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Axle gear oils: Friction, wear and tribofilm generation under boundary lubrication regime

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ABSTRACT

The internal friction torque measurements in Cylindrical Roller Thrust Bearings (RTB) lubricated with axle gear oils under boundary film conditions were performed using an axial rolling bearing test rig generating tribofilms. The X-ray photoelectron spectroscopy (XPS) was used to characterize the tribofilms formed on the bearing rollers and raceways. After the tests, wear debris were found on the oil samples which lubricated the surface of the roller bearing raceways for that surface topography measurements and oil analysis (ferrography) were mandatory to measure and to visualize the occurring wear. The results obtained indicate that axle gear oil formulations and their additive packages have got a significant influence in controlling roller bearing friction and wear under boundary film lubrication.

1. Introduction

The automotive industry has become increasingly interested in reducing the fuel consumption. Many efforts are employed on the increase of vehicle fuel economy due to its significant environmental impact since it will directly contribute towards reduction of CO_2 polluting emissions to the atmosphere [1–4]. Transportation is one of the key areas for this legislation as it accounts for a large proportion of energy consumption and of carbon dioxide emissions. According to the technical report published by the Environmental Protection Agency (EPA) in 2015, the transportation activities accounted for more than one-third (33.4%) of U.S carbon dioxide emission in 2013, where passenger cars and light-duty trucks are responsible for 60% of all transportation emissions [5]. In studies of standard automobiles used in urban and highway driving, it was found that around 15–22% of the energy produced actually is used to drive the wheels, and that a significant portion of the remaining energy is dissipated as heat [6,7].

A continuously tightening legislation is imposed on the automotive industries and lubricant and additives suppliers to improve fuel efficiency and reduce emissions [4]. Mandated legislation in the four largest automobile markets, US, EU, China and Japan, are demanding the automotive and lubricant manufacturers to meet certain fuel economy standards like the corporate average fuel economy (CAFE) in US and the New European Driving Cycle (NEDC) in the European Union [8–11].

Not only governments require a strong drive towards better fuel economy but also consumers are demanding energy efficiency in order to save energy, reduce expenditure and minimize the effect of global warming [4,9].

To achieve significant reductions in automotive emissions, the efficiency of all driveline components should be improved. That is the case of the axle transmission, which is a key component of the vehicle powertrain and is focused by the present research [12]. Of course, these targets cannot be reached only by tribological measures through overcoming the friction forces which take place in tribological contacts in axle components like rolling bearings and gears. Important additional steps have to be implemented based on including axle lubricants with enhanced durability, protection and lower operating temperatures. An effective lubrication of all axle tribological contacts is needed [13].

Since 1/3 of the total friction losses occur in the mixed film or boundary film lubrication regimes, the reduction of friction and wear is of particular importance when such lubrication regimes prevail [2]. According to Bartz et al. [2], this ratio is valid for the relative influences of friction modifiers or lower viscosities and it can be modified by changing the viscosity of the lubricant. Under these lubricating conditions, the chemical composition of the axle lubricants, i.e. the additive package is fundamental, while the rheological properties of the

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Notation and units

a	Hertzian contact width, [m]
a_A	ASTM D341 viscosity parameter, [-]
A_c	surface contact area, [m^2]
$CPUC$	Wear Particle Concentration, [-]
d	dilution factor, [-]
d	bearing bore diameter, [mm]
D	bearing outside diameter, [mm]
d_m	rolling bearing mean diameter, [mm]
D_L	large wear particles, [-]
D_S	small wear particles, [-]
E^*	effective Young modulus, [Pa]
F_a	axial load, [N]
F_n	normal force, [N]
G	material parameter, [-]
G_{rr}^5	factor depending on the bearing type, bearing mean diameter and applied load, [N mm]
G_{sl}^5	factor depending on the bearing type, bearing mean diameter and applied load, [N mm]
h_0	center film thickness, [m]
h_{0C}	modified center film thickness, [m]
$ISUC$	Severity of Wear Particles, [-]
k_L	thermal conductivity, [W/m K]
K_{rs}	starvation constant for oil bath lubrication, [-]
l	roller element width, [m]
K_z	bearing type related geometry constant, [-]
L	thermal parameter of the lubricant, [-]
LP	lubricant parameter, [s]
m_A	ASTM D341 viscosity parameter, [-]
M_{drag}	friction torque of drag losses, [N mm]
M_{r1}	peak material ratio, [%]
M_{r2}	valley material ratio, [%]
M'_{rr}	rolling friction torque, [N mm]
M_{seal}	friction torque of seals, [N mm]
M_{sl}	sliding friction torque, [N mm]
M_t	internal bearing friction torque, [N mm]
M_t^{exp}	total bearing friction torque measured experimentally, [N mm]
n	rotational speed, [rpm]
n_A	ASTM D341 viscosity parameter, [-]
p	load, [N]
p_0	maximum Hertz pressure, [Pa]
p_m	medium pressure, [Pa]
p_{max}	maximum contact pressure, [Pa]
PLP	Percentage of Large Particles, [-]
R	radius, [m]
$R1$	geometry constant for rolling frictional torque, [-]
R_a	average surface roughness, [m]
R_{ku}	kurtosis of the roughness profile, [m]
R_{max}	maximum peak-to-valley height, [m]
R_{pk}	reduced peak height, [m]
R_q	root mean square profile height, [m]
R_{sk}	skewness of the rough profile, [m]
R_{vk}	reduced valley depth, [m]
R_z	mean peak-to-valley height, [m]
R_{x1}	radius of curvature raceway, [m]
R_{x2}	radius of curvature roller, [m]
R_x	equivalent radius of curvature in x direction, [m]
s	pressure-viscosity parameter, [-]
$S1$	geometry constant for sliding frictional torque, [-]
S_a	arithmetical mean height, [m]
S_{ku}	kurtosis of the roughness areal, [-]
S_p	maximum peak height, [m]
Sp	modified Stribeck parameter [36], [-]
S_q	root mean square height, [m]
S_{sk}	skewness of the rough areal, [-]
S_v	maximum valley depth, [m]
S_z	maximum height, [m]
t	pressure-viscosity parameter, [-]
T	operating temperature, [°C]
T_0	reference temperature, [°C]
U	speed parameter, [-]
$U1$	raceway speed, [m/s]
$U2$	roller speed, [m/s]
Ve	slip rate, [-]
VI	viscosity Index, [-]
W	load parameter, [-]
z	number of rollers, [-]
α	pressure viscosity coefficient, [Pa^{-1}]
α_t	thermal expansion coefficient, [-]
β	thermoviscosity coefficient, [K^{-1}]
η	dynamic viscosity, [Pa s]
$\dot{\gamma}$	shear strain rate, [s^{-1}]
Λ_1, Λ_{24}	specific film thickness, [-]
μ_{bl}	coefficient of friction in boundary film lubrication, [-]
μ_{EHL}	coefficient of friction in full film lubrication, [-]
$\mu_{sl}{}^{exp}$	experimental sliding coefficient of friction, [-]
ν	kinematic viscosity, [cSt]
ρ	density, [g/cm^3]
ρ_0	density at temperature T_0, [g/cm^3]
σ_1	raceway roughness, [m]
σ_2	roller roughness, [m]
σ_c	composite roughness, [m]
τ	shear stress, [Pa]
ϕ_{bl}	sliding friction torque weighting factor, [-]
ϕ_{ish}	inlet hear heating reduction factor, [-]
ϕ_{rs}	kinematic replenishment/starvation reduction factor, [-]
ϕ_T	thermal reduction factor, [-]

lubricant are of secondary importance. For reducing friction and wear in contacts that are lubricated in such regimes, the tribofilms generated from lubricant additives and their properties are very important.

Several studies were developed by Evans et al. [14–16] in order to increase the understanding of the role of lubricant additives through analyzing the composition of real bearing surfaces on nanometer scale after been tested in severe conditions. The authors in an earlier work [12] discussed the tribological behaviour of the axle gear oils under full film condition. In this subject, the scope of this work is set to establish a relation between axle gear oil formulations and their additives, rolling bearing friction torque and wear under boundary lubrication conditions. For that purpose, one methodology was adopted through analyzing the structure and composition of real bearing surfaces. Experimental measurements of internal friction torque in cylindrical roller thrust bearing (RTB-81107) lubricated with several axle gear oils with different formulations were carried out, using an axial rolling bearing test rig. SKF Friction Torque Model was used to understand the influence of oil's formulation in the bearing's power loss. After each test, several analysis were performed, using X-ray photoelectron spectroscopy (XPS), roughness measurements and ferrography techniques.

2. Axle gear oils properties

Five fully formulated gear oils, suitable for axle lubrication, were selected. All the lubricants are polyalphaolefin base oils (PAO) except