SECTION 8.

GENERAL MECHANICS AND MECHANICAL ENGINEERING

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ANALYSIS OF TRIBOLOGICAL PROCESSES AND INVESTIGATION OF WEAR MECHANISMS IN THE CAMSHAFT OF INTERNAL COMBUSTION ENGINES

Abstract. *This study presents a tribological analysis and investigation of wear mechanisms in the camshafts of internal combustion engines. It provides a comprehensive analysis of high contact pressures occurring specifically in the cam-follower pair, instances of elastohydrodynamic lubrication (EHL) breakdown, and adhesive galling resulting from boundary friction, as well as contact-fatigue wear. The impact of modern surface modification techniques and tribochemical additives aimed at reducing component wear is examined on a scientific basis. The results of the research are focused on enhancing engine efficiency and extending operational service life.*

Keywords: *camshaft, tribology, wear, internal combustion engines, engine service life.*

Introduction. The fundamental role of the camshaft is to carry out the gas exchange process in the engine cylinders the intake of the fresh air-fuel mixture and the expulsion of combustion products with precise valve timing. This complex function is performed by converting the rotational motion of the shaft into linear reciprocating motion of the valve tappets via the cam lobe profiles. Tribology is a fundamental science that studies the laws of friction, wear, and lubrication in surfaces that are in contact and move relative to one another. The control of tribological processes in internal combustion engines is of critical importance. Research indicates that approximately 15–20% of the total mechanical friction losses generated inside an engine are attributed to the valvetrain (the gas distribution mechanism) [1-17]. An increase in the friction coefficient at the camshaft assembly of the gas distribution mechanism does not merely signify the loss of mechanical energy in the form of heat. It also leads to surface degradation, alterations in the geometric dimensions of components, and microscopic material detachment. For this reason, the tribodynamics of the cam–follower pair serves as one of the key factors that directly determines the service life of the engine [17-97].

Problem statement and research objective. Tribological disturbances occurring on camshaft lobes—such as adhesive wear, contact fatigue defects, and surface abrasion—remain a persistent global engineering challenge. Even micrometer-level wear on the cam profile alters the valve lift height and shifts the timing of gas distribution phases. This kinematic deviation significantly reduces the efficiency of the thermodynamic cycle, resulting in the following consequences:

1. A decrease in engine brake thermal efficiency (BTE) and output torque;
2. Increased fuel consumption;
3. Elevated emissions of harmful exhaust gases (NO_x, CO, and hydrocarbons) exceeding regulatory limits, due to incomplete combustion.

The primary objective of this article is to scientifically classify the complex wear mechanisms observed in camshafts, analyze the characteristics of lubrication regimes under extreme operating conditions, and investigate the potential of surface engineering approachessuch as advanced coatings and material modificationto effectively mitigate these tribological challenges [2]. The operating mechanism of a camshaft is a complex tribological system that integrates wear caused by severe conditions and the engineering solutions applied against them. In the non-conformal contact between the cam and the follower, the fundamental criterion that determines the nature of friction and the risk of wear is the specific film thickness parameter (λ). This parameter mathematically expresses the degree to which the surfaces are separated as follows [1]:

$$\lambda = \frac{h_{min}}{\sqrt{R_{q1}^2 + R_{q2}^2}}$$

Where:

h_{min} *– The minimum oil film thickness between the components.*

R_{q1} *and* R_{q2} *–The root mean square (RMS) surface roughness of the two contacting surfaces.*

When the engine operates at high speeds, $\lambda>3$, leading to elastohydrodynamic (EHD) lubrication, which provides protection. However, during low speeds or cold starts, the speed is insufficient, causing h_{min} to decrease sharply. Consequently, $\lambda<1$, the protective layer ruptures, and a transition to the critical boundary friction regime occurs.

Under boundary lubrication conditions, direct metal-to-metal contact becomes essentially unavoidable, which inevitably promotes both adhesive and abrasive wear. The amount of material detached from the surface in this regime is commonly estimated in tribology by the classic Archard wear equation [4]:

$$V = \frac{K \cdot F \cdot s}{H}$$

Where V is the wear volume, F is the applied normal load, s is the total sliding distance, H is the hardness of the softer contacting material, and K is the dimensionless wear coefficient. In addition, fluctuating normal loads (F) generate repeated cyclic stresses in the subsurface material. These stresses can initiate fatigue cracks that propagate over time, eventually causing small metallic fragments to detach from the surface a damage mechanism referred to as contact-fatigue (or surface-fatigue) wear.

In the Archard equation discussed above, the most detrimental condition leading to a sharp increase in wear volume *(V)* is lubricant starvation. When the protective physical oil film (h_{min}) collapses, the system can only be safeguarded by artificially reducing the wear coefficient *(K)*. This function is performed by tribochemical additives in engine oil, particularly zinc dialkyldithiophosphate (ZDDP). Under high contact pressure, these additives react chemically with the metallic surface of the shaft to generate a sacrificial, polymer-like tribofilm typically on the order of micrometers in thickness which resists sliding and prevents micro-welding and subsequent detachment of material.

However, current environmental regulations, driven by low-emission requirements, mandate a reduction in the concentration of these chemical additives in lubricants. To compensate for this shortfall, the modern automotive industry is increasingly relying on fundamental Surface Engineering approaches. Alongside traditional thermochemical treatments such as nitriding and carburizing, diamond-like carbon (DLC) coatings are applied to shaft surfaces. DLC coatings provide two key benefits: they substantially lower the composite surface roughness (R_q) that is used to calculate the lambda ratio (λ), and their ultra-hard structure significantly improves the material's resistance to critical Hertzian contact pressure (P_{max}).

The analysis presented in the concluding section shows that tribological processes in the camshaft of internal combustion engines are critical to both the mechanical reliability and the environmental performance of the engine. The conducted research leads to several fundamental conclusions.

It was demonstrated that the extreme Hertzian contact stresses and the variable lubrication regimes occurring in the cam–follower pair give rise to wear mechanisms that follow Archard's law directly. In particular, during engine cold-start phases, the collapse of the lubricant film to a critically low level $(\lambda<1)$ is the primary driver of adhesive wear and contact-fatigue damage. To mitigate these tribological failures, it is essential to address not only the viscosity temperature behavior of the lubricant, but also the targeted modification of the surfaces from a materials-science perspective.

Conclusion.

1. The conducted research indicates that tribological processes occurring in the camshaft of internal combustion engines have a direct impact on the engine's overall reliability, energy efficiency, and environmental performance. In particular, the high contact stresses and variable lubrication regimes arising in the cam follower pair contribute to the development of intensive wear processes on the contact surfaces.

2. It has been established that the breakdown of the elastohydrodynamic lubrication regime and the shift toward boundary friction particularly at low speeds and during cold start-up constitute the primary source of adhesive and contact-fatigue wear. These processes progress in accordance with Archard's law, resulting in the formation of microscopic surface defects and ultimately leading to a deterioration in the functional performance of the mechanism.

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