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Study of the wear process and damage characteristics of the "stationary shaft–bushing" tribological pair

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Abstract

The article investigates the causes of surface degradation in the "stationary shaft–bushing" tribological pair of the roller assembly of a diesel engine fuel pump plunger in a heavy-duty truck, operating under increased loads and boundary lubrication conditions. A surface damage passporting methodology was applied, including analysis of microhardness, surface roughness, geometrical accuracy, and structural transformations within surface layers of the components, supplemented by elements of X-ray diffraction analysis.

It was established that the dominant wear mechanism is hot scuffing (adhesive wear of the second kind), driven by irregular lubricant supply, chemical affinity of the materials of both components (bearing steel 100Cr6/ШХ15), localized load concentration, and the stationary configuration of the shaft. The formation of secondary hardened "white layers" was observed, indicating thermal overloading and a reduced load-bearing capacity of the surface layers after prolonged service.

A set of design, technological, and operational measures is proposed to improve the reliability and durability of this friction pair.

Keywords: hot scuffing, tribological pair, fuel pump, microhardness, secondary structures, surface damage.

Introduction

The increasing requirements for fuel efficiency and environmental performance of diesel engines necessitate higher fuel delivery per cycle and higher injection pressures in fuel injection systems. This results in elevated mechanical and thermal loads on the components of the plunger pump, particularly on the "stationary shaft–bushing" friction pair in the roller assembly of the tappet. Operational experience shows that with an increase in plunger diameter and the corresponding rise in axial loads, intensive surface damage due to hot scuffing occurs within this tribological pair. Premature failure of these components limits the service life of the fuel pump, reduces engine reliability, and leads to economic losses.

The complexity of this issue is further aggravated by boundary lubrication conditions and the structural and chemical similarity of the materials in frictional contact. Such operating conditions promote the formation of welding bridges between the asperity peaks in the contact zone of the surfaces. Therefore, there is a growing need for scientifically justified methods and design solutions aimed at improving the durability and performance of the "shaft–bushing" friction pair under the operating conditions of diesel fuel systems.

Literature Review

In modern research on diesel engine fuel injection equipment, significant attention is paid to the tribotechnical characteristics of the "cam–roller–shaft" contact pair in high-pressure fuel pumps. Increased injection pressures and stricter environmental emission requirements lead to higher mechanical loads on these components. In the studies by [1], the wear and running-in behavior of cam–roller systems in diesel engines was analyzed, demonstrating the development of complex surface topography under operating conditions and local variations in hardness in mixed lubrication regimes, which determine the further evolution of frictional interaction and the risk of scuffing. Research conducted by [2] for the "cam–roller tappet" pair in heavy-duty diesel fuel pumps, based on numerical modeling and lubrication analysis, revealed that boundary lubrication zones form already at the running-in stage, where load is transmitted through individual asperities, and local temperature spikes may initiate damage due to the onset of adhesive interaction followed by scuffing. A considerable amount of studies also focuses on the influence of fuel type and lubricants on the reliability of friction units in diesel fuel injection equipment. The review by [3] summarizes current understanding of the mechanisms of ZDDP additive action, the formation of protective tribofilms, and their role in preventing scuffing under boundary lubrication conditions. Recent works by [4-6]and others have shown that the kinetics of tribofilm growth, as well as its thickness and morphology, are strongly dependent on surface topology, loading regime, and additive chemistry. It has also been demonstrated that tribofilm breakdown may occur locally under severe loading, reopening direct metallic contact and promoting scuffing in frictional interfaces. Reviews concerning friction reduction in internal combustion engines emphasize that the friction units of fuel injection equipment — where high contact stresses, low sliding speeds, and boundary lubrication are combined — remain among the most critical elements in terms of scuffing and service life reduction. Another direction of research concerns surface modification of components — the application of hard wear-resistant coatings, surface texturing, deep thermal and cryogenic treatment, as well as the use of composite materials and coatings. PVD-coatings such as BALINIT applied to fuel pump components, rollers, and tappets have demonstrated a significant reduction in friction coefficient and increased scuffing resistance due to modifications in the chemical composition and thermophysical properties of protective surface layers. Research in the field of cryogenic treatment of tool and bearing steels has proven that deep cooling after quenching promotes more complete transformation of retained austenite into martensite and the formation of a more stable structure with enhanced wear resistance. This is particularly important for steels such as 100Cr6 (ШХ15), which are widely used in highly loaded bearing and plunger units. In the study [8], a comprehensive methodology for evaluating the tribological efficiency of automotive component couplings was proposed, combining experimental research, modeling, and diagnostic criteria for assessing the performance of surface layers. This approach enables an in-depth analysis of friction conditions and identification of the most vulnerable tribosystems. In the article [9], tribodiagnostics of surface damage during operation was examined based on changes in the structural and mechanical properties of surface layers, ensuring early detection of failure initiation and forecasting of remaining service life. The research conducted [10] established the patterns of variation in the lubrication degree of crankshaft bearings depending on engine load and speed regimes. The influence of the hydrodynamic lubrication film on reliable bearing operation was demonstrated, and methods were proposed to enhance durability by optimizing operating parameters. The summarized findings confirm the relevance of further development of diagnostic approaches and measures to improve the reliability of tribological components in automotive systems, particularly those operating under boundary lubrication, high contact loads, and significant thermal gradients. Studies [11–14] demonstrate the effectiveness of various protective coatings — including Fe–Mn–C–B–Si–Ni–Cr eutectic welding layers and polymer-modified thermosetting composites — in improving wear resistance, enhancing antifriction performance, and stabilizing adhesion properties of friction surfaces under elevated temperature and boundary lubrication conditions, which is relevant for extending the durability of highly loaded tribological contacts in automotive systems

Purpose of the study

To determine the dominant mechanism of surface damage in the "stationary shaft–bushing" tribological pair of the roller tappet assembly of a diesel engine fuel pump under increased loading and restricted lubrication supply, in order to provide a scientific rationale for a set of design and technological measures aimed at improving its operational reliability and service life.

Research results

Improving the reliability and service life of friction units in fuel injection equipment is only possible with a thorough investigation of the damage mechanisms of the most heavily loaded and vulnerable tribological contacts that determine system operability. These include the sliding "stationary shaft–bushing" tribological pair in the roller tappet assembly of the plunger pump of a heavy-duty diesel engine.

Intensification of fuel pump operation through an increase in plunger diameter from 9 to 10 mm leads to a 28% rise in maximum chamber pressure (from 42.4 to 54.2 MPa) and a 57% increase in cyclic axial force (from 2.7×10^3 to 4.25×10^3 N). As a result of such loading, premature surface failure of the tribological pair occurs: hot scuffing is detected after only 4 hours of pump operation on a calibration test bench. Therefore, it is crucial to identify the dominant wear mechanism and determine the causes of damage in this tribological contact. A surface damage passporting method was applied, involving a comprehensive assessment of: compliance of component geometry with design requirements, loading and lubrication conditions, and the actual state of working surfaces after operation. Three groups of tribological pairs were compared in the study: damaged shaft–bushing pairs after 4 hours of bench testing under elevated axial load; field-operated pairs with 1330 hours of service (≈50,000 km mileage) under optimal loading conditions; and new components. The obtained results of tribosystem passporting were summarized in the form of a technical function for the "stationary shaft–bushing" friction pair of the roller tappet assembly in the fuel pump (Table 1). Roundness profiles of the internal surfaces of the bushings for the different groups are presented in Fig. 1, and the quantitative results of form deviation analysis are shown in Fig. 2. It was determined that all examined bushings exhibit deviations from ideal geometry in the form of polygonalization; however, the nature and severity of deformation differ significantly depending on the loading conditions and service duration.

Table 1

Technical passport of the "stationary shaft–bushing" tribosystem of the roller tappet assembly of a diesel engine fuel pump

Section	Parameter	Description / Value
I. Analysis of friction and wear conditions	Type of interaction	Sliding friction
	Lubrication regime	Boundary (limited lubricant supply)
	Axial load	$2.7\times10^3 \ldots 4.25\times10^3$ N
	Sliding speed	0.1…2.5 m/s
	Contact zone temperature	1073…1123 K
	Operating time	4 h (bench test), 1330 h (in service)
II. Material and component characteristics	Shaft material	Bearing steel 100Cr6 (ШХ15)
	Bushing material	Bearing steel 100Cr6 (ШХ15)
	Initial surface roughness	Ra = 1.6 μm
	Shaft geometry (working dimensions)	$Ø9^{-0.01}$ mm / $Ø10^{-0.01}$ mm
	Bushing geometry (tolerances)	$Ø9^{+0.033-0.013}$ mm / $Ø10^{+0.033-0.013}$ mm
	Density	$\rho = 7811$ kg/m³
	Chemical composition (100Cr6), wt.%	C 0.95–1.05; Si 0.17–0.37; Mn 0.20–0.40; Cr 1.30–1.65; P ≤0.027; S ≤0.02; Ni ≤0.30
	Mechanical properties	$\sigma_v \approx 730$ MPa; $\sigma_{0.2} \approx 420$ MPa; $\delta \approx 21\%$; $\psi \approx 46\%$
	Thermophysical properties	$\alpha_n = 45\times10^4$ J/(m²·K)
III. Environmental factors	Contamination	Dusty air, impurities in fuel
IV. Risks and expected damage mechanisms	Potential wear types	Scuffing (adhesive wear of the second kind), fretting, abrasive wear
	Critical conditions	Surface overheating, direct metallic contact, local peak stresses at asperity tips
V. Geometry and surface heat treatment	Contact geometry	Cylindrical surfaces, line contact footprint
	Heat treatment	Hardening at 850 °C (210 min) + oil quenching; cold treatment at –30…–60 °C (200 min); tempering at 180 °C (200 min); air cooling
	Lubrication regime	Boundary friction
	Lubricant supply	"Splash lubrication" (insufficient and unstable lubricant flow to the upper contact zone)
VI. Tribological interactions	Contact interfaces	"Shaft–bushing", "bushing–environment", "shaft–environment"; load directions and displacements illustrated in Fig. 1a–c
VII. Tribological characteristics	Dominant wear mechanism	Adhesive wear (hot scuffing, Type II), thermal softening, formation of "white layers"
	Contact conditions	Cylindrical contact between shaft (1) and bushing (2); critical load zone located in the upper part of the bushing (minimum lubrication)
	Controlled parameters	Wear rate; coefficient of friction; contact temperature; contact electrical resistance (CER); specific damage energy; load-bearing capacity reserve of the surface layers

Bushings that have operated for 1330 hours under normal service conditions demonstrated the smallest non-uniformity of profile deviation — the polygonalization in this case is practically reduced to minor ovality

(Fig. 2, curve 1). New bushings are characterized by a tetragonal profile shape (Fig. 2, curve 2), indicating manufacturing inaccuracies and insufficient quality of finishing operations. The most pronounced multi-polygonal deformation was observed in bushings damaged during bench operation under increased axial loads (Fig. 2, curve 3), which leads to localized increases in contact stresses and promotes the development of hot scuffing.

Thus, the analysis of internal bushing geometry based on roundness profiles confirms that increased mechanical loading and unstable lubrication result in accelerated wear of the working surfaces, which consequently causes failure of the friction unit.

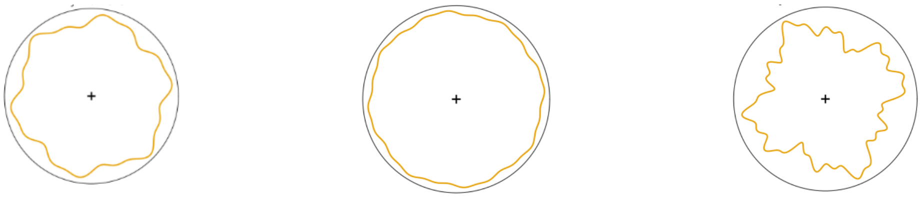

Fig. 1. Roundness profiles of the internal surface of bushings in the "shaft–bushing" friction pair after different operating conditions

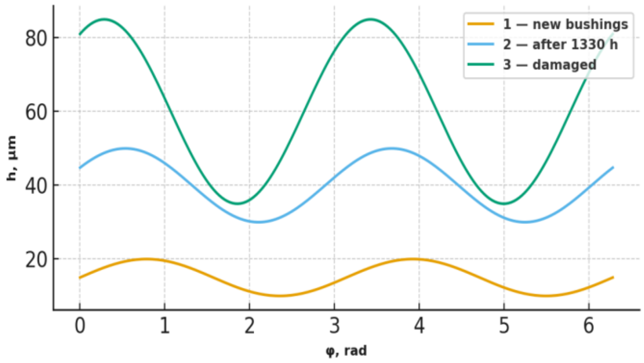

Fig. 2. Form deviation of the internal bushing surface after different operating conditions: 1 - new bushings; 2 - bushings after 1330 h of operation; 3 - bushings damaged during bench testing under increased loads

The surface topography analysis of the shafts in the new condition, after 1330 hours of operation, and after damage under increased loading conditions (Fig. 3) showed that normal operation results in a significant reduction of surface roughness compared to the new component due to running-in processes and plastic smoothing of asperities under mixed friction conditions. The machining quality of the new shaft's outer surface ($R_a \approx 1.6$ µm) is significantly higher compared to the bushing's internal surface ($R_a \approx 58$ µm), which does not meet the requirements of technical specifications stating that the roughness parameters of contacting elements must be compatible. Such inconsistency deteriorates the formation of a stable lubricant film and promotes localized concentration of contact stresses. The microhardness characteristics of the shaft surface layer are shown in Fig. 4. The average surface microhardness of the new shaft is approximately 5500 MPa (Fig. 4, curve 1), and the microstructure consists of hardened martensite with a high level of residual stresses. This provides increased initial wear resistance; however, it also creates susceptibility to thermal cracking and the formation of "white layers" in cases of overheating under boundary lubrication conditions.

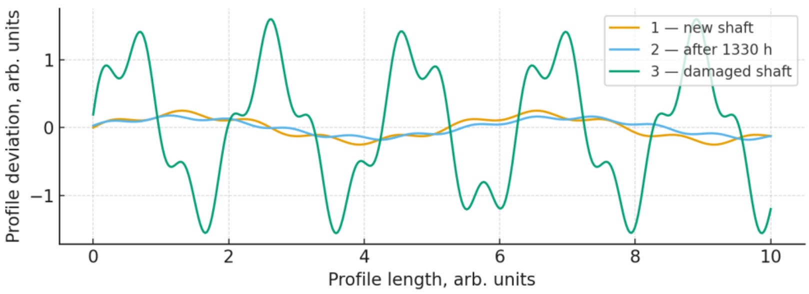

Fig. 3. Profilograms of the working surface of shafts in the "shaft–bushing" friction pair: 1 - new shaft (vertical scale ×10 000; horizontal scale ×80); 2 - shaft after 1330 h of operation (vertical scale ×10 000; horizontal scale ×80); 3 - shaft damaged during bench testing under increased loads (vertical scale ×4000; horizontal scale ×80).

After 1330 hours of operation, strengthening of the shaft surface layer was observed, associated with work hardening and phase transformations under variable loading. In contrast, the damaged components show the formation of a secondary-hardened “white layer” with an abrupt increase in hardness, which indicates thermal overload and serves as an initiator of hot scuffing.

During normal operation of the assembly, strengthening of the surface layers occurs due to work hardening and stabilization of secondary structures. It was established that after 1330 hours of operation, the surface microhardness of the shaft increases to approximately 6060 MPa (Fig. 4, curve 2), indicating partial transformation of the material into martensite, which is more resistant to wear. In this case, a reduction in micro-relief depth was observed already at the running-in stage.

In contrast, on the surfaces of damaged bushings and shafts that operated under increased mechanical and thermal loads, localized formation of a densified “white layer” with significantly higher hardness was detected (Fig. 4, curve 3). The microhardness of this layer exceeds the initial value nearly twofold, indicating the development of secondary hardening and the formation of a brittle structure with a high tendency to delamination. The presence of a white layer implies that temperatures in specific contact points reached levels sufficient to initiate thermal plasticity of the surface layers, reducing their strengthening and followed by rapid cooling when metallic junctions are ruptured. Such thermodynamic instability is the major driving factor behind the development of hot scuffing.

The results of X-ray diffraction analysis confirm the formation of new Fe_γ-type phases characteristic of rapid surface cooling after localized overheating, which is consistent with the mechanism of secondary hardening under boundary friction conditions.

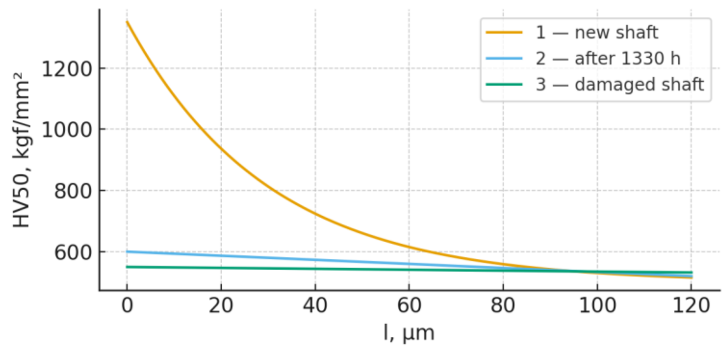

Fig. 4. Distribution of HV50 microhardness within the surface layer of the shafts in the “shaft–bushing” friction pair after different operating conditions: 1 - damaged shaft (secondary hardening, “white layer”); 2 - shaft after 1330 h of normal operation; 3 - new shaft.

Based on a set of experimental and diagnostic investigations, it was determined that the dominant surface damage mechanism limiting the serviceability of the “stationary shaft–bushing” friction pair in the roller tappet assembly of the fuel pump is adhesive wear of the second kind (hot scuffing). The development of hot scuffing is induced by boundary lubrication conditions, in which the lubricant supply to the contact zone is unstable or insufficient. Under such circumstances, the dynamic balance between the formation and removal of secondary structures in the surface layers of the frictional contact is disrupted. As the lubricant film collapses, contact occurs between nascent metallic asperities of both elements.

Since the shaft and the bushing are manufactured from the same steel grade (100Cr6), the chemical affinity of the materials promotes the formation of welding bridges at the interface. The action of tangential forces that cause relative displacement leads to rupture of these junctions, accompanied by sharp localized temperature rises. As a result, the surface layers undergo thermal softening and plastic deformation, local melting, and a decrease in load-bearing capacity, followed by secondary hardening during cooling (formation of a “white layer”).

Consequently, the surface loses structural stability. Repeated initiation and accumulation of these processes lead to accelerated degradation and eventual failure of the friction pair. The severity of hot scuffing is strongly influenced by the thermophysical properties of the material (thermal conductivity, heat capacity, high-temperature strength), which determine the ability of the surface layers to dissipate heat from the contact zone. In the analyzed friction pair, hot scuffing most frequently develops under boundary or starved lubrication; during rapid load increases at start-ups and transient modes; and under disrupted lubricant supply, as in the present study.

Thus, the combination of elevated mechanical loads, chemical affinity of the contacting materials, and limited lubrication is a decisive factor driving the failure of this friction pair due to the development of hot scuffing. Based on the established damage mechanism, a physical model of adhesive wear of the second kind was proposed, comprising five stages: breakdown of boundary lubrication layers and secondary structures due to irregular lubricant supply; approach of metallic asperities to contact distances and collapse of the lubricant film; intensive plastic deformation in microcontacts with the formation of dislocation-active zones and increased vacancy concentration; mutual diffusion of metallic surfaces and formation of metallic junctions in the true contact region; rupture of metallic junctions accompanied by material transfer and generation of wear debris.

The practical significance of this model is that the prevention of hot scuffing is governed by the durability and stability of secondary protective structures, and the thermophysical properties of the contacting materials determining heat dissipation capabilities.

To reduce the intensity of adhesive wear of the second kind, engineering solutions must be implemented to: suppress activation of metallic contact (strengthening of surface layers, improvement of high-temperature resistance); promote surface passivation, which ensures the formation of stable secondary structures and efficient heat removal.

Passivation control may be achieved by increasing the thermal conductivity and heat capacity of the materials in the friction pair; using lubricants with functional additives that promote the formation of robust anti-scuffing films on the contacting surfaces.

Generalization of the results confirms the feasibility of applying a set of design, technological, and operational solutions to eliminate or significantly reduce damage in the "stationary shaft–bushing" friction pair of the roller tappet assembly of a fuel pump. Based on the obtained results, a comprehensive set of measures for improving durability of the friction pair is justified and summarized in Table 2.

Table 2

A set of measures aimed at improving the durability of the "stationary shaft–bushing" friction pair in the roller tappet assembly of a fuel pump

№	Category of measures	Recommendation	Expected technical effect
1	Design-related	Introduction of axial lubrication grooves and eccentric relief in the upper zone of the shaft	Improved lubricant supply, reduction of boundary friction
		Use of dissimilar materials for the shaft and the bushing	Reduced chemical affinity, lower risk of metallic adhesion and scuffing
2	Optimization of load conditions	Parametric optimization of fuel injection equipment to increase delivery without additional load growth	Reduction of peak axial loads and thermal overload
3	Technological surface strengthening	Deep cryogenic treatment (≈ −90 °C) immediately after quenching	Strengthening and stabilization of surface layers, reduced susceptibility to scuffing
		Optimization of finishing operations and sealing technologies	Formation of favorable surface topography and durable secondary structures
4	Modification of operating media	Use of anti-scuffing and antiwear additives in lubricating and fuel media	Accelerated formation of protective tribofilms in the contact zone

Conclusions

It has been established that the dominant surface damage mechanism in the "stationary shaft–bushing" friction pair of the roller tappet assembly in a fuel pump is adhesive wear of the second kind (hot scuffing), which develops rapidly under boundary lubrication and increased axial loading.

It has been shown that bushings operated for 1330 hours under normal conditions exhibit minimal form deviations, whereas damaged bushings demonstrate pronounced polygonal deformation of the cylindrical surface profile, indicating intensive plastic deformation in the contact zone.

Analysis of surface topography and microhardness confirmed the formation of a localized densified "white layer" after failure, whose microhardness is nearly twice the initial value. This indicates secondary hardening of the surface layer caused by localized thermal overload.

It was determined that the primary cause of scuffing is insufficient lubricant supply during periods of maximum cyclic loading, resulting in direct contact between nascent metallic asperities and the formation of welding bridges.

The mechanism of hot scuffing has been defined, allowing the identification of key factors governing the progression of surface damage, including the strength of secondary structures and the thermophysical properties of the material.

A set of design, technological, and operational measures has been justified to reduce the intensity of hot scuffing in the studied friction pair, including the introduction of lubrication grooves and eccentric relief, the use of dissimilar materials in the pair, deep cryogenic treatment, and modification of the working media with functional additives.

Further experimental studies on tribological test benches are required to validate the proposed solutions and to optimize the parameters of the design and technological improvements of the assembly.

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Гупка А.Б. , Стухляк Д.П. , Міронов Д.В. , Тотосько О.В. , Хорошун Р.В. , Слободян Л.М., Костюк М.В. Дослідження процесу зношування та характеру пошкоджуваності трибоспряження «нерухома вісь-втулка»

У статті досліджено причини поверхневого руйнування трибоспряження «нерухома вісь – втулка» роликового вузла штовхача паливного насоса дизельного двигуна вантажного автомобіля за умов підвищених навантажень і граничного мащення. Застосовано метод паспортизації поверхневого руйнування з аналізом мікротвердості, шорсткості, геометричної точності та структурних змін у поверхневих шарах деталей, включаючи елементи рентгеноструктурного аналізу. Встановлено, що основним видом руйнування є гарячий задир (схоплювання II роду), зумовлений нерегулярним підведенням мастильного матеріалу, хімічною спорідненістю матеріалів обох деталей (Сталь ШХ15), локальною концентрацією навантажень та нерухомим положенням осі. Показано формування вторинно-загартованих «білих шарів», що свідчить про теплове перевантаження та зниження запасу несучої здатності поверхневих шарів після тривалої експлуатації. Запропоновано комплекс конструктивних, технологічних і експлуатаційних заходів для підвищення надійності й довговічності пари тертя.

Ключові слова: гарячий задир, трибоспряження, паливний насос, мікротвердість, вторинні структури, поверхневе руйнування.