**Assessing workability of greased bearings after long-term storage**

Michael VARENBERG1,*, Yuri KLIGERMAN2, Grigory HALPERIN2, Saad NAKAD2, Haytam KASEM2,3

1George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
2Department of Mechanical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel
3Department of Mechanical Engineering, Azrieli College of Engineering, Jerusalem 9103501, Israel

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**Abstract:** Here, we developed a technique to assess the workability of sealed-for-life greased rolling bearings after a long-term storage. In this framework, we devised a model of equivalent transition between the conditions of natural ageing under daily and seasonally fluctuating temperature, and the conditions of accelerated thermal ageing at a constant high temperature. The tested bearings were thermally aged, and then their steady state friction and outer ring temperature were examined in a custom high-speed spindle. These results were compared to the performance of a reference new bearing tested under the same loading conditions. Our findings suggest that long-term storage can significantly degrade the performance of sealed-for-life greased rolling bearings. However, a proper running-in can substantially deter the ageing-driven degradation of the bearings.

**Keywords:** grease lubrication; ball bearings; thermal ageing; lubricant degradation

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**1 Introduction**

The presence of a lubricant layer separating rolling elements, cages and raceways is a vital requirement for long-life and high-efficiency operation of rolling bearings. The most common lubricant applied today to rolling bearings is grease [1, 2], in part because replacing oil with grease can reduce sealing problems and enable simpler designs to be pursued.

Lubricating grease is a complex system consisting of oil, several additives and thickener. The actual lubrication is mainly provided by the base oil, which can be either mineral or synthetic. The additives are compounds used to improve both bulk and surface properties of the oil, such as resistance to oxidation [3] and interaction with a solid component surface defining the lubrication efficiency in a boundary lubrication regime [4]. The thickener consists of metallic soap molecules creating a fibre-based network structure [1, 3], which is able to hold the oil inside by a combination of physical and chemical forces [5, 6] and to slowly release it into the contact over a long period. The mechanism of the oil release is, however, still unclear, and there are works suggesting that the lubricating film is formed as a result of oil bleeding [7–9] or destruction of the soap matrix [10–12].

There are many applications, such as low-noise bearings, high-precision bearings or high-speed spindle bearings, that may require lifetime lubrication [13]. In such cases, bearing service life is defined by the grease degradation over time. This degradation (or ageing) manifests itself in a mechanical destruction of grease molecules within the contact zone, and in temperature-accelerated chemical changes that lead to the appearance of various deposits and oxidation products, to the alteration of viscosity and lubricity, and to oil bleeding, affecting both friction and wear [14–17]. Interestingly, though there were successful attempts to predict maximum period of reliable service of grease [18], due to a high complexity of the processes involved,
the effects of ageing are determined today solely based on experimental techniques.

The methods used can be generally subdivided into two categories. The first includes the tests of mechanically and thermally loaded greased bearings that are run until failure [19–21], which is usually determined by a certain change in the bearing temperature or the drive motor torque. Grease samples are taken from the different locations in the bearing both before and after failure, and changes in viscosity and chemical composition are assessed [22, 23]. The second category involves laboratory simulations of both mechanical and thermal ageing of grease [12, 16, 24]. Mechanical ageing can be modelled by forcing the lubricant through a sub-millimetre diameter capillary repeatedly [14]. Thermal ageing is most influenced by oxidation [15], and, in doing accelerated tests, the grease is heated in contact with actual solid, which may serve as a catalyst [1], while, as is generally accepted, a rise of 10 °C effectively doubles the rate of oxidation [15, 25, 26]. Laboratory simulations, however, are rarely analysed in relation to lubrication performance in real bearings [12, 15]. Another topic that did not receive much research attention is the effect of grease ageing on the operation of mechanisms designed for a very long storage [27].

In light of the above, the purpose of this work was to develop a technique to assess the workability of sealed-for-life greased rolling bearings after a long-term storage.

2 Accelerated ageing

2.1 Model of equivalent transition

Finding the correct conditions of accelerated ageing that is equivalent to a real storage requires taking into account the daily and seasonal temperature fluctuations in the storage area. Here, we show how a proper equivalent transition between the conditions of accelerated and normal ageing can be devised based on a generally acknowledged rule that a rise of 10 °C effectively doubles the rate of oxidation [15, 25, 26].

If we view ageing as an oxidative degradation reaction, and further assume that an incremental amount of reaction products, \(dP\), forms during the increment of time \(dt\) at a reaction speed \(V(T)\), when \(T\) is some given temperature, then we can write:

\[
dP = V(T)\, dt
\]

The total amount of reaction products, \(P_t\), formed during the storage time, \(t_s\), is then given by

\[
P_t = \int_0^{t_s} V(T)\, dt
\]

Based on the above rule of chemical reaction acceleration, the reaction speed \(V(T + 10)\) will be equal to \(k \cdot V(T)\), \(V(T + 20)\) will be equal to \(k^2 \cdot V(T)\), \(V(T + 30)\) will be equal to \(k^3 \cdot V(T)\), etc., where \(k\) is acceleration factor, and \(T_e\) is some reference temperature. This allows us to write a general expression for the reaction speed:

\[
V(T) = V(T_e) \left( \frac{T - T_e}{10} \right)^k
\]

Substituting Eq. (3) into Eq. (2) yields

\[
P_t = V(T_e) \int_0^{t_s} \left( \frac{T - T_e}{10} \right)^k \, dt
\]

Now, let us consider the two cases of accelerated and normal ageing, in which an equal total amount of reaction products, \(P_t\), should form. In accelerated ageing, \(P_t\) is expected to form at the constant equivalent (relatively) high temperature \(T = T_e\) held during the short (accelerated) period of time \(t_s = t_a\). In this case, Eq. (4) becomes

\[
P_t = V(T_e) \left( \frac{T_e - T_e}{10} \right)^k \int_0^{t_a} \, dt
\]

In normal ageing, \(P_t\) forms at the time-dependent (relatively) low temperature \(T = T(t)\) fluctuating during the long (normal) period of time \(t_s = t_n\). In this case, Eq. (4) becomes

\[
P_t = V(T_e) \int_0^{t_n} \left( \frac{T(t) - T_e}{10} \right)^k \, dt
\]

Finally, combining Eqs. (5) and (6) yields

\[
t_s = \int_0^{t_s} \left( \frac{T(t) - T_e}{10} \right)^k \, dt
\]

Thus, knowing the daily and seasonal temperature fluctuations, \(T(t)\), and the duration of normal storage,
Given that the sealed-for-life greased rolling bearings used in this work (see Section 3.1 for details) are limited to the temperature of 149 °C, we performed accelerated ageing at the equivalent temperature, $T_e$, of 143 °C to work at sufficiently high but safe temperature. Plugged into Eq. (7), these data yielded a total accelerated ageing time, $t_a$, of 105 hours (Fig. 2).
The signals going into the data acquisition board are measured using a K-type thermocouple connected to an amplifier ITMA2003 (Red Lion Controls, York, Pennsylvania), and a load cell LRM200 (FUTEK Advanced Sensor Technology, Irvine, California) connected to a strain gage amplifier AE101 (HBM, Darmstadt, Germany).

### 3.3 Test procedure

Each test sequence began with assembling the examined bearing on the spindle, fixing the thermocouple to the outer bearing ring and applying the axial load of 400 N. Then, the tests were run at speeds of 12, 24, 36, 48, 60, 72, 84 and 90 krpm. At each speed the tests continued until steady state conditions of temperature and friction moment were reached. Then the data was saved and the system was accelerated to the next speed level. The tested bearing was considered to have failed when the friction moment and the outer ring temperature started rising sharply. In this case the experiment was stopped.

### 4 Results and discussion

Figure 4 shows a characteristic chart of the friction moment and the outer ring temperature recorded as a function of rotational speed with a brand new bearing. It is evident that each increase in rotational speed results in the temperature rise. The reason for this is that, regardless of the main mechanism of energy dissipation, be it either sliding of the cage against the other bearing components or a viscous deformation of the grease [28], more heat is generated when the rolling distance increases. Obviously, the bearing that rotates faster moves a greater distance during the same time and, hence, generates more heat.

The changes in friction moment are not monotonic, with the friction signal fluctuating around the same value during the normal operation of the tested bearing. These fluctuations can be associated with local running-in due to changes in working conditions and with different processes dominating the bearing operation at different speeds, as explained below. The bearing failure seems to be initiated by the temperature increase, which leads to a steep rise in friction when
the temperature reaches the threshold value of about 150 °C that is specified as the highest allowed temperature by the bearing manufacturer. At the time of failure, both the temperature and the friction moment grow rapidly until either the test rig is stopped or the mechanical fuse/clutch between the motor and the spindle is broken.

The average friction moment and outer ring temperature measured with aged and new bearings in the steady state at different rotational speeds are presented in Fig. 5. Observing the behaviour of the reference new bearing, we see that friction first decreases and then starts increasing with increasing speed. This may be explained in the following way. At low speeds, such reasons as the temperature-driven reduction of the grease viscosity or a growing centrifugal force and the related cage deformation leading to a decrease of the contact area between the balls and the cage may dominate the frictional behaviour. At high speeds, the effect of constantly growing temperature and corresponding thermal expansion leading to the growth of the contact area and more intensive frictional interactions between the bearing components may become more significant, with a temperature of about 50 °C being a threshold for the change in behaviour. Along this line of thought, it should be mentioned that the presence of an external heat source might also have a tremendous effect on the bearing behaviour. We have learned during preliminary tests that, at the transition from 48 to 60 krpm, the front spindle bearing, whose housing was designed to have a sliding fit, slightly moves forward. This leads to a significant relaxation of the stresses generated due to a thermal expansion of the shaft and a subsequent decrease in the spindle bearings’ temperature. Since the test bearing is assembled on the same shaft at the distance of only 25 mm from the front spindle bearing, both friction moment and temperature of the tested bearing are also affected significantly by this relaxation as can be seen in Fig. 5.

The behaviour of the aged new bearing differed significantly from that of the reference new bearing. The temperature increased much more steeply with the rotational speed, so the aged new bearing came to the critical temperature of about 160 °C already at 48 krpm and failed at 60 krpm, not being able to reach its maximum designed operational speed of 71 krpm. The friction moment of the aged new bearing was lower than that of the reference bearing at the low rotational speed, but, being governed by the sharply rising temperature, surpassed the reference values already at 36 krpm, well before approaching its speed limit of 60 krpm. Given that most of the mechanical energy expended in bearings is dissipated through the
cage sliding and the lubricant film deformation [28], this behaviour is clearly associated with the grease ageing, as a result of which oil molecules are damaged via carbon-carbon chain scission due to thermal decomposition [15, 22, 23]. These changes lead to lower temperature and friction at low speeds, but interfere with the grease’s ability to protect surfaces from direct contact at higher speeds. Presumably weaker bonds between the oil molecules and the working surface let the protective grease layer be removed more easily, which results in earlier bearing failure under extreme loading.

A very interesting result was obtained with the bearing that was run-in under low loads and speeds before ageing. Surprisingly, despite being aged, this bearing demonstrated similar temperatures and friction moments to those of the reference new bearing, and was even able to operate at higher speeds, eventually failing at 90 krpm as opposed to 84 krpm, at which the reference bearing failed. This result can probably be explained by noting that the churning of excess grease and the smoothening of raceways [29] are further supported by the mechano-chemical modification of the topmost surface layers that can also take place during running-in. The mechano-chemically modified layers can be less sensitive to the oil composition [30] and can allow for a proper operation even with a significantly degraded grease. The latter assumption, however, is yet to be verified, though the main finding remains the same: new greased-for-life bearings have to be run-in [31] before they go to a long-term storage.

5 Conclusion

The paper shows that it is possible to find a consistent equivalent transition between the conditions of natural ageing under daily and seasonally fluctuating temperature, and the conditions of accelerated thermal ageing at a constant high temperature. The test results obtained with artificially aged and reference new bearings suggest that long-term storage can significantly degrade the performance of sealed-for-life greased rolling bearings. It is also evident that a proper running-in performed prior to the long-term storage can substantially deter the ageing-driven degradation of the greased bearings.

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Michael VAREMBERG. He has received his Ph.D degree in mechanical engineering from Technion-Israel Institute of Technology in 2004. He joined the George W. Woodruff School of Mechanical Engineering at Georgia Tech in 2014. He is currently an assistant professor and the head of Tribology & Surface Engineering Lab. His research areas cover friction and wear of engineering surfaces, micro/nano tribology, bionic tribology, tribological instrumentation, and contact mechanics.
Yuri KLIGERMAN. He received his D.Sc degree in mechanical engineering from Technion-Israel Institute of Technology in 1997. He was with Surface Technologies Ltd., Haifa, where he was responsible for developing analytical models for tribological components with laser-textured surfaces. Since 2000, he has been a laboratory engineer with the Faculty of Mechanical Engineering at Technion. Dr. Kligerman is an adjunct senior teaching fellow. He teaches in courses on theory of elasticity and contact mechanics. Dr. Kligerman has coauthored 48 scientific papers. He participated in a scientific guidance of 25 graduate students. His current research interests include hydrodynamic lubrication, surface texturing, contact mechanics, adhesive friction, and bio-tribology.

Grigory HALPERIN. He received his Ph.D degree in mechanical engineering from Saratov State Agrarian University in 1972. He joined the Department of Mechanical Engineering at Technion-Israel Institute of Technology in 1992 and served as a senior tribologist until he retired in 2016. His research area covered all aspects of experimental tribology, with a particular interest in friction, lubrication and wear of engineering surfaces, laser surface texturing, and tribological instrumentation.

Saad NAKAD. He received his B.Sc and M.Sc degrees in mechanical engineering from Technion-Israel Institute of Technology in 2009 and 2015, respectively. During his M.Sc studies, he joined the Tribology Laboratory as a research assistant. He joined MotoRad LTD as an R&D and validation laboratory manager in the field of automotive advanced engine and thermal management in 2014. In 2018 he joined Lumenis Medical Devices as a product leader.

Haytam KASEM. He received his M.S degree in mechanical engineering from the University of Haute Alsace in Mulhouse, France, in 2004. He received his Ph.D degree in tribology of composite materials from the University of Orleans, France, in 2008. He joined the Tribology Laboratory at Technion, Israel, in 2012 and the Azrieli College of Engineering in Jerusalem, Israel, in 2013. His current position is an assistant professor. His research areas cover the tribology of bionic microstructures, biotribology, mechano-chemical surface treatment and tribology of friction brakes.