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ABRASION RESISTANCE OF RESTORATIVE COATINGS FOR CRANKSHAFTS AND BEARINGS IN AGRICULTURAL MACHINERY

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The paper presented examines the dynamics of wear of restored parts using different materials for the friction pair. The pair of crankshaft and sliding bearing largely determines the machine service life – although their overall wear index is less than 1%, it can still lead to a large number of failures and malfunctions. Vibrating arc overlaying in a shield of gas mixture of 60% argon and 40% carbon dioxide was used for restoring the surface of rollers. Subsequently, these were treated by heating with high-frequency current (HFC) and lowered to a hardness of 55±2 HRC and ground to the final size. It was found that the antifriction coating of plain bearings with electrochemical lead alloy EO92 showed excellent performance and insignificant wear in combination with reference material St45 and welded coating DUR500. In combination with electrochemical lead alloy EO92, the welded coating DUR500 showed a significantly higher wear on actuation compared to the reference material St45 at sliding friction. The relative wear resistance enhancement of crankshafts and bearings by restorative coatings represents an essential measure, as their service life can be prolonged by 20–50% in contrast to the new parts without restorative coatings.

Keywords: recovery; friction; roughness; vibrating arc; overlaying process

As a result of operation – and auxiliary and harmful processes occurring in it – modern agricultural machinery loses efficiency due to wear of the working surfaces. The crankshaft – sliding bearing pair is one of the parts that are the most frequently exposed to high duty and tends to wear out especially intensively. The wear of these surfaces is very insignificant and represents less than 1% of their size and 0.1% of their mass in the majority of cases. The absolute amount of wear is also very small and usually ranges from 0.1 mm to 0.5 mm (Beloev et al., 2008; Dimitrov, 2018; Fürstenzeller et al., 2019; Nikolov and Kangalov, 2014; Tkáč et al., 2017). Despite the minimal wear values, it still can lead to a large number of failures and malfunctions. Increasing the durability by application of restorative measure to parts is one of the ways to save energy, materials, and spare parts (Nosian et al., 2021; Todorov, 2019).

Increasing the durability and reducing the cost of spare parts, materials, and energy by restoring worn parts is extremely important for the economy of each country in the current crisis of material and energy resources. The durability of restorative coatings is one of the most important conditions for increasing the service life of the restored parts from the various mechanisms and systems of agricultural machinery. The main factors influencing the wear resistance are determined by the quality characteristics of the restorative coating (structure, chemical composition, and material hardness).

There are various methods for restoring the crankshaft – plain bearing pair. Restoration of the joint between them can be performed by restoring the dimensions of crankshaft and bearing, both separately and simultaneously.

The tribology characteristics of the restorative coatings of DUR500 and electrochemical alloy EO-92 has not been fully examined so far (Beloev et al., 2008; Dimitrov, 2019; Ping et al., 2015). Therefore, the actual data on the wear resistance of restorative coatings (based on DUR500 and EO-92 alloy) in crankshafts are essential for the general restorative practice. Both these materials were investigated separately, as well as a frictional pair.

The paper objectives include:

1. determination of the wear dynamics for standard and restored frictional pairs (crankshaft-bearing pair) in agricultural machinery in modes of initial operation and established wear;
2. determination of the wear dynamics for standard and restored frictional pairs (crankshaft-bearing pair) utilizing DUR500 in agricultural machinery in modes of initial operation and established wear;
3. determination of the wear dynamics for standard and restored frictional pairs (crankshaft-bearing pair) utilizing EO-92 alloy electroplating in agricultural machinery in modes of initial operation and established wear;
4. determination of the surface wear resistance for standard and restored frictional pairs (crankshaft--bearing pair) in agricultural machinery.

Material and methods

Vibration arc overlaying in shielding gas mixtures – argon and carbon dioxide – is widely used for the crankshaft neck

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restoration (Nikolov and Kangalov, 2014; Starodubtseva et al., 2018). One of the modern methods for plain bearing restoration is by application of electrochemical antifriction alloys (Dimitrov, 2018; Stanev et al., 2005). As the spare parts for bearings are expensive, these parts must show high durability and exceptional performance.

Unfortunately, the tribological characteristics of these two restorative coatings has not been sufficiently studied, hindering thus their wide application in the agricultural machinery maintenance. Reduction of the friction forces and wear of the restored parts largely depends on the appropriate selection of the co-working materials and coatings.

The composition and properties of restorative coatings for surfaces exposed to friction in crankshafts and bearings were considered the main input factor of the model for studying the process of operation and wear of the sliding surfaces in liquid friction (Fig. 1). The following was subjected to a comparative study: 45-hardened steel with HFC accepted as a standard and the most common material for shafts in agricultural machinery (Jablonický et al., 2020; Nikolov and Kangalov, 2014); restored shaft surface with coating welded in a gas mixture of DUR500 hardened with HFC at a vibration frequency of 47.6 Hz; bearing material BO30 accepted as a standard and restorative material; and antifriction electrochemical lead alloy EO92 applied on the bearing lead bronze.



Fig. 1 Cybernetic model for the tribological studies of restored coatings during liquid friction
Rc – parameters of the restored coatings for crankshafts and bearings; $\vec{J}_i$ – wear parameter vectors of surfaces exposed to friction

The vector of wear parameters (the wear amount of friction pair, roller and sector; the wear rate of friction pair, roller and sector; the wear resistance of pair (Fig. 1)) was adopted for the evaluation of wear process and operation of sliding friction surfaces.

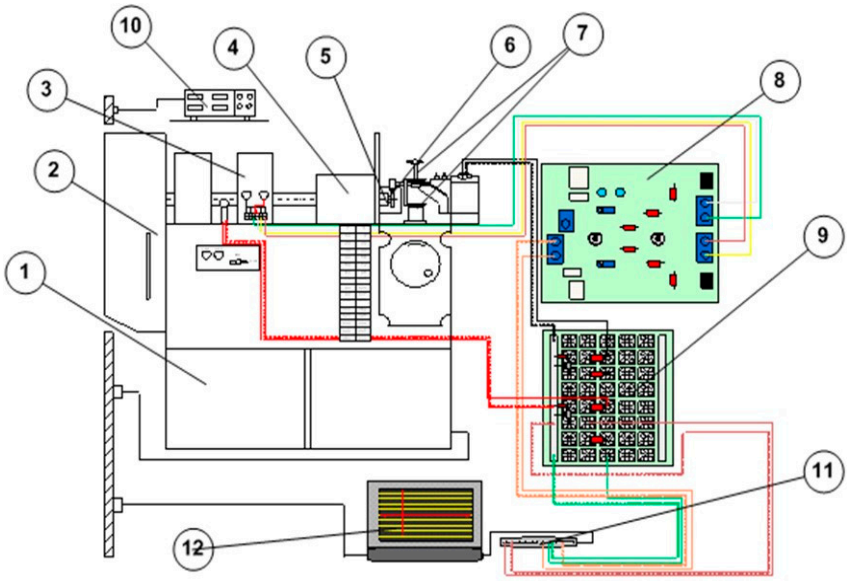


Fig. 2 Principal scheme of laboratory equipment for tribology examinations
1 – testing friction stand CMC-2; 2 – driving mechanism; 3 – torque sensor; 4 – oil mixing system; 5 – cooling chamber; 6 – roller–sector friction pair; 7 – loading system; 8 – friction torque differential plate; 9 – shaft rotary plate; 10 – impulse time counter for applied loading; 11 – multifunctional device NI-USB 6210; 12 – laptop

The wear resistance study of various restorative materials during sliding friction was performed based on a methodology presented in Kučera et al. (2016) and Tkáč et al. (2017). As a physical model of the friction pair "shaft – bearing", the pair "roller – sector" with the corresponding parameters of geometric and physical similarity was accepted. Specimen parameters were selected with structural characteristics and determined based on the statistical examination of recoverable parts in agricultural machinery (Kučera and Aleš, 2017).

The experimental research was conducted using modified laboratory equipment (Fig. 2) consisting of: testing friction stand CMC-2; system for constant working fluid mixing; system for cooling and supporting a constant working temperature in the friction chamber; electronic system for measuring and registering the friction torque, loading, interaction and established wear times; electronic system for measuring and registering the working temperature and cooling liquid quantity; electronic recording system for summarized roller speed and trial time with an accuracy of 1 min^{-1} and 1 s (Dimitrov, 2018; Nikolov and Kangalov, 2014).

The testing stand CMC-2 comprised a special small water-cooled chamber providing liquid friction with SAE 30 oil at a constant temperature of 40 °C. The loading of friction pair was performed continuously at a speed of 1 MPa·min^{-1} and a compression force of the sectors on the rollers of 100 daN, providing a pressure of 5 MPa, and at a speed of 540 min^{-1}, and thus a relative sliding speed of 85 m·min^{-1} and tribological characteristic PV = 7 MPa m·s^{-1}. These values were selected in accordance with the requirements for the permissible values for sliding bearings.

The pair consisting of steel St45 and lead bronze BO30 was accepted as a standard since these two materials are the most frequently used for the purposes of sliding bearings in agricultural machinery (Tulík et al., 2013; Stanev et al., 2005). It served as a comparison to the pairs with restorative coatings. The operation and the wear of reference and recovered pairs were performed in oil SEA 30.

The recovered rollers were made of St45 deposited with electrode wire DUR500 (with a diameter of 1.6 mm) in a gas mixture of argon and carbon dioxide with a composition of 60% of A and 40% of CO_2, providing high hardness and wear resistance of the welded surface (Nikolov and Kangalov, 2014; Todorov, 2019). The surface treatment was performed under the following conditions: operating voltage – 20 V; electric current magnitude – 150 A; overlaying speed –

1.26 m·min^{-1}; electrode wire feed speed – 2.3 m·min^{-1}; step of overlaying – 3 mm·tr^{-1}; electrode wire outlet – 15 mm; shielding gas consumption – 15 l·min^{-1} in a system with inertial axial vibrating arc apparatus ABH 60 with a vibration frequency of 46.7 Hz.

The reference and welded samples were thermally and mechanically processed. They were hardened by heating with HFC and lowered to a hardness of 55 ±2 HRC (HV_5 = 6100 ±400 MPa); subsequently, the samples were ground to the final size employing a standard method for a test roller production. The rollers had a friction surface diameter of $50^{+0.02}$ mm, width of $12^{+0.05}$ mm, welded coating thickness in radius of 0.5 mm, roughness of 0.28–0.32 µm, and mass of 160–170 g. The misalignment and non-perpendicularity did not exceed 0.01 mm.

The sectors were bimetallic (steel – lead bronze) with electrochemical antifriction alloy EO92 based on lead from silicofluorohydrogen electrolyte with the following composition: lead silicofluoride ($PbSiF_6$) – 100–150 g·l^{-1}; tin silicofluoride ($SnSiF_6$) 20–30 g·l^{-1}; copper silicofluoride ($CuSi|F_6$) – 5–15 g·l^{-1}; and silicofluorohydric acid (H_2SiF_6) up to pH of 0.5 (Decrozant-Triquenaux et al., 2021; Kučera and Aleš, 2017).

The deposition of the electrochemical coating was performed utilizing a direct current density Dk = 2 A·dm^{-2} at a temperature range of 18–25 °C.

The reference and restored friction sectors with the rollers were cut at a central angle of 46° from the pre-prepared steel rings with an antifriction layer of BO30 with a thickness of 0.50 mm and layer of EO92 with a thickness of 0.15–0.25 mm along the radius and with width of $10^{+0.05}$, length of 20 mm, friction surface of 2 cm^2, and mass of 18–19 g. The outer surface of rings was ground to a diameter of $70^{+0.1}$ mm, and the inner surface of reference and restored bearing rings was scraped to a diameter of $50^{+0.06}$ mm with sector roughness: R_a = 2.0–2.8 µm for BO30 and R_a = 0.95–1.20 µm for EO92. The pair gap ranged from 0.04 mm to 0.05 mm in order to ensure an even operation at the required oil wedge.

In the process of operation and wear of the samples, the test duration for each experiment, oil temperature, engine speed, and overall roller speed were measured and recorded; before and after each experiment, the weights of roller and sector were measured. The wear amount was determined by the weight method separately for each of the friction elements (roller and sector) using analytical balance WA-33 with accuracy of 0.05 mg, as all samples were cleaned using gasoline, dried and weighed before and after the experiment.

Results and discussion

The STATISTICA was employed for the purposes of calculation of main statistical characteristics and their error levels; furthermore, the rates of determination coefficient and Fisher's criterion were also determined. Based on the obtained and statistically processed study results, graphical dependences of the change dynamics in the wear amount in different materials on the friction surfaces of crankshafts and bearings were plotted (Figs 3–7).

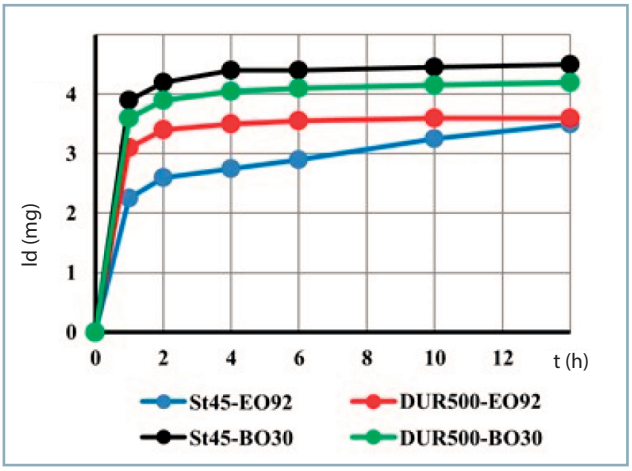


Fig. 3 Integral curves of operation and wear of reference and restored pairs

The amount of wear in studied pairs was primarily determined on the basis of the actuation and final antifriction alloy wear of the sector, as its hardness is 10 times lower than hardness of working surface material of restored steel and cast-iron rollers.

The wear dynamics of reference and recovered friction pairs (Fig. 3) have equidistant character, corresponding to the classic Lorenz-Kazartsev wear curve during sliding friction, with a very strong actuation section and almost horizontal linear change of the established wear.

In all pairs, the active operation ended during the first two test hours; the operation of the reference pair and the pairs with welded shaft coating DUR500 ended earlier and completely; a horizontal section with a zero rate of change was observed at their established wear. The operation of antifriction lead alloy EO92 with reference material St45 had two sections: active operation during the first two test hours, and passive operation from the second hour until the test end. The wear in the beginning of operation resulted from mechanical shear of the tips and micro-irregularities, and plastic deformation of the surface layer.

The wear of bearing alloy EO92 with St45 was the lowest, however, at the test end, its total wear was equal to that of

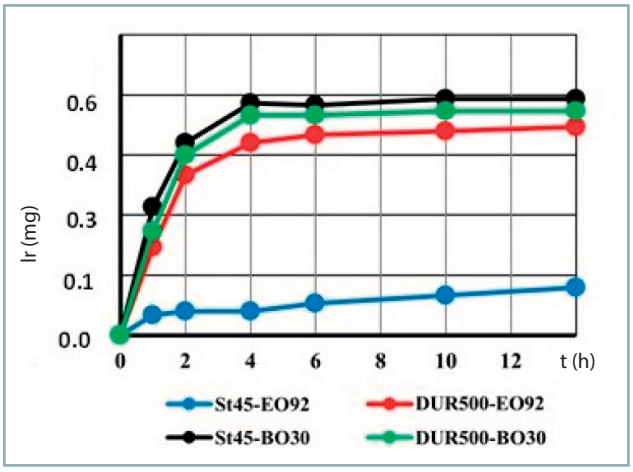


Fig. 4 Integral curves of operation and wear of the roller with different friction surface materials

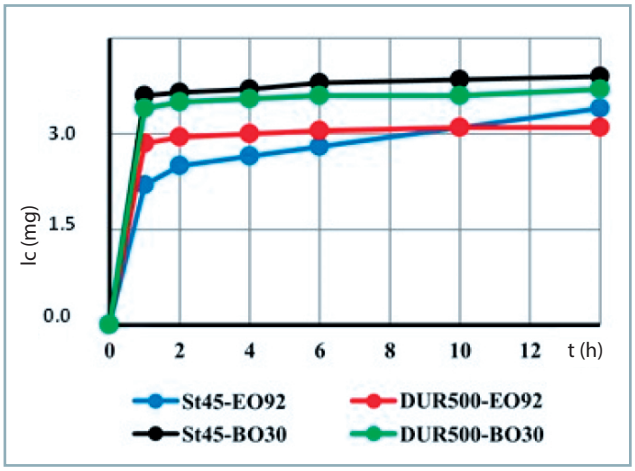


Fig. 5 Integral curves of operation and wear of the sector with different material of the friction surface

the fully recovered pair DUR500–EO92. Throughout the test, the total wear of pair with recovery coating on the shaft and bearing remained less than the total wear of pair with reference material St45 in the shaft and BO30 in the bearing (Fig. 3). As a result of this phenomenon, the pairs with restorative coatings had reduced initial clearance and service life of the repaired agricultural machinery, to which they were installed, increased. This can be explained by the higher wear rate of reference pair and the incomplete and passive operation. During active operation, the wear rates of recovered pairs were twice as high as the reference pair, but then an inversion could be observed, as the wear rate of reference pair became higher (Fig. 6).

The total wear of the pair with restorative coatings at the test end was lower by 25% (3.5 mg) compared to the total wear of reference pair (4.5 mg). The lower wear of the pair with restorative coatings on the roller and sector lead to an increased service life of the shaft–bearing joint in the machinery, to which these restored parts were installed.

The reference and recovered pairs showed a relatively even and smooth increase in the amount of removed material in the process of established wear. This property is favourable under operating conditions, as it does not cause sharp fluctuations in the size of parts during their wear and allows the preventive management of repairs and prediction of residual life of the joints. Along with the total pair wear, the size and ratio of wear of its elements (roller and sector) were of great interest as well.

The change in wear amount of the roller during friction is shown in Fig. 4. Despite the compliance with the classic curve, the operation and wear of reference material and roller with welded coating DUR500 differ significantly in dynamics, size, and character in contrast to the roller with EO92. The operation of reference roller with a replacement alloy EO92 was activated quickly during the first two hours at a very low total wear (0.10 mg). The operation of reference roller and DUR500 roller was 2 times longer (4 and 6 hours) and showed 4 to 6 times higher wear (0.45–0.60 mg).

Subsequently, for the rollers, there was a period of established wear with almost zero wear rate, immediately indicating very good tribological properties of the electrochemical alloy EO92. The welded coating showed a significantly higher wear under operational conditions than the reference material operating with EO92. This could be explained by its heterogeneous composition, uneven hardness and 1.20 μm initial and 0.80 μm equilibrium roughness.

The dynamics, size, and nature of wear of the tested pairs were primarily determined by the wear of antifriction material on the sector friction surface, representing 83% of the pair wear in size (Fig. 5). This significant share was caused by the hardness ratio of friction surfaces of rollers and sectors, which was 10 times lower for BO30, and 60 times lower for EO92 than the surfaces of rollers. The pattern of curves in sectors is analogous to that of the friction pairs (Fig. 5), indicating that the friction pair wear is determined mainly by the sector antifriction alloy.

The electrochemical alloy EO92 proposed by us and used for antifriction coating of sliding bearings showed a very good operation and insignificant wear, both with the reference material St45, and with the welded coating DUR500 (Fig. 5). The active operation of antifriction alloy took place for a very short time (during the first hour) and immediately after that, the established wear began with very low, almost zero wear rates (Fig. 7). The investigated alloy EO92 showed a better performance and lower values of established wear at sliding friction with welded coating

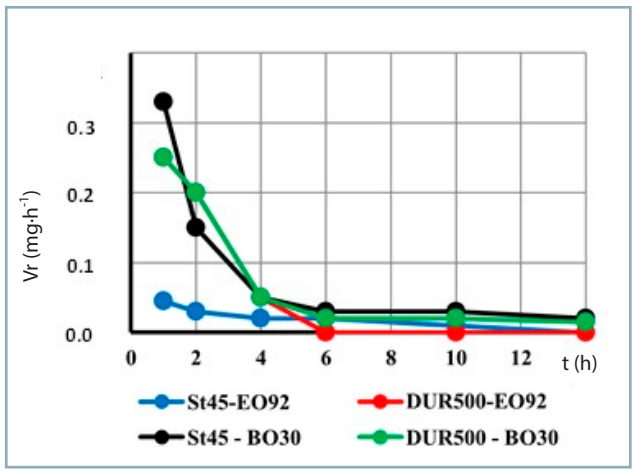


Fig. 6 Roller wear rate of different friction surface materials

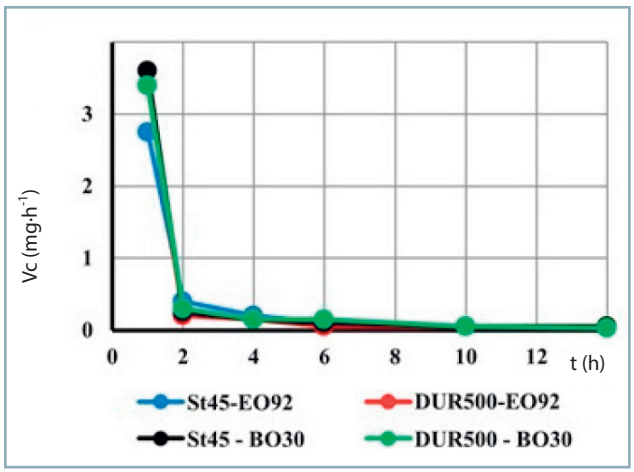


Fig. 7 Sector wear rate of different friction surface materials

Table 1 Wear resistance of the pair friction surfaces

Friction pair	Total wear of the pair (mg)	Percentage reduction in weight loss (%)	Wear resistance of the pair ($l \cdot mg^{-1}$)	Relative wear resistance
St 45-BO30	25.85	0.0	0.039	1.00
DUR 500-BO30	24	7	0.042	1.08
St 45-EO92	17.25	44	0.058	1.49
DUR 500-EO92	20.75	20	0.049	1.26

DUR500 despite the slightly higher values of wear during the active operation (Figs 4 and 5).

In addition to the wear amount, the wear rate (one of the primary tribological characteristics) is important for assessing the operation and wear of friction surfaces. It allows comparison of the operation and wear of pairs with different materials, providing information on the material loss depending on the operating time of friction pairs.

The curves of change in the wear rate at operation and established wear of the friction surfaces with reference material and restored rollers and sectors utilizing different coatings are shown in Figs 6 and 7. In nature, these curves are similar to the wear amount curves, however, with a reciprocal value. The given curves indicate that the rate of operation of welded rollers was high in the first six hours, decreasing from 0.30 $mg \cdot h^{-1}$ to 0.05 $mg \cdot h^{-1}$. After the sixth hour, a process of established wear occurred, and the wear rate of recovered pairs remained almost constant until the test end. The operation of reference roller with EO92 ended in the first two hours, and the rate decreased from 0.05 $mg \cdot h^{-1}$ to 0.02 $mg \cdot h^{-1}$.

One of the main requirements for restored crankshaft and bearing parts is their wear resistance under the given working conditions. It is a complex property and depends on multiple factors: hardness, toughness, fragility, structure, etc. The results for wear resistance and relative wear resistance of the reference and recovered pairs are presented in Table 1. The relative wear resistance was determined as a ratio between the wear resistance of standard pair εe and the wear resistance of the reconditioned pair ε_j, equated as $\varepsilon_o = \varepsilon_e \times \varepsilon_j^{-1}$.

The data given in Table 1 suggest that the pairs of St45 and EO92, and EO92 and DUR500 showed the highest wear resistance. This was also confirmed by the results of wear of elements (roller – sector) of these pairs presented in Figs 3–5. The highest relative wear resistance was showed by the restorative coatings, as the ratio to the reference material was 1.25–1.5 times lower. It can be assumed that the service life of restored crankshafts and bearings will be greater by 20–50% in contrast to the new, non-restored parts. Dimitrov (2018) observed the wear index rate of recovered pairs that was 2 to 2.5 times lower. This difference is probably a result of complex ester application as a friction modifier, leading to better results.

Conclusion

The restorative anti-friction coating for sliding bearings with electrochemical lead alloy EO92 showed a very good performance and insignificant wear in combination with reference material St45 and welded coating DUR500.

The electrochemical lead alloy EO92 showed a better performance and lower values of established wear at sliding friction in combination with welded coating DUR500 despite the slightly higher values of wear during active operation.

The welded coating DUR500 showed a significantly higher wear on actuation compared to the reference material St45 in combination with electrochemical lead alloy EO92 at sliding friction.

The highest relative wear resistance was showed by parts treated with restorative coatings, as the service life of restored crankshafts and bearings was higher by 20–50% in contrast to the new, non-restored parts.

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