in the lubricating film thickness to below 1 μm induces partial direct contact between the mating surfaces of the friction pair, leading to their intensive wear. An analysis of the causes of connecting rod bearing failures indicates that, under significant loads, insufficient lubrication of the contact zone is one of the primary reasons for their breakdown. This results in a shift in interaction regimes, causing a transition from Zone II (semi-fluid friction) to Zone I (boundary friction). Consequently, the formation and maintenance of a stable lubricating film is a priority objective for normalizing operating conditions and achieving the designed service life of the friction pair. An effective technological solution to this problem is the application of micro-grooved bearings (MGBs) – plain bearings with circumferential micro-grooves machined on their working surfaces [13, 14].

Compared to conventional non-profiled bearings (NPBs), MGBs are distinguished by a number of significant operational advantages. Specifically, they demonstrate enhanced resistance to seizure (scuffing) and fatigue failure, provide a lower operating temperature regime under high loads, and are characterized by improved starting properties at low temperatures [15, 16].

The formation of a regular micro-relief on the working surfaces of the bearings is objectively accompanied by a partial reduction in their relative load-bearing area. However, according to static calculations [17], the application of micro-grooves does not lead to a decrease in the load-carrying capacity of the bearing. Highly indicative are the results of studies investigating the operating time to seizure under conditions of an artificial interruption of the lubricant supply [17]. Unlike standard bearings, where premature seizure was recorded in three out of five test samples, the bearings with a micro-relief functioned stably for an extended period without any signs of critical failure. Such operational performance convincingly confirms the high capacity of micro-grooved bearings to accumulate and retain lubricant within the contact zone of the friction pair.

To prevent the occurrence of operational defects, it is proposed to form a regular micro-relief on the working surfaces of the connecting rod bearings. This technological solution contributes to increasing the temperature threshold for the onset of seizure between the contacting surfaces in the «bearing–journal» tribological pair [18]. Previous studies have demonstrated that the application of a micro-relief on cylindrical surfaces with the following parameters: relative area of the micro-relief F_n = 25–45%, groove inclination angle γ = 25–32°, and groove depth h_k = 22–27 μm, guarantees the formation of a lubricating film with a thickness of 3–3.5 μm [19].

The high effectiveness of forming regular micro-asperities to optimize the performance characteristics of friction surfaces is further corroborated by the research findings of other authors [20–22]. In light of this, the development of a technological process for applying a regular micro-relief to the working surfaces of connecting rod bearings emerges as a highly relevant scientific and applied objective in modern automotive engineering. The successful resolution of this task will enable a substantial increase in the overall service life of internal combustion engines.

The aim of this work is to develop and implement a technological process for forming a Type II regular micro-relief on the working surfaces of connecting rod bearings using a vibration-free plastic deformation method. The study also aims to determine the technological parameters required to obtain specified relative micro-relief areas and to experimentally validate the proposed process on connecting rod bearings of an internal combustion engine.

Research materials and methodology

The design of the technological operation for forming a regular micro-relief was carried out using a specially developed tool. These micro-reliefs are formed on the inner surface of the connecting rod bearings of a Volvo V50 1.6 HDI vehicle with the following geometric parameters: D_{ring} = 47.0 mm; B_{ring} = 16.9 mm, during their machining in a holding fixture (Fig. 1).

To calculate the relative area of the micro-relief, equation (1) was utilized, which allows for establishing the relationship between the area of the micro-relief grooves and the forming parameters.

$$F_a = \frac{\dfrac{2B_{ring} \cdot n_{in} \cdot b_g}{\pi D_{ring} tg(\gamma_{c.g}/2)} \sqrt{(\pi D_{ring})^2 + (\pi D_{ring} tg(\gamma_{c.g}/2))^2} - \dfrac{n_{c.g.tot} \cdot b_g^2 \cdot \sin(\gamma_{c.g})}{\sin^2(2\gamma_{c.g})}}{\pi \cdot D_{ring} \cdot B_{ring}} \quad (1)$$

where B_{ring} – width of the connecting rod bearing, mm;
D_{ring} – diameter of the inner cylindrical surface of the connecting rod bearing, mm;
n_{in} – number of deforming elements involved in the formation of the micro-relief, units;
b_g – width of the micro-relief groove, mm;
$\gamma_{c.g.}$ – angle between the micro-relief grooves, deg;
$n_{c.g.tot}$ – total number of groove intersections, units.

Taking into account the geometric parameters of the connecting rod bearings, a schematic layout of the regular micro-reliefs was developed with two values of the relative micro-relief area: 28.5% and 14.9% (Fig. 1).

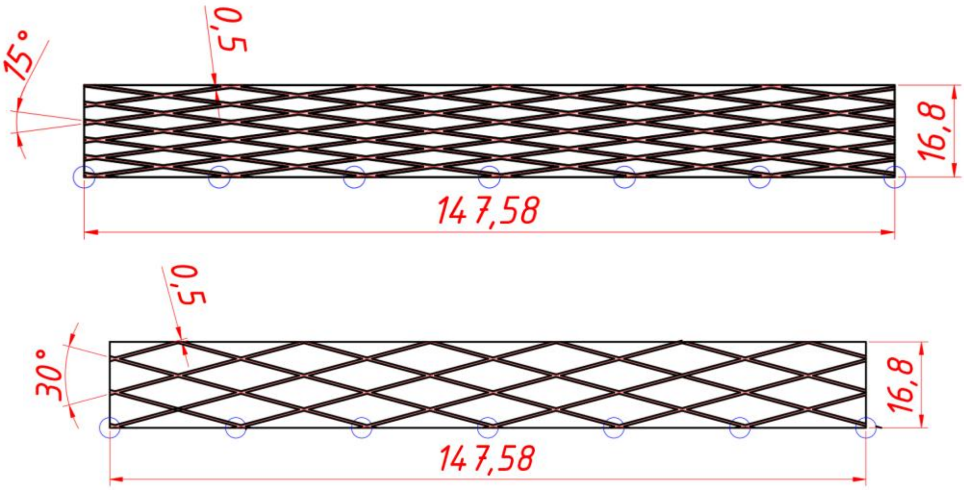


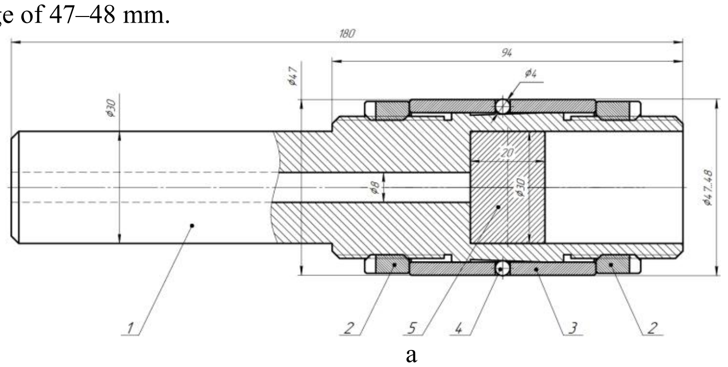
Fig. 1. Unfolded view of two pairs of Volvo V50 1.6 HDI connecting rod bearings for the formation of regular micro-reliefs with a relative micro-relief area of 28.5% and 14.9%

In this case, the axial feed of the tool f_{in} is determined from equation (2).

$$f_{in} = \pi D_{ring} tg(\gamma_{c.g}/2) \quad (2)$$

Thus, the feed rate required to achieve a relative micro-relief area of 28.5% is f_{in} = 19.43 mm/rev, whereas for an area of 14.9%, it is f_{in} = 39.56 mm/rev. The calculations were performed taking into account that the deforming elements form a groove with a width of 0.5 mm.

The formation of a regular micro-relief on the working surfaces via plastic deformation significantly reduces the height of surface micro-asperities, particularly those involved in contact interaction during the initiation of the adhesive seizure process. The generation of the regular micro-relief on the working surface must be carried out during the finishing stage of machining the copper-lead base of the bearing, which has a thickness of 250–400 µm. Only after the regular micro-relief has been formed should the protective metal layers of nickel, copper, or composite materials be applied. A dimensional analysis [24] of the tool design was conducted using the method of complete interchangeability by solving the inverse problem of the dimensional chain. Based on the performed calculations, the nominal dimensions and tolerance zones of the tool's closing link were determined, taking into account the elastic and elasto-plastic deformation of the surface layer material. The proposed tool design (Fig. 2) provides the capability for the continuous adjustment of the protrusion height of the deforming elements within a range of 47–48 mm.



a

b

Fig. 2. Tool for forming a regular micro-relief on the inner surface of connecting rod bearings: a – drawing; b – actual view 1 – tool body; 2 – front and rear nuts; 3 – cage; 4 – deforming elements; 5 – magnet

The application of the developed tool enables the formation of surfaces with an optimal relative micro-relief area, thereby enhancing the oil retention capacity and operational reliability of internal combustion engine connecting rod bearings.

Adjusting the protrusion height of the deforming elements allows them to penetrate the surface of the connecting rod bearings to various depths, consequently forming grooves of varying widths.

It was decided to use the base of the connecting rod for these bearings as the technological tooling (the holding fixture), since its internal mounting diameter is precisely fitted to the outer diameter of the connecting rod bearings (Fig. 3). The fixture possesses sufficient stiffness to ensure the plastic deformation of the bearing surface.

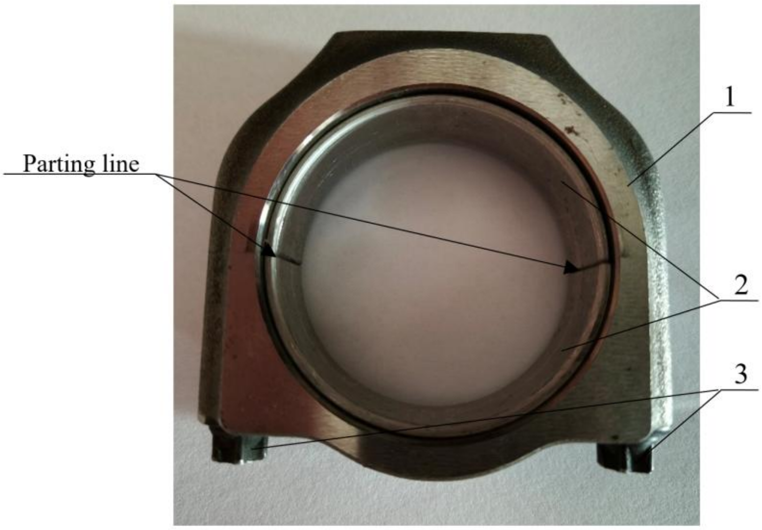


Fig. 3. Split holding fixture for the formation of regular micro-reliefs on the working surfaces of connecting rod bearings: 1 – fixture body; 2 – connecting rod bearings; 3 – fastening elements

The process of forming the micro-relief grooves was performed on a HAAS VF-B/40HE CNC vertical milling machine. The regular micro-reliefs obtained on the working surfaces of the connecting rod bearings are shown in Fig. 4.

a)

b)

c)

d)

Fig. 4. Internal combustion engine connecting rod bearings: a – without the formation of a regular micro-relief; b – with the formation of a regular micro-relief using a Ø3.5 mm deforming element and a relative micro-relief area of 14.9%; c – with the formation of a regular micro-relief using a Ø4.0 mm deforming element and a relative micro-relief area of 14.9%; d – with the formation of a regular micro-relief using a Ø3.5 mm deforming element and a relative micro-relief area of 28.5%

The depth of the grooves in the formed micro-relief is related to their width, as the grooves are formed by a spherical deforming element. Therefore, by varying the diameter of the deforming element and positioning it on different parts of the tool's conical surface, grooves can be formed within a relatively narrow yet sufficient range of geometric parameters. An increase in the diameter of the deforming element widens the groove but reduces its depth, and conversely, a decrease in the deforming element's diameter narrows the groove and increases its depth. Altering the diameter of the deforming element changes not only the groove parameters but also the physics of the interaction between the contacting surfaces. A smaller diameter of the deforming element results in a smaller contact area, which consequently increases the specific pressures within the contact zone.

This groove shape in the formed micro-relief correlates with the optimal groove design for plain bearings, which feature a "herringbone" geometry that ensures a guaranteed level of lubricant in the friction zone [25]. The eccentricity ratio, number of grooves, spiral angle, groove width ratio, and groove depth are selected as the key factors for designing a spiral-groove plain bearing. Under normal operating conditions, the heat generated by friction is dissipated and absorbed by the engine housing; wear debris is minimal and is continuously removed by the lubricant circulating within the friction zone.

Although the groove formation operation demonstrated excellent results regarding the shape of the formed micro-relief grooves, this process leads to the destruction of the antifriction coating and the formation of material pile-ups at the edges of the created grooves, which can negatively affect operational performance. Therefore, the process of forming the regular micro-relief grooves should be carried out prior to the application of the antifriction coating.

Conclusions

A technological operation was developed for the formation of Type II regular micro-reliefs on the inner cylindrical surfaces of a pair of connecting rod bearings by machining in a split holding fixture using a vibration-free method in a single pass. To implement the process of forming the regular micro-relief (RMR) on the working surfaces of Volvo V50 1.6 HDI connecting rod bearings, a special tool was designed and manufactured based on dimensional analysis. The operating parameters of the tool were calculated in accordance with the required value of the relative micro-relief area to be achieved. The implementation of this operation made it possible to form the designed regular micro-relief with the specified geometric parameters.

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Дзюра В.О., Дживак Т.Р. Реалізація процесу формування регулярних мікрорельєфів на робочих поверхнях шатунних підшипників

В статті наведено результати проектування технологічної операції формування регулярного сітчастого мікрорельєфу ІІ типу із канавками трикутної форми безвібраційним способом за один робочий хід на внутрішній циліндричній поверхні шатунних вкладишів. Технологічну операцію реалізовано з використання спеціально розробленого інструменту обробкою в розбірній обоймі пари шатунних вкладишів. В якості обоми використано корпус шатуна для даного типорозміру шатунних вкладишів. Необхідну глибину канавок мікрорельєфу реалізовано за рахунок розмірного аналізу конструкції спроектованого спеціального інструменту для пластичного деформування поверхні шатунного вкладиша. Відносну площу мікрорельєфу у 14,9% та 28,5% досягнуто визначенням відповідної величини подачі та частоти обертання інструменту. Отримано дослідні зразки шатунних вкладишів для автомобіля Volvo V50 1.6 HDI та параметрами D_{ring} = 47,0 mm; B_{ring} = 16,9 mm із сформованим регулярним мікрорельєфом. Процес реалізовано при осьовій подачі інструменту складає f_{in} = 19,43 мм/об, а для площі 14,9% – f_{in} = 39,56 мм/об на вертикально-фрезерному верстаті з ЧПК HAAS VF-B/40HE. Встановлено, що дану технологічну операцію можна виконувати як на стадії фінішної обробки мідно-свинцевої основи вкладиша, товщина якої становить 250-400 мкм, безпосередньо перед нанесенням захисних металевих шарів нікелю, міді та/або композитних матеріалів так і після нанесення захисного покриття. Створення регулярного мікрорельєфу забезпечуючи високу експлуатаційну надійність, довговічність та стабільну роботу шатунних вкладишів і двигуна внутрішнього згоряння в цілому.

Ключові слова: шатунні вкладиші, технологія, інструмент, параметри, режими формування, регулярний мікрорельєф