AN ENERGY INVESTIGATION OF THE FLUID FRICTION INSIDE A LUBRICATING GREASE FILM

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ABSTRACT
This work compares the friction and wear behaviour of different types of lubricating greases. The focus is oriented to the fluid friction and the effects of this tribological stress (inside the grease). Rheometer tests were done to obtain experimental data. An analysis of the energetic situation of the modelled system is described by using irreversible thermodynamic aspects.

Keywords: Lubricating greases, fluid friction, wear, entropy

INTRODUCTION
One of the most given questions in Tribology is: how big is the share of friction energy that leads to a loss of material? There exist a number of empirical models that correlate friction and wear by consideration of material properties. And some of them show a direct proportionality between friction energy and loss of material.

The question that’s arises from this work is more into the direction: what is the reaction of a tribo-system during an energetic stress? What counts is the energetic situation. The system is situated in a thermodynamic equilibrium before the friction process starts. The friction energy that reaches the observed system leads to the exit of the equilibrium state. Different ways are possible to change (at least) into a stable state. That stable situation could be a stationary non-equilibrium. The initiation of additional dissipative processes is one possibility to neglect the energy distribution caused by the friction process.

DESCRIPTION OF THE ENERGETIC SITUATION
The observed tribo-system in this paper is a volume element of a stressed greases sample. The idea of fluid friction shows a sub-triobosystem of a higher-lever tribosystem. For example a mixed friction contact. State of fluid friction is defined as a friction process that is situated inside a lubricant.

It is interesting to investigation the structure of the greases. That means we are observing the thickener (behaviour) (Fig.1). The phenomenological effects of friction on the lubricant are well know. Prof.Franco et al. observe the change of the grease structure caused by friction simulated in a rheometer test [Franco, Fig.3]

What can be stated is an enlargement of the number of particles with a simultaneous decrease in volumes. One result is the change in the tribological properties. The question what are the driving forces and what the consequences leads to energetic investigation.
Fig. 1 - Oil covered thickener structure of a Li-model grease (window size=88µm)

Fig. 2 - Change of big agglomerates caused by friction (unstressed and stressed grease sample, window size=135µm)

Fig. 3 - Unstressed Li-model greases and stressed grease sample (AFM) [Franco]
As shown in a number of papers [Abdel-Aal], [Khonsari], [Bryant], [Kuhn] it could be helpful to analyse the system from a thermodynamic point of view.

Starting point should be the contemplation of the system entropy.

\[ dS = dSi + dSe \]  

(1)

It means the system entropy can be changed by two terms: the entropy production and the entropy flux. We have to note the important statement that

\[ dSi > 0 \]  

(2)

or in other form

\[ \rho \cdot \frac{ds}{dt} = -\nabla j_s + \gamma \]  

(3)

We want to shed light on the role of production and flow.

In the case of stationary non-equilibrium no time dependencies are detectable. And we found \( dS/dt = 0 \). Assuming the idea of Fig.4:

![Fig. 4 - Entropy transport for the observed thermodynamical system (stresses volume element)](image)

We rewrite the eq.(1)

\[ \frac{dS}{dt} = S_i(t) + SQ(t) + m_i \cdot se - m_i \cdot sa \]  

(4)

and obtained for energy stressability [Kuhn]

\[ e_R^* = T_f \cdot (\rho_{out} \cdot s_{out}) - \frac{T_f}{v_{out}} [m_{in} \cdot s_{in} - S_Q] \]  

(5)

What we see is a direct influencing of the entropy transport (linked with the degradation structure) on the stressability of the system (apparent frictional energy density \( e_R^* \)).
To investigate the role of entropy production the degradation theorem by [Bryant et al.] is used. It means we observe a system near the equilibrium what is given by assuming the stationary period of the tribological process. We define:

The process of structural degradation ($P_{st}$) as a dissipative process starts by reaching a critical energy level ($U_{crit}$) caused by a process of energy supply. This dissipative process depends on phenomenological time dependent variables ($P_E$). $P_{st} = P_{st}(U_{crit}(P_E))$

The production of entropy ($S_i$) is triggered by this dissipative process of exceeding a critical energy level ($U_{crit}$) caused by the same energy supply influenced by time dependend phenomenological parameter ($P_E$).

Forming a process rate.

$$\frac{dP_{st}}{dt} = \left[ \frac{\partial P_{st}}{\partial U_{crit}} \cdot \frac{\partial U_{crit}}{\partial P_E} \right] \cdot \frac{\partial P_E}{\partial t} \quad (6)$$

$$\frac{dS_i}{dt} = \left[ \frac{\partial S_i}{\partial U_{crit}} \cdot \frac{\partial U_{crit}}{\partial P_E} \right] \cdot \frac{\partial P_E}{\partial t} \quad (7)$$

Assuming a linear relationship (stationary state) Bryant et al. applied the terms generalized force $X_i$, generalized flow $J_i$, and he defined a degradation force $Y_i$. We find in Eq.(7) and (6) that the process rate can be written as a product of forces and flow ($X_i \cdot J_i$) and ($Y_i \cdot J_i$).

And it follows from eq.(6) and eq.(7) that

$$\frac{\partial P_{st}}{\partial S_i} = \frac{Y_i}{X_i} = B \quad (8)$$

B is called degradation coefficient (Bryant).

For the application of the degradation process of the thickener structure of greases some assumptions are helpful.
- We have to note that wear focused on solid bodies is measured as volume \( w_{v} \) of lost material.
- The structural degradation within the meaning of wear is observed as a growing number of solid units (particle).

After a strong time dependence, let us assume a linear change of particle number \( n_p \)

\[
I = \frac{dn_p}{dt} \quad (9)
\]

We want to continue to accept that friction energy is proportional to change in particles number.

\[
E_f \sim n_p \quad (10)
\]

and with the proportionality \( E_p \)

\[
dE_f = E_p \cdot dn_p \quad (11)
\]

the structural degradation intensity is found to be

\[
I = \frac{dE_f}{E_p \cdot dt} \quad (12)
\]

Investigating a single variable system we write

\[
\frac{dP_{st}}{dt} \left( \frac{dS_i}{dt} \right) = \frac{Y}{X} = B
\]

and we obtain

\[
\frac{dP_{st}}{dt} = B \cdot X \cdot Y \quad (13)
\]

Finaly we link the change of thickener structure with the entropy production term. And assume that the friction energy dissipated inside the subsystem into an exceeding of a critical level (without any chemical reactions) \( dU_{crit} = -dE_f \).

With

\[
\frac{dP_{st}}{dt} = B \cdot X \cdot Y = \frac{B \cdot \tau \cdot V \cdot dy}{dt} = \frac{dn_p}{dt}
\]

(14)

with \( P_E = \gamma \) and from eq.(11)

\[
\frac{dn_p}{dt} = \frac{\tau \cdot V \cdot d\gamma}{E_p \cdot dt}
\]

(15)

as a model to describe the structural degradation of lubricating greases, and delivers that

\[
E_p = \frac{T}{B}
\]
SOME EXPERIMENTS
Experiments were done with a rheometer to get information about the friction energy and heat evolution. A shear test is done in a rotational modus for 900s.

Fig. 6 - Expended energy for a shear test. Two Li-greases (NLGI2 circle and NLGI 0 square)

Fig. 7 - Measured change of temperature during the shear process of the greases.

For our studies these experiments help to estimate the term entropy production $S_i$. 

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The idea is to obtain a diagram like Figure 8:

![Diagram of entropy production](image)

**CONCLUSION**

The investigation of structural changes of a visco-elasctical lubricant leads to an observation of the energetic-stress-energetic release situation. We define a sub-tribo-system to describe the situation of a friction process inside the lubricant.

Tribo-systems are energy driven systems and what we observe are consequences of energy flow and energy transformations in defined control volume. What we recognize are the attempt of a system to delete (energetic) disturbances and to restore a stable situation. Often that state is a stationary –non-equilibrium. It could be helpful to use an entropy balance for an analysis of the energetic situation. To investigate the role of entropy production the degradation theorem of Bryant et al. is applied. The structural degradation of the grease structure is described as an increasing number of solid units inside the grease filmuc.

**ACKNOWLEDGMENTS**

The author is thankful to Ministry of Research and Education of German for the financial support.
REFERENCES


