Determination of Grease Life in Bearings via Entropy

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A Summary of the Final Report Submitted to NLGI

Executive Summary

Lubricating greases play a vital on the performance and functionality of nearly all tribocomponents such as bearings, gears, and the like. While some machine elements are grease-lubricated for life, many others require periodic replenishment to ensure that the mechanical component performs efficiently and to avoid premature failure. A grease's performance tends to degrade with use due to prolong shearing, evaporation, oxidation, etc.—akin to the well-known phenomenon of fatigue in mechanical systems. Thus, the determination of grease life is an important endeavor for both manufacturer —to gain a better understanding of the nature of degradation that leads to new and improved developments— and the users to ensure that tribocomponents are adequately lubricated.

This report provides the results of a potentially transformative approach in treating grease degradation modeling. The premise of this research is that degradation of grease is an irreversible dissipative process that ages the grease and affects the bearing performance. During normal operating conditions, as grease is sheared at contacts between rolling elements and raceways it experiences a breakdown of its thickener's structure due to the cumulative energy dissipation. This is an irreversible mechanism related to the production of thermodynamic entropy associated with the dissipative processes involved. This realization provides a powerful enabling tool for assessing degradation, aging, and evaluation of remaining useful life.

A team of researchers at LSU Center for Rotating Machinery developed the framework and methodology of applying the thermodynamic entropy to evaluate grease degradation. This report contains the results of significant accomplishments made far beyond the originally proposed expectations. Specifically, two papers were presented at 1999 NLGI Conference in Las Vegas. Of the corresponding papers appeared in NLGI Spokesman in January 2020, and the other is due for publication in March 2020. Both papers underwent peer review. Other articles were published in Peer-reviewed tribology journals such as Lubricants, Tribology Letters, and Tribology International. We believe that this research has been extremely productive and worthwhile and gratefully acknowledge NLGI's support with was augmented with additional resources from LSU Center for Rotating Machinery to make such enormous accomplishments to fruition.

<u>The text of contributed papers were submitted previously in the full report to NLGI. In this summary report, we provide a synopsis of the work accomplished.</u>

1. Predicting Grease Life with Entropy--A Practical Overview
2. The Use of Entropy in Modeling the Mechanical Degradation of Grease
3. Procedure for evaluating the mechanical degradation of a grease
4. On the assessment of mechanical degradation of grease using entropy generation rate
5. Experimental Investigation of the Chemical Degradation of Lubricating Grease from an Energy Point of View

Summary Report

on Determination of Grease Life in Bearings via Entropy

1. Introduction

The methodology and conceptual frame that entails the application of entropy to degradation problems involving grease were recently developed by a team of researchers at the Center for Rotating Machinery at Louisiana State University. The research involved the development of experimentally verified methodologies that can be reliably applied to analyze mechanical degradation of grease due to prolonged shearing under normal use in a typical tribo-component such as in ball and rolling element bearings. Extensive laboratory testing and analytical development have shown that this framework is extremely powerful and versatile. It is also worthwhile to mention that many leading researchers with specific expertise in grease have taken notice of this approach, and the results are gaining substantial attention worldwide.

1.1 Background

To set the stage for the project, we thought that it would be useful to, first, report the shortcoming of the current practices in evaluating grease degradation and describe the underlying features of the entropic characterization for evaluating the useful life of a grease. In our first report, we described that although there exist estimates for the life of grease in specific applications, and accepted methodology to predict the life of grease is still lacking. We then went on to describe how thermodynamic entropy can be utilized for this purpose for general readership who may not have expertise in irreversible thermodynamics and discussed how further research in this field can provide a useful tool for the grease industry. This paper was peer-reviewed and published in NLGI *Spokesman* in January 2020. To quote the comments of one reviewer: “Excellent manuscript and should be accepted as it is. It can be considered for both Application Award and Development Award, with Application Award first, in my opinion.”

1.2 Types of Degradation

Grease degradation can be broadly down into two regimes: physical degradation and chemical degradation. Physical degradation includes mechanical degradation of the thickener structure due to shearing, separation of the base oil and thickener, evaporation of the base oil, and contamination of the grease by foreign particles. Chemical degradation involves all chemical reactions that take place, including oxidation of both the base oil and thickener and the depletion of additives. Chemical degradation is dominant at higher temperatures and during long-term storage of grease. In contrast, mechanical degradation is typically dominant when a greased interface is subjected to shearing or working the lubricant at high speeds. This information can be visualized with Fig. 1. In practice, both chemical degradation and all types of physical degradation must

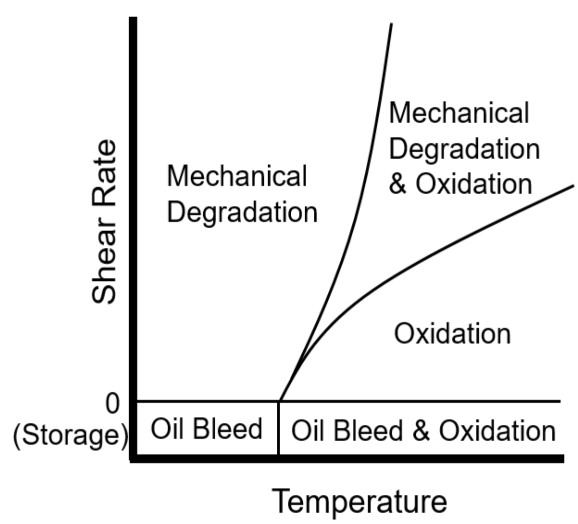
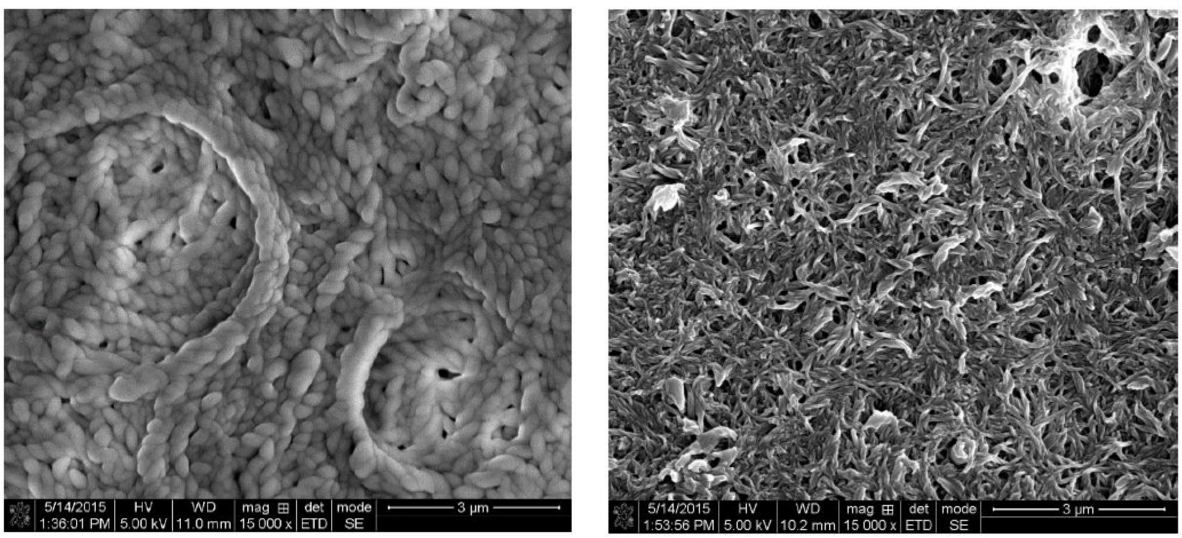


Fig. 1. Dominant degradation mechanisms

be considered, and their significance is heavily dependent on grease chemistry. Nevertheless, as long as the operating temperature is well below the oxidation temperature and there is no significant contamination or evaporation, one can assume that mechanical degradation is the main determinant of grease life for many common greases

Degradation is a central issue with the use of grease since it means a grease sample has a limited life. As grease is put to use, its thickener structure degrades, its base oil leaks and/or evaporates, both the thickener and base oil oxidize, and it tends to become contaminated with foreign particles. All these elements cause the grease's overall properties to change permanently. Eventually, the properties deteriorate so substantially from those of the pristine grease specified for its application that the degraded grease becomes unusable for its intended purpose and must be replaced. A key property that changes as a grease degrades is consistency: a measure of a grease's overall "firmness". Consistency generally determines a grease's suitability for a particular application and has a major influence on a device's performance. The destruction of the thickener can be visualized through microscopy such as AFM or SEM, and Figure 2 shows SEM comparing pristine grease to mechanically degraded grease. It clearly shows the breaking down of the structure after prolonged shearing action.



(**a**) (**b**)

Figure 2. SEM comparing (**a**) fresh and (**b**) mechanically degraded grease

1.3 Literature Survey

A more comprehensive paper that covers a literature survey with details of entropic characterization was published in the *Lubricant* Journal, which is available freely online. Table 1 provides a summary of notable work on grease degradation.

Table 1. Summary of literature relating entropy and the mechanical degradation of grease (For references, see Paper #2 in a comprehensive report submitted to NLGI)

Paper	Novelty	Remarks	Conclusions
Friction and Wear of a Grease Lubricated Contact [35]	Proposes a model describing entropy flow in a grease system	Measures energy dissipated, resulting in temperature increase	Provides detailed model of entropy flow within a model grease system
Correlation between Mechanical Degradation and Entropy [17]	First to model consistency reduction of grease using DEG theorem; establishes linear trend	Measures comparative penetration using rheometer; validated using grease worker and bearing tests	DEG theorem can be applied to grease using "net penetration" as the degradation measure
Correlation between Entropy and Structural Changes [18]	Provides new structural degradation model; proposes crossover stress as an indication of degradation	Uses dissipated frictional energy and temperature increase to calculate entropy generated	Structural degradation vs entropy supply shows different slopes at low entropy values
Tribological Stress of Lubricating Greases [19]	Compares mechanical structural degradation for different grease chemistries	Uses dissipated frictional energy and temperature increase to calculate entropy generated	Differences in grease chemistry lead to vastly different degradation behavior
Engineering Model to Estimate Consistency Reduction of Grease [20]	Proposes a method for predicting grease life that allows variable operating conditions; proposes failure as drop by one NLGI grade	Uses a model of shear stress over time with characteristic line to estimate grease life	Life prediction model shows agreement with experimental data
Mechanical Degradation of Lubricating Grease in an EHL Line Contact [24]	Identifies three distinct regions of grease lubrication	Rollers pressed together, exposing grease to high shear rates	Grease within EHL contact degrades very quickly but is held in place by grease walls
Model for Shear Degradation at Ambient Temperature [13]	Shows two phases of grease mechanical degradation; proposes an aging equation	Grease aged through Couette aging device at various shear rates; properties measured with a rheometer	Rapid degradation occurs initially followed by slower degradation; entropy concept validated
Master Curve for the Shear Degradation of Lubricating Greases [36]	Included the effect of temperature to previous results	Used Couette aging device with added temperature-controlled bath	Higher temperatures increase mechanical degradation; temperature component added to the previous model
Assessment of Mechanical Degradation Using Entropy Generation [21]	Explains two regions of mechanical grease degradation; proposes online degradation monitoring method	Uses torque meter to estimate entropy generated; estimates the time until grease drops by one NLGI grade	Mechanical degradation is akin to running-in followed by steady-state; steady-state is reached faster at low shear rates
Thermodynamics of Grease Degradation [23]	Includes thermal effects in DEG-based analysis	Measures work done in shearing grease	Grease life experiments well-modeled by DEG trajectories

2. Analytical approach: Irreversible thermodynamics and entropic characterization of grease

Irreversible thermodynamics refers to the second law of thermodynamics, which defines entropy, *S*, and necessitates that the entropy of the universe always increases. The generation of entropy means that this process is irreversible. For example, as a grease-lubricated bearing rotates, the grease sample between the moving parts is sheared, irreversibly breaking down its structure. This means that it will never again have exactly the same properties as it did initially. The use of entropy, therefore, offers excellent potential for describing degradation in general and is well-suited for lubricating grease.

A general framework for formulating degradation was developed and applied to problems involving wear and fatigue. Bryant, Khonsari, and Ling established the framework for this by proposing the Degradation-Entropy Generation (DEG) theorem, which introduces a degradation measure to be directly proportional to the entropy produced for each dissipative process that occurs. The theorem also establishes that if there is a critical value of degradation at which a failure occurs, there is also a corresponding critical value of accumulated entropy generation. This idea was then successfully applied to problems involving wear and fatigue, where the results consistently gave further support to the DEG theorem.

Our team showed how the irreversible thermodynamics could be applied to model grease degradation and experimentally validated the results. Specifically, we established that consistent with the DEG Theorem, a linear trend between penetration values (a measure of mechanical grease degradation) and entropy density generation (entropy generated per unit volume). Further, we showed that, in fact, one could use the results to estimate the useful life of a grease undergoing mechanical shearing operating under.

We have developed a methodology to evaluate the performance of the grease by continuously measuring the entropy generation rate from the values of friction torque and angular velocity. The proposed method enables continuous monitoring of degradation by measuring the entropy generation rate. A criterion is defined for grease replacement based on the measure of its consistency in terms of the NLGI grade level. The efficacy of the proposed methodology is demonstrated by conducting a series of experiments in a custom-built ball bearing testing apparatus.

3. Experimental test rigs and measurements

Three different NLGI grades of lithium-complex based greases shown in Table 2 are considered for the comparison and to test the proposed hypothesis. Further, to illustrate the proposed theory in the real-time application of the degradation criterion, experiments are performed on a ball bearing setup. Details of the rheometer and ball bearing setup are elaborated in the full paper submitted in the original report to NLGI. A representative summary follows.

Table 2 Properties of different grades

Grease	NLGI Grade	Appearance, color	Thickener	Viscosity @ 40°C (m^2/s) × 10^{-6}
XHP 222	2.5	Applesauce, Blue	Li-Complex	220
XHP 221	1	Soft, Blue	Li-Complex	220
XHP 005	00	Normal grease, Blue	Li-Complex	220

3.1 Rheological evaluation

Shearing and penetration tests on different grades of grease are performed using the Anton Paar MCR 301 rheometer (see Fig. 3). This rheometer is equipped with a rotating vane ~25 mm in diameter connected to the driving motor using a coupling. The shear test involves longer durations whereby the grease sample is placed in the gap between the rheometer vane and the stationary surface, and the sample is sheared for a long period of time at room temperature. The gap thickness is maintained constant throughout the experiment for 1.5 mm with zero penetration. During the experiments, the values of rheological parameters such as shear rate, shear stress, torque as a function of time are measured and recorded.

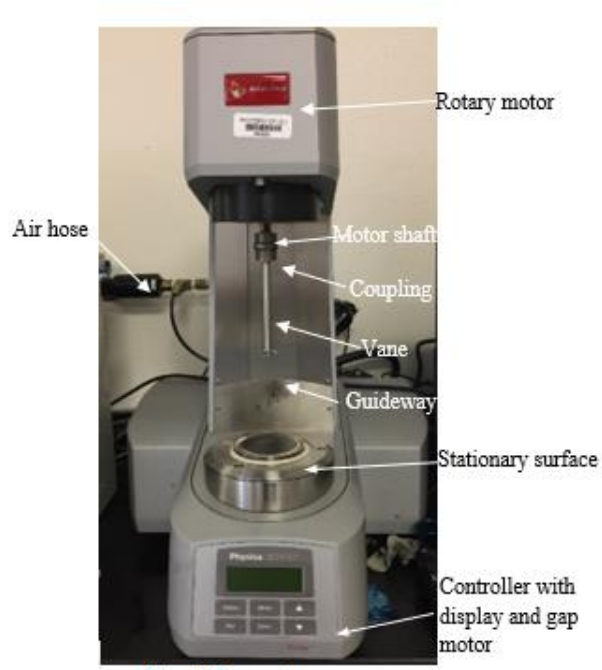


Fig. 3 Rheometer instrument

3.2 Ball bearing apparatus

A custom-built ball bearing apparatus designed in-house is utilized to analyze the degradation of the grease in a real-time application. See Fig. 4. The experiments are performed for 50 hrs, and the performance of the grease is evaluated by measuring the torque as well as acceleration. The setup consists of a 5 hp AC motor, two couplings, a torque sensor, an accelerometer, two ball bearings, a shaft, a data acquisition system, and a disk. A disk is attached at the end of the shaft to provide eccentric loading on the bearing.

An ICP Accelerometer of measuring rage ± 50 g, frequency range 0.5 Hz - 10 kHz and sensitivity 100 mV/g is used to evaluate the performance of the bearing by measuring its vibration. The accelerometer is placed on the casing of the ball bearing, and the measured values are saved onto the computer using NI 9234 and NI USB 9162 data acquisition system manufactured by National Instruments. A contactless torque sensor of 15 N•m capacity is attached between the rotating and motor shafts using the aluminum jaw couplings to measure the torque between the motor and bearings. The torque sensor requires the input of 12 VDC to 28 VDC supply and provides output in the range of ± 5 VDC. The value of torque from the torque sensor is acquired using 16-Bit NI USB-6210 multifunction data acquisition system.

4. Sample results and discussion

The first set of experiments involve testing Grade 2.5 grease for the shear rate and test duration provided in Table 2. The obtained penetration depth for different shear rates is plotted in Fig 4a. The penetration depth with respect to entropy generation density is plotted in Fig. 4b. The entropy generation density $S_{g,vol}$ is calculated using Eq. (1)

$$S_{g,vol} = \int_{o}^{t} \frac{\tau\dot{\gamma}dt}{T} \qquad (1)$$

where $\dot{\gamma}$ is the shear rate, τ is the shear stress, T is the temperature, and t is the time of operation.

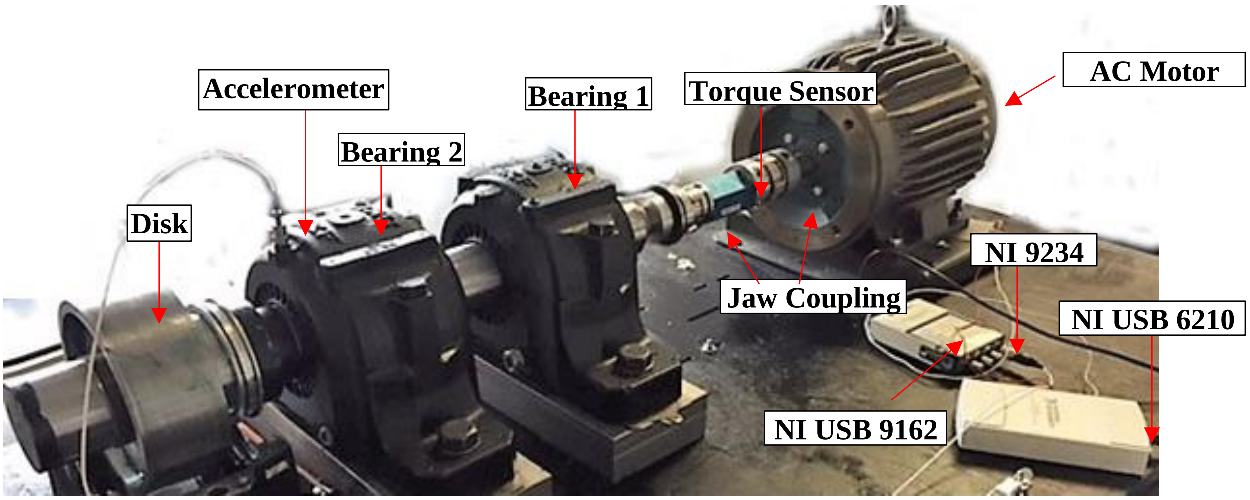
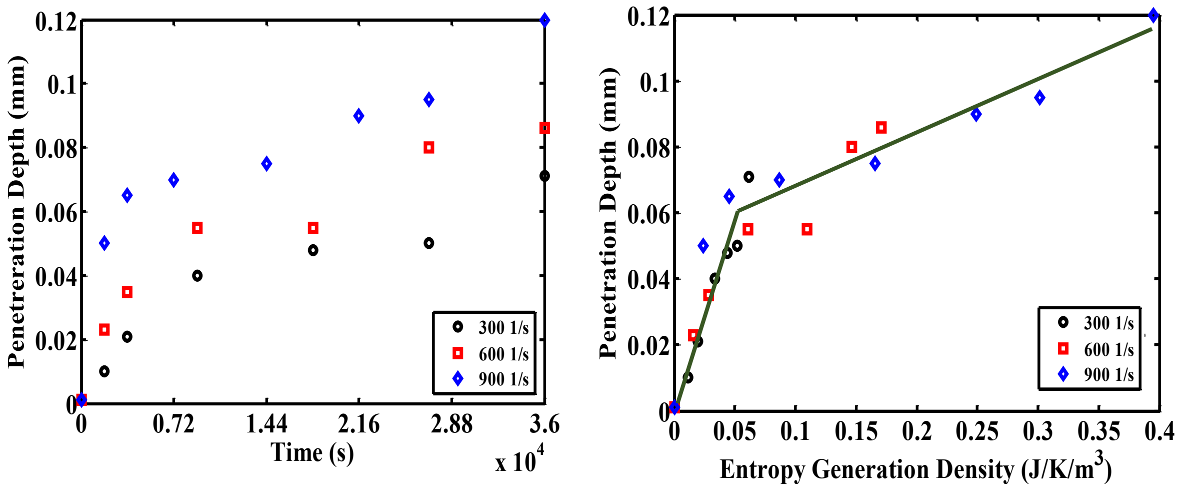
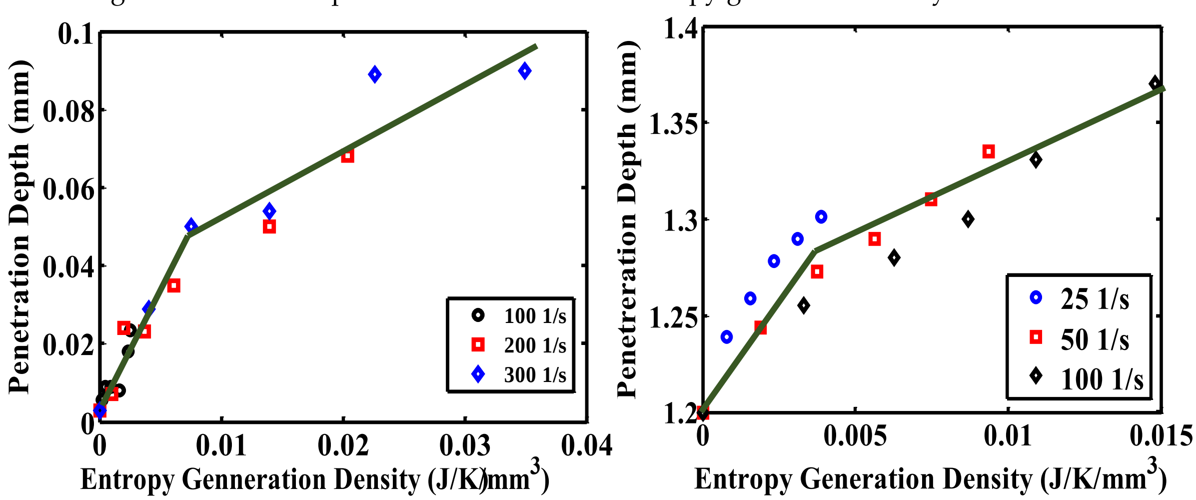


Fig. 4 Setup to analyze the grease performance



(a) Penetration depth vs time (b) Penetration depth vs entropy generation density

Fig. 5 Penetration depth at different time and entropy generation density for Grade 2.5



(a) Grade 1 (b) Grade 00

Fig. 6 Penetration depth with entropy generation density for Grades 1 and 00

We now proceed to investigate the physical mechanism of different rates observed in Figs. 5b and 6. For this purpose, the penetration data with time are analyzed by developing a curve-fit equation to the penetration data points for each shear rate and grades.

The variation of the penetration depth with time is akin to that of wear of a tribo-pair during its running-in period that involved transient and steady-state regimes, as shown in Eq. (2).

$$w_v = A\big(1 - exp(-Bt)\big) + Ct \qquad (2)$$

In this equation the first term on the RHS, $A\big(1 - exp(-Bt)\big)$, represents the transient wear behavior and the second term, Ct, represents the steady wear. Note that the steady state wear rate $\dot{w}_v = C$ is a constant, independent of time. Here, A and C are constants to be determined from experimental results. They are depended on the shear rate and grade of the grease. Considering the curve fit equation of wear volume w_v Eq. (2), the proposed equation for penetration depth δ is expressed in Eq. (3). Unlike wear volume of a tribo-pair, there exists a penetration depth value at t = 0, which represents the penetration depth of fresh grease. To characterize, a third factor D is introduced in Eq. (2) and represented as.

$$\delta = A\big(1 - exp(-Bt)\big) + Ct + D \qquad (3)$$

Additional results of the penetration depth values with time for different shear rates and for three grades of lithium greases are published in Paper #4 of the comprehensive report submitted to NLGI.

4.1 Measurement of entropy generation rate

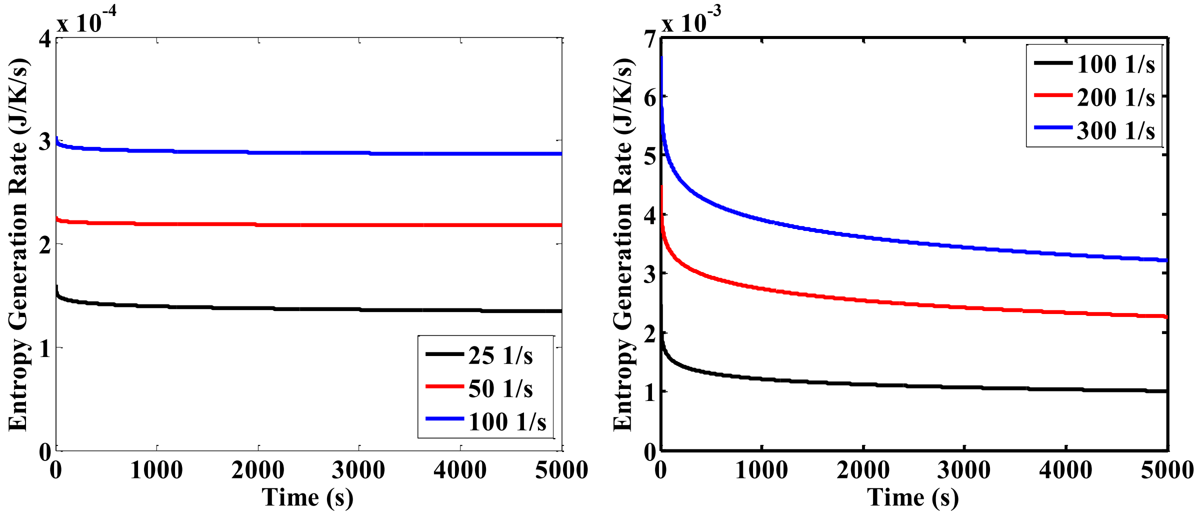
Penetration measurement is an indirect method for measuring the degradation of grease. It depends on the applied load during the test, quantity of grease, time of application of load, etc. In practical applications, stopping the machine and taking the samples for testing would result in a reduction of production time and cost. Further, the location at which the degraded grease samples are collected can impact the results. Therefore, an online measuring method to evaluate grease degradation is highly desirable. Here, instead of evaluating the grease performance using the penetration rate, an attempt is made to evaluate grease degradation by measuring the entropy generation rate. The entropy generation can also be determined from the product of frictional torque and angular velocity as a function of time t; see Eq. (4)

$$S_{g,i} = \int_0^t \frac{T_{or,i}\omega}{T}\, dt \qquad (4)$$

Note that the angular velocity ω is constant but the frictional torque changes with time, and it is represented as $T_{or,i}$. The instantaneous value of torque is directly obtained from the rheometer. For a field application, a torque sensor would be needed for this purpose. The measured entropy generation rate for Grades 00 and 1 greases are plotted in Fig. 7. Further development on an apparatus for measuring degradation and its associated details are reported in Paper #3 of the comprehensive report submitted to NLGI.

5. Experimental Investigation of the Chemical Degradation of Lubricating Grease

The chemical degradation/oxidation of lubricating grease is investigated experimentally from an energy point of view. A Pressure Differential Scanning Calorimeter (PDSC) is used to measure the activation energies of two lithium-complex greases and to monitor their chemical degradation through induction time. For this purpose, an experimental setup consisting of a heating chamber, a temperature controller, and an energy meter is designed, built, and calibrated to heat up grease samples and measure pure energy absorption during the chemical degradation at different test temperatures. A relationship between the energy absorption of the grease and its chemical degradation is established that is independent of the testing time and temperature. It is shown that the energy absorption of the grease approaches to an identical maximum value in a shorter time in high temperatures and a longer time in low temperatures. The maximum energy absorption depends on the grease type, and experimental results reveal that it can be used to estimate the grease chemical life. A roller tester rig is used to measure and compare the lubrication ability of two chemically degraded grease samples and to validate the results of the research. To gain further insight, experimental results are presented to examine the flow characteristics of a chemically degraded grease in an elastohydrodynamic (EHL) line contact with a comparison to that of the fresh grease.



(a) Grade 00 (b) Grade 1

Fig. 7 Entropy generation rate from curve fit for Grades 00, 1 and 2.5 greases

5.1 Roller bearing test apparatus

Fig. 8. Heating chamber designed for roller

Mechanical degradation of an EHL contact between two rollers was investigated using a roller tester machine that mimics the lubrication of gear teeth contact. Fig. 8 shows the grease chamber with the heating elements designed for this study. At the first stage of the test, the grease sample is chemically degraded inside the chamber at high temperature for a specific time (several hours) while the rollers are not touching each other and primarily serve as a "grease mixer." During this period, the lowest possible shear rate (0.025 m/s rolling speed, zero slide-to-roll ratio, and 3 mm gap between the rollers) was applied. Here, the grease sample is blended during the heating process to create oxygen exposure conditions for the whole grease sample, and the shear rate is kept low to minimize the mechanical degradation inside the grease sample. After the heating process, the heating elements are turned off and enough time is provided in order for the grease to cool down to the room temperature.

At the second stage of the test, the degraded grease —which is still in the chamber— is used to lubricate the contact between rollers and its lubricating ability is tested to determine the grease's remaining useful life. The rollers are loaded with a maximum Hertzian pressure of 0.7 GPa, and the rollers are rotating with the rolling speed of 0.065 m/s with a slide-to roll ratio of 1.3 at room temperature. The traction force between the rollers is monitored during the test. When the traction force increases dramatically, the test is terminated automatically by a built-in stopping mechanism that halts the motors to avoid damaging the rollers and the rig. This test was performed on Grease A at two temperatures of 180 ˚C and 210 ˚C. The heating period was 7 hours in both tests.

Reported in Paper #5 is a comprehensive method for the determination of a correlation between the chemical degradation of lubricating grease and energy. Two different Li-complex greases are chemically degraded inside the heating chamber of the experimental setup, and their energy absorption during the heating process was accurately measured. A theory is introduced based on the acquired experimental results. It is shown that the level of absorbed energy can be used to determine the state of chemical degradation regardless of temperature and time. A grease absorbs the same amount of energy when heated in a shorter time at a higher temperature or in a longer period of time at a lower temperature. It is shown that, for the tested greases, the plot of the energy absorption versus time always follows a power equation in the format of $\mathrm{E}(\text{energy absorption}) = a.(\text{time})^{b}$. The power curves are linear ($b \cong 1$) at lower temperatures and become nonlinear at higher temperatures. All the power curves are approaching a maximum energy absorption value when time goes to infinity. Physically, the maximum energy absorption value can be considered as the total energy given to the grease for it to burn completely and degrade to its final state when all its chemical compounds are decomposed. The maximum energy absorption values are calculated for tested greases and are compared to their measured activation energy. The predictions of the theory are verified using a roller tester rig. According to the power equations of Grease A, it absorbs the same amount of energy when heated for 7 hours at 210 ˚C or is heated for 8.5 hours at 180 ˚C. The same remaining lubricating life is measured by testing the two grease samples heated for 7 hours at 210 ˚C and for 8.5 hours at 180 ˚C in a roller test rig operating in line-contact EHL. This concept is useful for estimating the chemical life of grease at different temperatures.

Figure 9. Visualization of degraded (left) and fresh (right) greases in roller bearing

6. Concluding statements

This brief summary is offered as evidence that significant accomplishments were made, far beyond the originally proposed expectations. We gratefully acknowledge the support of NLGI for making this research possible. We believe that the research has paved the way for many researchers to follow and the society to benefit from the continuation of this research. We hope for the opportunity to further extend the enormous progress made in this research to tackle the very challenging problem of grease contamination.