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MEASUREMENT OF EHL CONTACT TEMPERATURE FOR DIFFERENT BULK AND COATING MATERIALS

CATEGORY
Lubrication Fundamentals

AUTHORS AND INSTITUTIONS

Martin EBNER[1], orcid.org/0000-0002-5102-9191
Andreas PETER[1], -
Thomas LOHNER[1], orcid.org/0000-0002-6067-9399
Karsten STAHL[1], orcid.org/0000-0001-7177-5207

[1]Gear Research Centre (FZG), Technical University of Munich (TUM), Boltzmannstraße 15, 85748 Garching b. München, Germany

INTRODUCTION
In thermo-elastohydrodynamically lubricated (TEHL) contacts, the contact temperature strongly influences the local lubricant properties. Thereby, a higher contact temperature leads to a lower effective lubricant viscosity and, hence, to lower fluid coefficients of friction. Friction measurements with Diamond-like Carbon (DLC) coated test parts in ball-on-disk machines, gear model test rigs and gear test rigs show lower coefficients of friction even under fluid film lubrication. This is referred either to the different wetting behavior of DLC compared to steel resulting in wall slip (e.g. [9]) or to the different thermophysical properties of DLC resulting in thermal insulation (e.g. [3]). Theoretical investigations on DLC coated surfaces indicate a strong thermal insulating effect compared to uncoated steel surfaces (e.g. [2][3][7][19]). To the authors' knowledge, the influence of thermophysical properties on the contact temperature has rarely been validated experimentally. The EHL contact temperature can be measured by the infrared (IR) thermography technique (e.g. [1][13]) and by thin film sensors often applied to twin-disk test rigs (e.g. [4][8][16][17]).
The aim of this study is to analyze the influence of thermophysical properties on the EHL contact temperature using thin film sensors on a twin-disk test rig.

SETUP AND TEST PARAMETERS
A FZG twin-disk test rig is used. The reader is referred to [6][12] for detailed descriptions of the test rig. Only the main characteristics of the test rig are repeated in the following.

The upper and lower disk are independently driven, allowing continuous adjustment of sum velocity ($v_\Sigma = v_1 + v_2$) and slip ($s = (v_1 - v_2)/v_1$). In case of $s \neq 0$, the upper disk is defined to have the higher velocity.

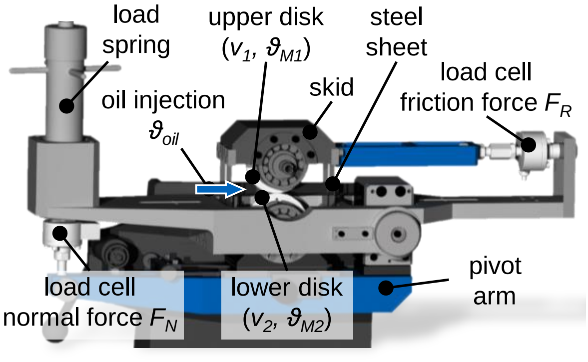

Figure 1: FZG twin-disk test rig

The normal force F_N in the disk contact is applied by a load spring via the pivot arm where the upper disk is mounted. Injection lubrication is applied. Normel force F_N, friction force F_R, surface velocities v_1 and v_2, oil injection temperature ϑ_{Oil} and bulk temperature of the lower disk ϑ_{M2} are measured. To ensure an evenly distributed load in the line contact of the disks, a contact print on aluminum foil is carefully evaluated before each test.

For all experiments, ceramic sensor disks with thin film sensors are mounted as upper disks and a steel test disk is mounted as the lower disk (Figure 2). Table 1 shows the material data and thermophysical properties. To ensure fluid film lubrication, the disks are polished mechanically to arithmetic mean roughness values of Ra < 0.05 µm (measured by the profile method with L_t = 4 mm and λ_c = 0.08 mm perpendicular to the circumferential direction of the disk).

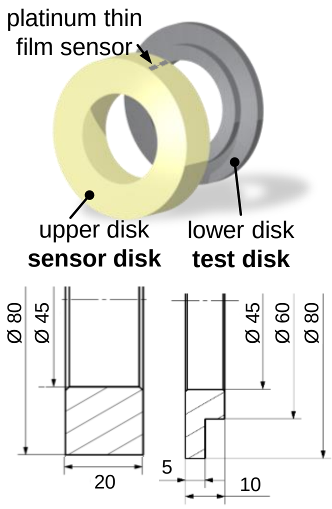

Figure 2: Sensor disk and test disk

Table 1: Material data and thermophysical properties of the test and sensor disks

			Test disk	Sensor disks	
Material			16MnCr5 [5]	Zircon ceramics ZrO_2 [15]	Aluminum oxide ceramics Al_2O_3 [15]
Young's modulus E	in	N/mm²	210000	200000	350000
Poisson ratio ν			0.30	0.30	0.22
Density ρ	in	kg/m³	7760	6000	3900
Thermal conductivity λ	in	W/(m·K)	44	2.5	28
Specific heat capacity c_p	in	J/(kg·K)	431	400	900
Thermal inertia $I = \sqrt{\rho \cdot \lambda \cdot c_p}$	in	J/(m²·K·s$^{-0.5}$)	12131	2449	9914

A Hertzian pressure of p_H = 1000 N/mm^2, a sum velocity of v_Σ = 16 m/s, a bulk temperature of ϑ_{M2} = 52 °C and slip ratios of s = {20, 30} % are investigated. The bulk temperature ϑ_{M2} results from an adjusted oil injection temperature of ϑ_{Oil} = 40 °C. Mineral oil MIN100 (ISO VG 100) with extreme pressure additive is used [14].

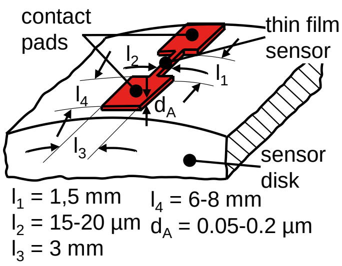

Figure 3: Geometry of thin film sensor

Figure 3 shows the geometry of the considered thin film sensor made from platinum. The sensor is applied by photolithography to mask the sensor on the disk and by using an ion beam sputtering device to coat platinum [8]. The thin film sensor represents a passive resistor changing its ohmic resistance ΔR with temperature and pressure (equation 1). ΔR is measured by a Wheatstone bridge according to [16], which is based on [8] and [17]. The ohmic resistance of the thin film sensors under ambient conditions is about R_0 = {100 …200} Ω. The sensors have to be calibrated before each experiment to determine the temperature coefficient α_T and pressure coefficient α_p [8]. The ohmic resistance of the platinum sensors is very sensitive to temperature, but also decreases with increasing pressure. Hence, the temperature measured when the thin film sensor runs through the EHL contact must be corrected for pressure change. To do this, pressure distributions were calculated by TEHL simulation [11] for the considered operating conditions.

$$\frac{\Delta R}{R_0} = \alpha_p \cdot \Delta p + \alpha_T \cdot \Delta T \qquad (1)$$

RESULTS AND DISCUSSION

Figure 4 shows measured temperature rises ΔT over the dimensionless gap length direction for a transition of the thin film sensor through the EHL contact. The mean value is based on ten pressure corrected measurements. The measured temperature distributions show the well-known trend of temperature distributions in TEHL contacts. Figure 4 compares the temperature rise ΔT between the contact pairings ZrO_2/steel and Al_2O_3/steel for a slip of s = 20 % (solid line) and s = 30 % (dashed line). The maximum temperature rise ΔT_{max} of the contact pairing Al_2O_3/steel is significantly lower than for ZrO_2/steel: 57 % for s = 20 % and 59 % for s = 30 %. For the pairing ZrO_2/steel, ΔT_{max} is 22 % lower for s = 20 % compared to s = 30 %, whereas for the pairing Al_2O_3/steel ΔT_{max} is 18 % lower for s = 20 % compared to s = 30 %.

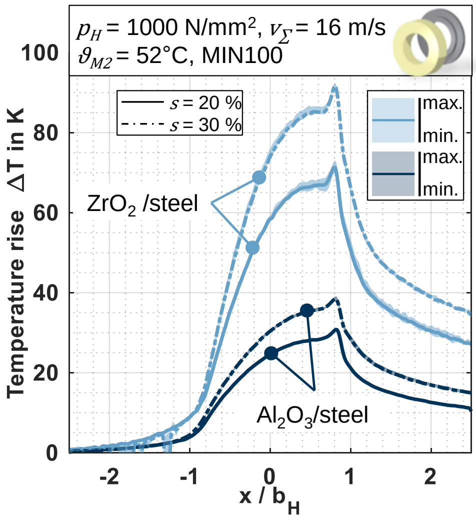

Figure 4: Measured EHL temperature rise for p_H = 1000 N/mm², v_Σ = 16 m/s, ϑ_{M2} = 52 °C and s = {20, 30} % for ZrO_2 and Al_2O_3

The signal of the thin film sensor represents one over-its-size averaged temperature value. The temperature across the lubricant film can differ significantly from the temperatures on the surface of the disks [10]. Because the thin film sensor is applied on the surface of the upper sensor disk, the sensor represents the temperature level close to the surface of the sensor disk. The sensor itself is assumed to exert insignificant influence on the EHL contact [10]. Table 2 compares the measured maximum temperature rise ΔT_{max} with the calculated temperature rise T_{Bl} according to Blok [18]. Thereby, the measured contact temperatures are roughly twice as high as the calculated flash temperature. This has already been observed in e.g. [8][14], and is likely due to the assumptions of Blok and to the fixed height position of the sensor within the EHL contact.

Table 2: Comparison of measured maximum temperature rise ΔT_{max} to calculated temperature rise T_{Bl} acc. to Blok [18]

	Al_2O_3/steel		ZrO_2/steel	
slip s in %	ΔT in K	T_{Bl} in K	ΔT_{max} in K	T_{Bl} in K
20	30.8	15.1	71.3	24.6
30	37.4	19.5	91.7	32.0

The measured temperature rise is higher with sensor disks made from ZrO_2 compared to Al_2O_3. ZrO_2 features a lower thermal inertia compared to Al_2O_3 and Al_2O_3 itself has a lower thermal inertia compared to steel (see Table 1). Hence, it can be derived that materials with low thermal inertia act like a thermal insulator for the EHL contact [7]. This thermal insulation effect also applies to thin coatings because the temperature penetration depth of TEHL contacts is usually smaller than the coatings' thickness of a few micrometers. This confirms results of recent studies (e.g. [10][14]). The results of this study can also be transferred to DLC-coatings, because the thermal inertia of DLC-coatings is reported to be in the order of magnitude of ZrO_2 and below (e.g. [3]). Due to the small thickness of DLC-coatings, its influence on the contact mechanics is usually negligible [7].

SUMMARY AND OUTLOOK

Within this study, EHL contact temperature measurements with thin film sensors were carried out on a FZG twin-disk test rig. Thin film sensors were applied on ceramic sensor disks, which were paired with a steel test disk. By varying the material of the sensor disk, results clearly show the influence of thermophysical properties on the EHL contact temperature. Due to the fixed position of the thin film sensor within the TEHL contact, the height and position of the sensor is important. For greater in-depth analyses and interpretation on measured EHL contact temperatures, measurements with different sensor heights as well as TEHL simulations will be conducted.

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KEYWORDS
Elastohydrodynamic lubrication, EHL, thermal effects, contact temperature, thin film sensor