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THE RHEOLOGIC HYSTERESIS PARAMETERS INFLUENCE ON THE EHD FILM THICKNESS

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Abstract. The paper presents further researches on the rheologic hysteresis of the EHD line contact. The first observations on the rheologic hysteresis were presented in [11]. The rheologic parameters analisis shows their influence on film thickness. These newly introduced parameters for the film thickness are: the absolute rheological deflection (CD), the relative rheological deflection (Δ_{CD}), the absolute area of the hysteresis loop (A_{CL}) and the relative area of the hysteresis loop (Δ_{ACL}).

Key Words: rheologic hysteresis, elastohydrodinamic lubrication, Hertzian line contact.

1. INTRODUCTION

The film thickness of the EHL regime depends on several factors: oil properties, surface roughness, materials, speed, load etc. Until now, all these influences were studied only while loading. This paper presents some interesting results observed during a complete cycle of loading and unloading, similar to the real functioning.

The major result of the research consists in the observation of a phenomenon called "rheological hysteresis" (HR) that occurred during the loading-unloading cycle [9, 11].

The measurements were made using a two disk rig that was described in a previous paper [11], together with this newly observed phenomenon. The new parameters that were defined for a proper analysis of the rheological hysteresis are presented in Appendix. Their variations will be presented further on in this paper.

2. RHEOLOGIC PARAMETERS ANALISIS

It is obvious that the load (maximum Hertzian pressure) has a direct influence on rheological hysteresis [8, 9]. Therefore we present some diagrams showing the variation of the rheologic hysteresis parameters versus load and contact percent. The use of these parameters is considered very important for a proper and synthetic description of the RH behavior of a certain lubricant and in a certain situation.

A complete rheologic parameters analisis consists in the observation of the influence of the main factors (load, rolling speed, rolling and sliding speed, temperature, roughness, type of oil etc.) on the two main rheological parameters of the EHD line contact: film thickness and traction.

This paper presents only the influence of the main parameters on film thickness. A future paper will present the influence of the main parameters on traction.

2.1. CONTACT RHEOLOGIC ANALYSIS

The rheologic hysteresis parameters and their formulas are presented in Appendix. Also, in the Appendix it is presented the way the film thickness is replaced with the contact percent. The reason for this replacement is shown in [11].

Figures 1-3 present the contact rheologic hysteresis (CRH) parameters for the curve plotted in Figure A.2. from Appendix.

It can be clearly seen the difference between the relative deflection related to pressure, Δ_{CDP}, (presented in Figure 1) and the relative deflection related to contact (presented in Figure 2), Δ_{CDC}.

Figure 3 presents the total deflection, Δ_{CD} measured on the mean line and related to the Hertzian pressure.

The curves in Figures 1-3 have the shapes similar to the Gauss curve.

From Figure 1 it can be seen that the maximum deflection related to Hertzian pressure is 12% and that it occurs at 0.8 GPa (at the upper quarter of the maximum Hertzian pressure).

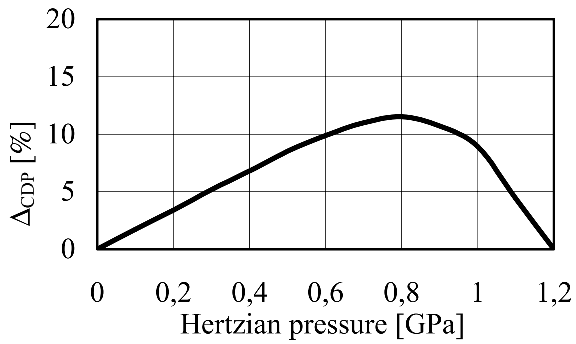

Figure 1. Relative deflection related to pressure

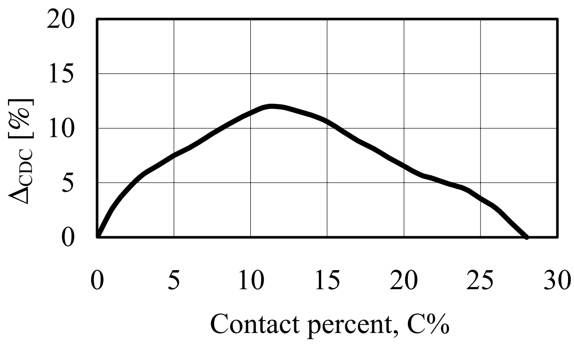

Figure 2. Relative deflection related to contact percent

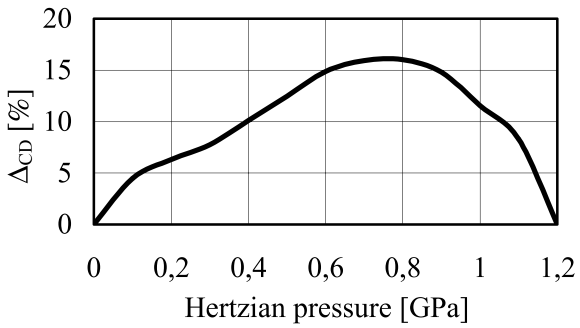

Figure 3. Total relative deflection related to pressure

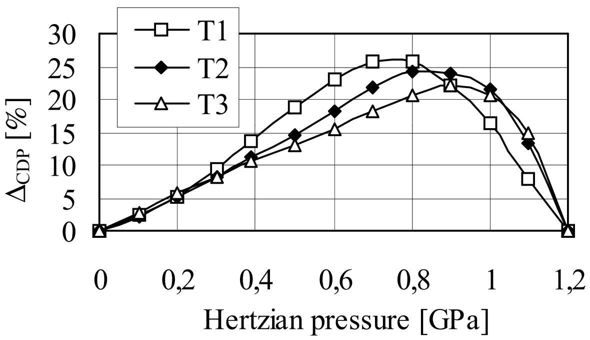

Figure 4. Relative deflection related to pressure

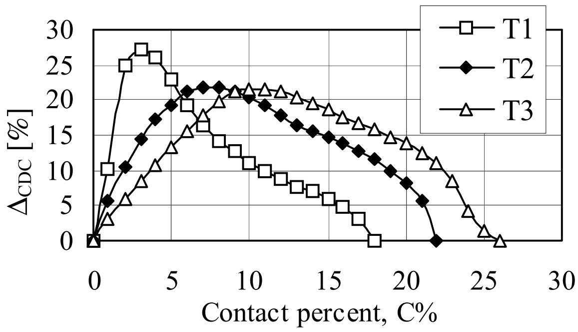

Figure 5. Relative deflection related to contact percent

The deflection related to contact (Figure 2) shows its maximum at 12% of contact.

The maximum value of the total deflection appears at a lower value (0.7 GPa) and it is computed with the formula (5) from Appendix.

Figures 4 and 5 present the rheological hysteresis parameters for different temperatures (T1 = 50° C, T2 = 60° C, T3 = 70° C) and at the rolling speed v_r = 26.8 m/s.

Figures 6 and 7 present the rheological hysteresis parameters for the rolling speed v_r = 31 m/s.

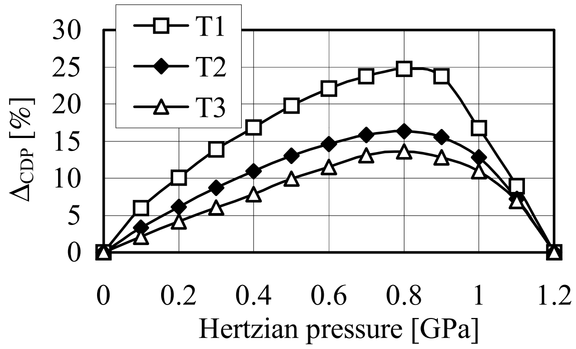

Figure 6. Relative deflection related to pressure

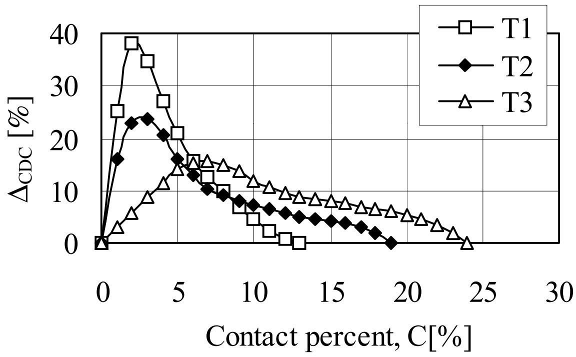

Figure 7. Relative deflection related to contact percent

Observations:

• It can be seen that temperature has an important influence on the Δ_{CDP} at medium speed, while, at high speed, temperature has a larger influence on both deflections.

• The maximum value of the Δ_{CDP} occures at the same pressure value (0.8 GPa) for all temperatures and increases to larger contact percent values with the temperature rise.

• At high temperatures the rheological hysteresis influence is diminished, especially at high speed.

• The maximum value of the Δ_{CDC} occures at low contact values (2 – 7 %).

• The temperature rise from 50° C to 70° C produce a decrease of the relative deflection related to contact Δ_{CDC} from 27 % to 22 % at at the rolling speed v_r = 26.8 m/s and a decrease of the relative deflection related to contact Δ_{CDC} from 40 % to 15 % at at the rolling speed v_r = 31 m/s. This means that temperature rise has a benefit influence on rheologic deflection, specially at high rolling speed.

The curves in Figure 8 present the variation of the relative contact hysteresis area (Δ_{ACL}) with temperature and for two rolling speeds.

In Figure 9 it is plotted the variation of the relative hysteresis area (Δ_{ACL}) with the rolling speed at the temperature T = 50° C.

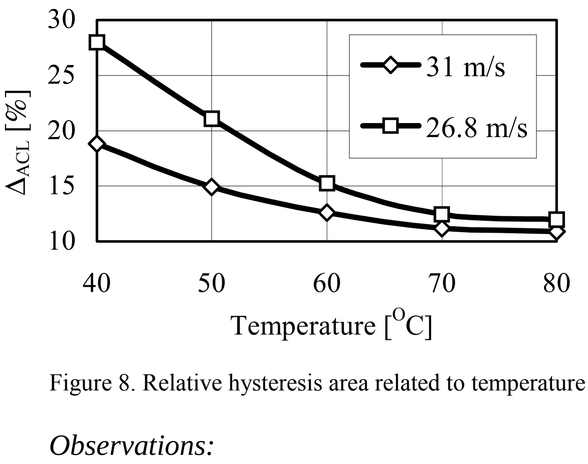

Figure 8. Relative hysteresis area related to temperature

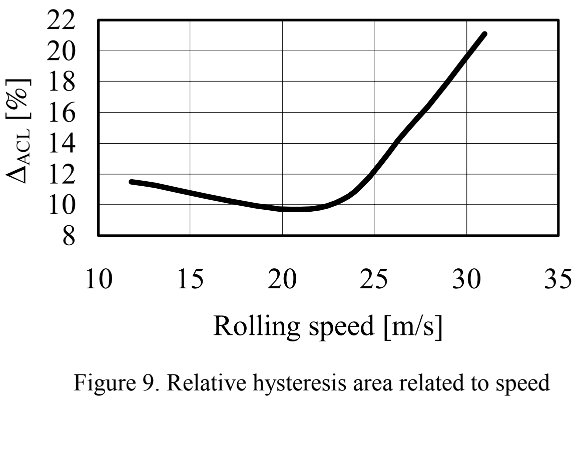

Figure 9. Relative hysteresis area related to speed

Observations:

• It can be seen that the temperature rise diminishes the hysteresis loop area..

• The increasing of the rolling speed has a bad influence on the hysteresis loop area.

• At very low speed, the hysteresis loop area is getting larger, probably because the lubrication regime is no longer full EHD and becomes partial EHD (film percent is 72%; Figure A.1, Appendix).

The general observation is that temperature and rolling speed have opposite influence on the contact hysteresis behavior.

For a comparative study, in Table 1 there are presented some of the values of the rheological area, computed from equation (6) in Appendix.

Table 1. Relative hysteresis area values

Speed [m/s] \ Temperature [°C]	50	60	70
11.28	11.5	–	–
22	9.8	–	–
26.8	14.8	12.6	11.2
31	21.1	15.2	12.5

All the experiments presented in this paper were made using:

- an extreme pressure additivated mineral oil for gears with the dynamic viscosity η_0 = 0.441 Pa·s at 20 °C, temperature coefficient β = 0.076 °C^{-1} and pressure coefficient α = 2.15 GPa^{-1};
- the disks were made of hardened steel and had the roughness R_a = 1.156 μm and R_z = 1.071 μm.

CONCLUSIONS

A complex SAE equipment was used for the film thickness study of the line Hertzian lubricated contact and, for the first time, several phenomena were observed.

• The film thickness behavior and the presence of the rheological hysteresis phenomenon were studied on a complete loading-unloading cycle, similar to the real functioning.

• The hysteresis type phenomenon, that we called rheological hysteresis, appears only in the full EHD lubricant film. This phenomenon is similar with the hysteresis loop of elastic materials with inner friction or with the one of some electric circuits.

• For an easier study of this phenomenon, a new representation was proposed: contact percent–load diagram.

• Also there were defined the rheologic hysteresis parameters of the film thickness: contact hysteresis loop area and contact rheologic deflection. Their behavior was studied related to some of the main factors: load, speed and temperature.

• Hysteresis loop area of the film thickness is largely influenced by load.

Temperature rise leads, up to a limit, to the decrease of the loop area, hence to an improvement of the rheologic behavior of the EHD lubrication regime. This influence can be seen mostly at high rolling speed values, as seen in figures 6 and 7.

Rolling speed has practically no influence on loop area for values up to 25 m/s. At larger speed values, its influence is very strong, leading to a very quick rise of the loop area. The form of speed curve presents an inflexion point similar to the ones that appear at the curves of oil viscosity variation. This represents a direct connection between the oil rheology and the hysteresis behavior presented in this paper.

• Rheologic deflection of the film thickness presents a maximum value towards the large pressure values (around 0.8 GPa). These maximum values increases with temperature rise. The rheologic deflection values diminish for low pressure values and also for larger speed values.

• This means that high speed values, high temperature (up to a limit) and low Hertzian pressure improve the EHD lubrication regime by reducing the rheologic hysteresis.

Film thickness measurements using a SAE equipment for line contact show the presence of the rheological hysteresis phenomenon in the zone of the Hertzian lubricated line contact. In this zone of the Hertzian contact, pressure rises at very high values (up to 1.2 GPa) in very short passing times ($2\cdot10^{-6}$ s) so the lubricant transforms itself, from a newtonian fluid, in a quasi-solid with elasto-plastic properties similar with elastomers [4, 5, 9-12].

The authors would be grateful for any suggestions and shared experience.

APPENDIX

For the film thickness, we propose to change the presentation from this classical SKF form (in Figure A.2.1) to the one in Figure A.2.2.

The reasons for this modification are presented in [11].

The film percent (h%) was replaced with the term contact percent, C%, defined as:

$$C\% = \left(1 - \frac{h\%}{100}\right) \cdot 100 \tag{1}$$

There were also defined the next new parameters:

For the contact percent (formulas 2 – 7):

- **CD** is the absolute rheological contact deflection and $\boldsymbol{\Delta_{CD}}$ is the relative rheological contact deflection;
- **CDP** and $\boldsymbol{\Delta_{CDP}}$ are the absolute and the relative contact deflection related to pressure (along the pressure axis);
- **CDC** and $\boldsymbol{\Delta_{CDC}}$ are the absolute and the relative contact deflection related to contact percent (along the contact axis);
- $\boldsymbol{A_{CL}}$ is the aria of the contact hysteresis loop and $\boldsymbol{\Delta_{ACL}}$ is the relative aria of the contact hysteresis loop.

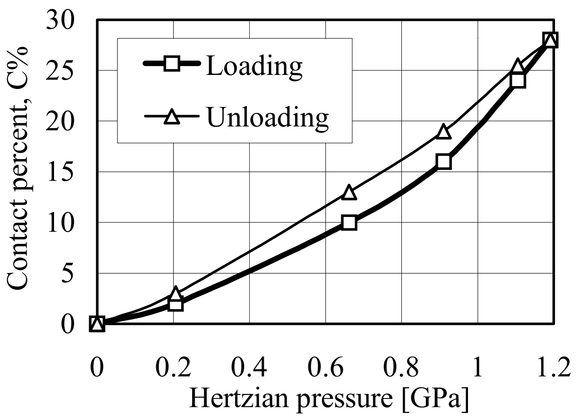

Figure A.1. Load influence on film contact

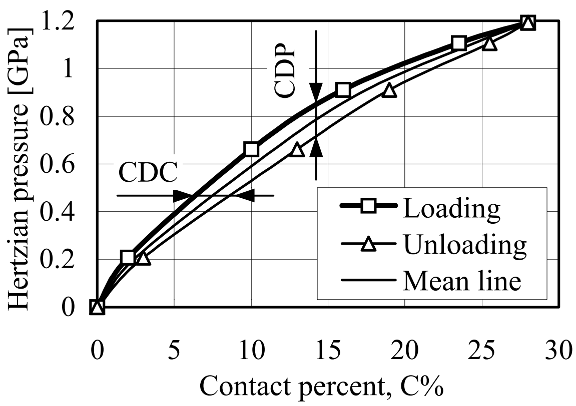

Figure A.2. Load influence on film contact (reversed axes)

There were defined the next new parameters:

$$\Delta_{CDP} = \frac{CDP}{P_{H,\max}} \tag{2}$$

$$\Delta_{CDC} = \frac{CDC}{C\%_{\max}} \tag{3}$$

$$CD = \sqrt{CDP^2 + CDC^2} \tag{4}$$

$$\Delta_{CD} = \sqrt{\left(\frac{CDP}{P_{H,\max}}\right)^2 + \left(\frac{CDC}{C\%_{\max}}\right)^2} \tag{5}$$

$$A_{CL} = \int_0^{P_{H,\max}} f_{CL}(p)dp - \int_0^{P_{H,\max}} f_{CU}(p)dp \tag{6}$$

$$\Delta_{ACL} = \frac{A_{CL}}{\int_0^{P_{H,\max}} f_{Cm}(p)dp} \cdot 100\ \% \tag{7}$$

The annotations used are:

- $P_{H,\max}$ is the maximum Hertzian pressure;
- $C\%_{\max}$ is the maximum contact percent (corresponding to the maximum pressure $P_{H,\max}$);
- f_{CL} is the functions that estimates the contact percent variation with pressure at loading;
- f_{CU} is the functions that estimates the contact percent variation with pressure at unloading;
- f_{Cm} is the function that estimates the mean contact variation with pressure.

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