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Investigation of tooth wears from scuffing of heavy duty machine spur gears

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ABSTRACT

In this paper, we present results from theoretical and experimental investigations into the teeth wear of spur gears of heavy duty machines. During operation, boundary friction and scuffing result on their working surfaces. Theoretical investigations were carried out using the tooth wear model, which takes into account the instantaneous contact temperature according to Blok's concept. The model simulates the continuous interaction of the teeth forms as a function of contact parameters and the effect of these parameters on the shape of the teeth profiles. The validity of the theoretical model was confirmed by experimental investigation.

1. Introduction

One of the main forms of damage to gear teeth occurs as a result of wear on their surfaces. Two types of teeth wear exist: low-intensity wear (normal wear) and high-intensity wear, which appears with scuffing.

Normal wear is usually understood as a process of gradual change in size by friction, and it is characterized by the removal of particles of tooth material from the contact surface. Teeth wear results from the rubbing of surfaces with a gradual increase in damage. This leads to deterioration in the involute tooth profile and to a worsening of the quality of engagement. Theories of slow wear are well-developed and a large number of papers see for example [1–7], are based on different wear models. These theories are justified in the field of transmission parameters relevant to experimental studies.

Scuffing is defined as the damage caused by the solid-phase welding between surfaces in relative motion. It is accompanied by the transfer of metal from one surface to another because of the welding and subsequent tearing. The American National Standard ANSI/AGMA 1010-E95 "Appearance of Gear Teeth — Terminology of Wear and Failure" (1995) describes the characteristics of the failure modes. When scuffing occurs, the lubricating films between the teeth are damaged and a molecular interaction of the working surfaces occurs, i.e., contact between the teeth takes place through oxide films. In the friction zone, new structures, such as needle-shaped martensite and the so-called "white zone", are formed. This white zone is of high hardness [8]. At first, a weak interaction exists, i.e., scoring appears, and sometimes this process stops. More often, after a period of time, the mating surfaces are so deeply engaged that the particles of one tooth become welded to the others and scuffing occurs. The newly formed welds lead to a destruction of the other teeth in the form of deep grooves. As a result, the working surfaces of the teeth are destroyed completely in a very short period of time (some minutes).

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Nomenclature

m	module (mm)
z_1 and z_2	number of pinion and wheel teeth
$i = \frac{z_2}{z_1}$	gear ratio for unworn teeth or average gear ratio for worn teeth
x_1 and x_2	shift profile coefficients of pinion and wheel
d_{a1} and d_{a2}	diameters of addendum circle of pinion and wheel (mm)
ρ_1 and ρ_2	radius of curvature at pinion and wheel contact point (m)
$\rho_{red} = \frac{\rho_1\rho_2}{\rho_1+\rho_2}$	reduced radius of curvature at contact point (m)
a_w	center distance (mm)
$b_{\min}$	minimal face width from two toothed wheels in contact (mm)
T_1 and T_2	input and output torques (Nm)
w_n	load per unit width (N/m)
ω_1	angular velocity of pinion (rd/s)
BHN_1 and BHN_2	Brinell hardness numbers of working surfaces of pinion and wheel teeth (N/m^2)
RHN_1 and RHN_2	Rockwell hardness numbers of working surfaces of pinion and wheel teeth;
σ_{H}	contact stress (Hertz) (N/mm^2)
E_1 and E_2	modulus of elasticity for pinion and wheel (N/mm^2)
$E_{red} = \frac{2E_1E_2}{E_1+E_2}$	reduced module of elasticity materials of pinion and wheel (N/mm^2)
υ_{ty1} and υ_{ty2}	velocities of moving contact zone on pinion and wheel tooth shapes (m/s)
$\upsilon_{gz} = \upsilon_{ty1} - \upsilon_{ty2}$	sliding velocity between teeth (m/s)
ν_{t^o}	kinematic viscosity of oil at a working temperature of teeth t^o (m^2/s)

No theoretical methods exist for the determination of the tooth wear of gears that take into account the scuffing of working surfaces. This can be explained by two reasons. Firstly, the teeth scuffing process occurs over a very short period of time, and it can either stop or cause catastrophic teeth wear. Secondly, teeth scuffing calculations are made according to the initial parameters of the engagement (when the teeth are not worn), whereas teeth distortion as a result of their wear results in a significant change in contact parameters [9,10].

In the calculation of teeth wear, it is necessary to consider a range of wear lubrication conditions. These conditions are among the most important factors affecting the wear of the working surfaces of the teeth. Usually, three main types of lubrication regimes are taken into account: boundary, elastohydrodynamic (EHL) and partial or mixed elastohydrodynamic lubrication.

A prerequisite for the appearance of an EHL (liquid) regime is the existence of a grease lubricant layer where the thickness under load exceeds the total height of the roughness of the contacting surfaces. In this mode, the direct contact of friction surfaces is eliminated completely, which leads to a significant reduction in the friction coefficient and, consequently, to reduced wear as the wear process occurs only during startup and shutdown.

The boundary lubrication regime most often occurs in highly productive and heavy-duty machines in the mining, mineral processing, and metallurgical industries, and in transport vehicles. The gears in these machines function under difficult conditions, such as high specific dynamic loads, high speeds, and significant lubricant contamination in an abrasive environment.

Under certain conditions, partial EHL occurs, i.e., some portions of the contacting surfaces are separated by a layer of lubricant, while other surfaces exist in the boundary regime. With an increase in the boundary lubrication regime, the friction coefficient is increased, and the wear of the working surfaces also increases, although to a lesser extent than in the boundary friction regime.

Gears of heavy-duty machines exist mostly in the boundary lubrication regime and rarely in the mixed regime. In these modes, the scuffing of teeth is likely to occur, especially in the boundary lubrication regime.

Scuffing influences tooth surface wear significantly through the appearance and development of damage to the friction surface by the grasping and transferring of material from one contact surface to another. A local connection occurs in the solid state because of the friction of the molecular forces (microwelding). Numerous investigations have been conducted to determine a variety of factors that have a significant influence on scuffing such as specific load, sliding velocity, total rolling velocity, physical and mechanical properties of metals, and lubricant properties. The opinions of most researchers coincide with the qualitative estimation of factors that affect scuffing, whereas the quantitative estimations are often very different.

The criteria approach is usually used for the calculation of scuffing. Several functions that describe variables that affect scuffing have been selected based of experimental studies. It is expected that when these functions reach a critical value, scuffing occurs. The most famous criteria are those suggested by Olmen [11], Olmen–Straub [12], Hofer [13], Blok [14], Petrusevich [15], Kistjan [16], Roslivker [17], and Drozdov [18,19].

The most theoretically based criterion is Blok's temperature criterion, which has been verified experimentally in the laboratory and in industry. This criterion is based on the hypothesis of the existence of a critical temperature for oily film destruction. The critical temperature is characteristic for each material and lubricant combination. The contact temperature is defined as the sum of the