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TRIBOLOGY & LUBRICATION TECHNOLOGY

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STLE 75 1944-2019

Unstoppable Wind Turbines

Why they keep growing in numbers, capacity and physical size.

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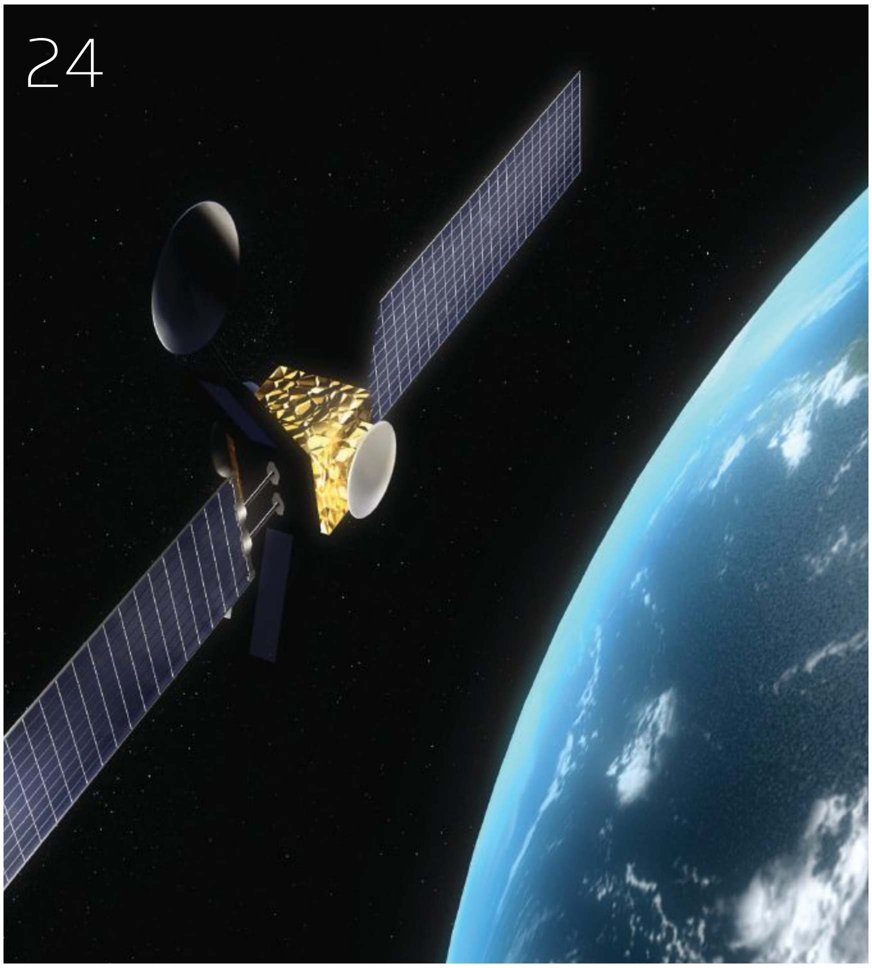

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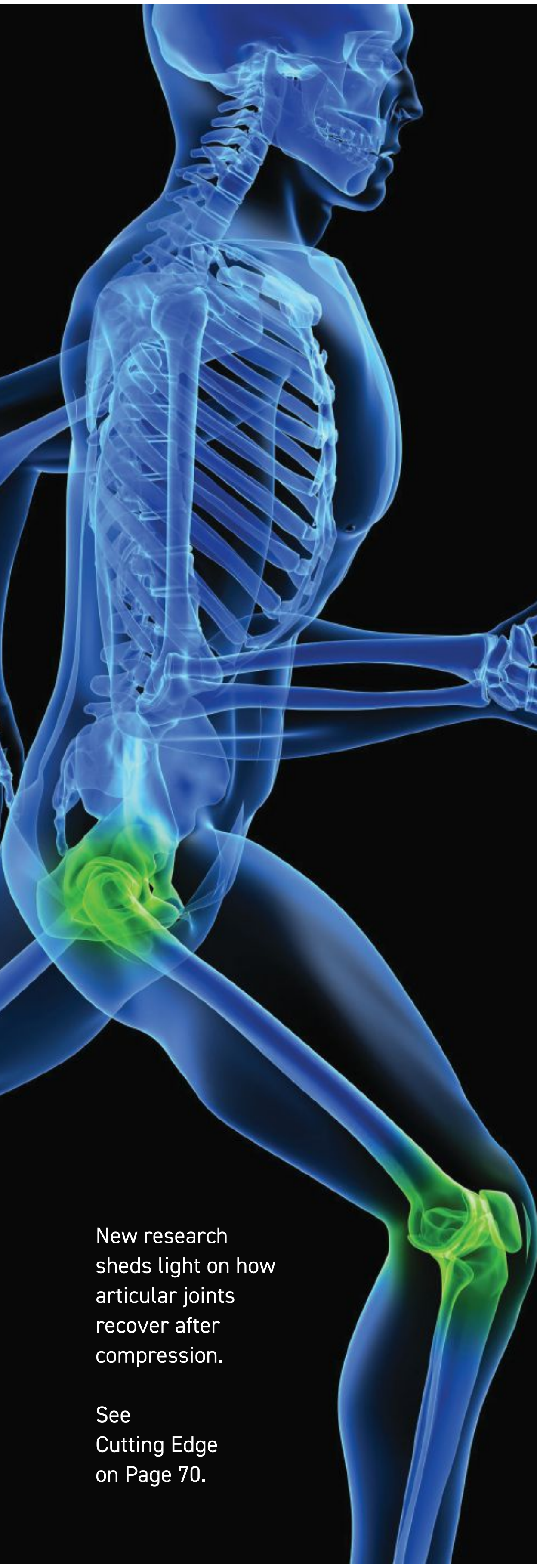

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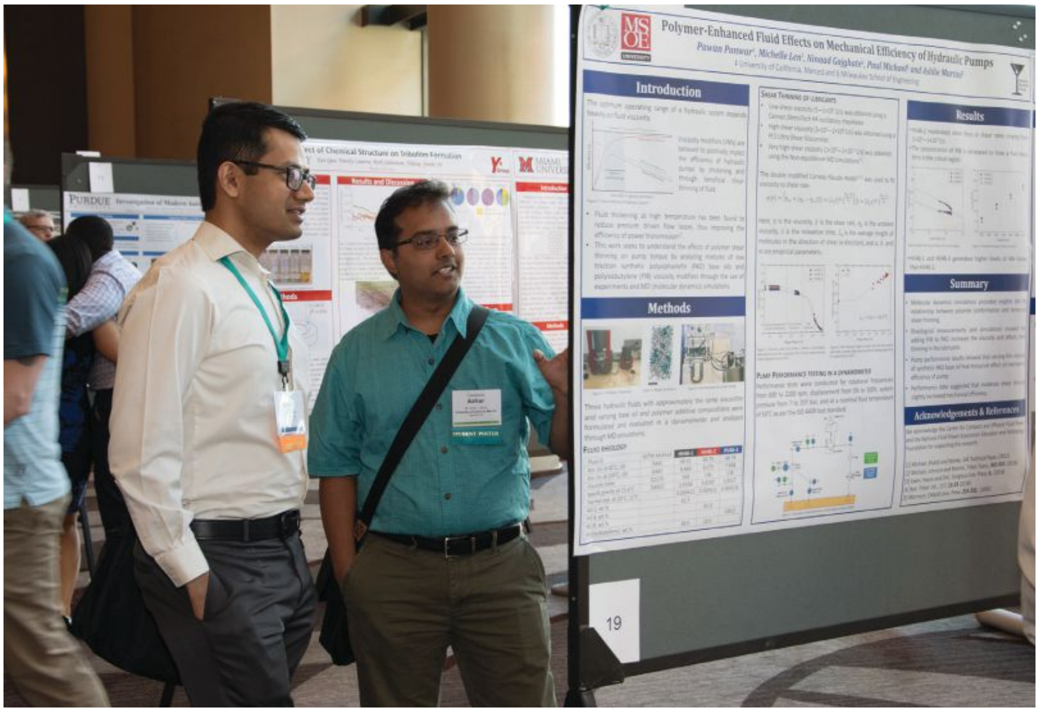
Follow STLE on:

The New Generation Gap

We must continue educating young people about the role our products play in making the world a better place.

By Michael P. Duncan



Whether you're in industry or academia, encourage your younger employees or students to get involved in STLE.

One of our strategic goals for the STLE board of directors is to communicate with the general population (people not familiar with tribology and lubrication engineers) in order to inform and advocate the merits of our organization for the betterment of society. With that in mind, I would like to share a conversation that my son and I had a few years ago.

My son came home after a day at school during his freshman year of high school and said to me, "Dad, you're a chemist, right?" I said, "Yes," and he continued, "You make stuff that is bad for the environment?" I thought for just a second because I knew he was taking a course in school on the environment. I responded with, "My company wouldn't stay in business if I didn't consider the effect of our products on the environment. Yes, we produce chemicals, but we are a responsible producer. We minimize waste and follow all laws and regulations regarding air and water emissions and possess the necessary licenses and permits to operate.

"Also, our products extend the life of cars, trucks, planes, trains and heavy machinery exponentially, thus reducing the need for additional energy. If we didn't manufacture chemicals for this purpose, we would be irresponsible to the environment. We are always trying to find better ways to manufacture our current products. We also work with our customers to develop cleaner, greener and longer-lasting products."

We need to be better advocates for our profession.

He looked at me and said, "Well, that is good then," and walked away.

Obviously we need to remember that learning happens everywhere, not just in the classroom. And, obviously, we need to be better advocates for our profession.

My advice to you—connect with our younger generation in some fashion, and the earlier the better. Perhaps just talk with your children or grandchildren in the car on a family vacation or a young relative at a family get together. Consider getting involved in a local STEM activity in your community. Volunteer to be a science fair judge in your local town or city. Encourage a younger employee to become more active in an STLE local section. Our younger STLE members seem to be able to better understand and connect to the younger generation.

In addition, STLE Past President Maureen Hunter is heading up a poster contest for children as part of our year-long 75th Anniversary celebration that culminates at the 2020 Annual Meeting & Exhibition in Chicago. There are four age divisions ranging from four to 18, and you can learn more details, including how to enter, on Page 55. Keep your eyes open for further information of this activity.

Have a great summer.

Mike Duncan is vice president of technology of Daubert Chemical Co. in Chicago. You can reach him at ***mduncan@daubert.com.***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Grease (in)compatibility

Just say, 'No!'

By Evan Zabawski

Photo courtesy of Evan Zabawski.

Compatibility charts do not contain enough data to properly determine compatibility between two products but may provide a quick reference for known incompatibilities.

"Are these two greases compatible?" is a question that is not answered simply by referring to a grease-compatibility chart. Such charts vary in both terminology and data but also do not represent a conclusion determined by comprehensive testing. Even so, existing standards may not completely fill that void.

Some of the variations in terminology for the thickeners are minor and not likely to cause confusion, such as clay versus bentonite clay. Others, like stearate, 12-hydroxy and 12-hydroxy stearate, are not clear that they refer to the same lithium- or calcium-based thickener. These differences can make it difficult to match the terminology from the packaging or product data sheet to the compatibility chart.

The data is often presented as a matrix, with trinary recommendations (compatible, incompatible and moderate/borderline compatibility). The variances between two charts are easily explained with an example: suppose the current grease is a clay-based grease from Company A, and the new grease under consideration is a lithium-based grease from Company B.

Company A's chart may list clay/lithium as incompatible, while Company B's chart may say it is compatible. Neither chart is wrong, though neither may be right. The problem lies in the proprietary nature of the data. Company A's chart is comparing Company A's clay-based grease with Company A's lithium-based grease, and Company B's chart is comparing Company B's clay-based grease with Company B's lithium-based grease. But neither chart shows Company A's clay-based grease with Company B's lithium-based grease.

These charts are generally not based on an exhaustive regimen of testing but, rather, only the structural stability of mixtures of different thickeners. They also do not address any performance characteristics of the grease mixtures, nor do they identify any base oil or additive differences or incompatibilities. Compatibility charts simply do not contain enough data to properly determine compatibility between two products but may provide a quick reference for known incompatibilities.

Even if two different greases of the same thickener type were being compared, the base oil itself must be taken into consideration. The base oils could have different viscosities that might lead to increased friction or wear, but they also could be different oil types. Some of the API Group V synthetics, in particular, are not compatible with other mineral and synthetic base oils.

However, even if the thickener, base oil type and viscosity are identical, there is still a potential issue for the additives to be incompatible with each other or some metallurgies. A common example would be using a non-EP grease and switching to an EP grease; there is a possibility that the EP additive could interfere with the performance of other surface-active additives like rust inhibitors or that the EP additive could be reactive toward yellow metals (brass or bronze) in contact with the grease.

One method used to determine compatibility is ASTM D6185; this standard prescribes performing a series of tests on three different mix ratios: 50:50, 10:90 and 90:10. The standard describes evaluating the mixture to confirm there is no significant decrease in dropping point, the mechanical stability remains in range and the consistency remains in range after heating.

While this provides a standardized approach, the greases are not really put into completely realistic working conditions. As such, certain additive properties like rust and corrosion protection or wear prevention cannot be evaluated without requesting extra testing not required by the standard. Still, this is far better at unveiling potential incompatibilities that would not be seen by visual inspection alone.

Evidently, compatibility charts cannot be relied upon as the sole source to confirm compatibility, but even standardized testing could be expanded to uncover more potential issues between two greases.

Evan Zabawski, CLS, is the senior technical advisor for TestOil in Calgary, Alberta, Canada. You can reach him at ***ezabawski@testoil.com****.*

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Charting our future

Work is under way. Please help STLE collect data for the 2020 edition of our Emerging Trends Report.

By Edward P. Salek, CAE
Executive Director

STLE's Report on Emerging Issues and Trends in Tribology and Lubrication Engineering, informally known as the Trends Report, has gained a reputation for identifying current and future developments in the field since it was first published in 2014. A second edition, released in 2017, continued to capture the interest of individuals and companies in the tribology and lubricants business sector, as well as other stakeholders in academia, government and the general public.

STLE and others have used the report to facilitate a conversation on a global scale through conference presentations in North America, Europe and Asia and at individual meetings with corporate members. The report has helped to identify and predict the impact of important technologies and areas of concern as they relate to the field, industry and even society and the world economy.

Work is underway on a third edition of the Trends Report with a target release date of early 2020. The research is being directed by a blue-ribbon Advance Innovations team of STLE members chaired by Thomas W. Scharf, professor in the department of materials science and engineering at the University of North Texas. McKinley Advisors (Washington, D.C.) is again serving as research and data analytics consultant as well as providing overall project management.

The third edition builds on the previous trends and conclusions but also has been refocused and reorganized to reflect the rapid pace of change affecting all areas of relevant technology. As a result, the 2020 report has consolidated application sectors into four high-interest topics: transportation, medical and health, energy and manufacturing.

Work to date has identified more than 140 trends for consideration in these four sectors. The Advance Innovations team has been supported in this analysis by 20 invited experts from industry, academia and government labs. Transportation yielded the highest number (57) with considerable interest surrounding the implications and opportunities presented by electric and self-driving vehicles but also developments in internal combustion engines.

Work to date has identified more than 140 trends in the report's four target sectors: manufacturing, transportation, energy and medical and health.

"Improving lubricants and additives in response to unique torque performance of electric motors. They have a much higher torque and lower RPM than internal combustion motors, and the lubricants we have today weren't designed to deal with that," is how one expert characterized the impact of EV technology.

Part two of the 2020 report examines 80 trends in five field discipline areas, a section that includes three holdover topics (workforce issues, government regulations and safety, the environment and basic human needs) and two new topics (research funding and materials cost and availability).

That last topic was added to incorporate new challenges that have emerged since the Trends Report series began in 2014. For example, "A potential lithium shortage for the grease market has an indirect impact on lithium batteries in electric vehicles. How much will that restrict the growth of electric vehicles?" wondered one expert.

The research funding discussion has revolved around the fact that tribology is not a "buzz word" to get research money from public or private sources, especially in the U.S. "We have to sell tribology differently, incorporate it into different topics. What we would need is success in a field that doesn't have a solution yet, like osteoarthritis. That would bring us back on the map," is how one individual framed the issue.

The next phase for the 2020 Trends Report is collecting data through a general survey of STLE members this month and September. The Advance Innovations team invites STLE members to support the project and take the opportunity to contribute their expertise to this important research project. They survey questionnaire asks members to rate the significance of trends and to comment on their future impact.

Data analysis and editorial work on the 2020 Report will occur in the fourth quarter of this year in advance of the target release date early next year. In the meantime, all TLT readers have the opportunity to download a free copy of both the 2017 and 2014 reports from **www.stle.org**.

*You can reach Certified Association Executive Ed Salek at **esalek@stle.org.***

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ADDING UP®

Developing a hybrid heavy-duty truck

By Dr. Neil Canter
Contributing Editor

Current battery technology does not enable an all-electric heavy-duty truck option to be viable.

KEY CONCEPTS

An approach developed for a hybrid heavy-duty truck uses a spark ignition engine with a battery.

The spark ignition engine was preferred over a diesel engine because it can produce lower emissions when used with a flexible fuel such as a combination of gasoline and an alcohol.

Researchers proposed several options to boost performance and reduce emissions, including running the truck at a high compression ratio, using pre-chamber jet ignition and alcohol-enabled high-performance exhaust recovery.

The movement to commercializing alternatives to the internal combustion engine has focused on light-duty vehicles. This column has shared different research approaches such as batteries and fuel cells.

With the growth of hybrid electric vehicles, attention again is being paid to improving efficiency. In a previous TLT article,[1] a real-time energy-management system was devised to optimize the use of the battery pack and the internal combustion engine. A reinforcement-learning energy management system was used to maximize efficiency. This system also was given the ability to learn through a reward-by-action factor. In a commuter study done in Southern California, this reinforcement model reduced fuel consumption by 12%.

In contrast, there has been limited development of a hybrid heavy-duty truck *(see Figure 1)*. Dr. Leslie Bromberg, principal research engineer in the Plasma Science and Fusion Center at the Massachusetts Institute of Technology in Cambridge, Mass., says, "Efforts are underway to produce an all-electric heavy-duty truck. We believe this approach will be extremely challenging because the truck would require between 10 and 15 tons of batteries that would add excessive weight and be costly. Both size and weight would limit the payload the truck could carry and limit its driving range."

> 'We are looking for the SI engine to operate in the sweet spot that is optimized by use of high-octane fuel.'

Consideration should be given to finding an alternative to trucks using an internal combustion engine, because such vehicles contribute two gigatons of carbon dioxide emissions globally of the seven gigaton emissions attributed to all vehicles. Bromberg believes the only logical alternative is to develop a concept for a hybrid heavy-duty truck that relies on both batteries and an internal combustion engine.

A new approach to produce a hybrid heavy-duty truck concept has now been developed by Bromberg and his co-author and research scientist Dr. Daniel Cohn.

Spark ignition engine

Bromberg and Cohn outlined an approach for the development of a hybrid heavy-duty truck that uses a spark ignition (SI) engine in combination with a battery. They provided options that can be used to further enhance the performance of this heavy-duty truck.

One interesting strategy used by the researchers was to not use a diesel engine but, rather, to propose that a flexible fuel gasoline-alcohol spark ignition engine be the preferred choice. Bromberg says, "We believe the SI engine has advantages over a diesel engine in running cleaner with lower levels of emissions, particularly when combined with a flexible fuel that can be a combination of gasoline and an alcohol (either methanol or ethanol)."

Diesel engines typically run at higher fuel efficiencies than gasoline engines. The researchers believe that this disadvantage can be overcome by optimizing the operating conditions of the hybrid heavy-duty truck.

Bromberg says, "In our approach, we are looking for the SI engine to operate in the sweet spot that is optimized by use of high-octane fuel." Two strategies to optimize the SI engine include running at a compression ratio of 14 that is higher than the typical ratio of 10 and using a smaller gasoline engine. The latter case will reduce the amount of fuel required which will save weight."

Bromberg says, "To achieve this objective, the SI engine will need to operate under higher temperature conditions than the diesel engine. This will lead to an exhaust emanating from the gasoline engine at a higher temperature (700-800 C) than for a conventional diesel engine (400-500 C)."

In Bromberg's opinion, the higher operating temperature will represent a challenge to the lubricant industry to develop an engine oil that will be able to handle severer conditions than what are currently experienced. In their modeling,

Figure 1. **A concept for a hybrid heavy-duty truck that contained a spark ignition engine and a battery was devised that has the potential for excellent performance while minimizing emissions.** *(Figure courtesy of the Massachusetts Institute of Technology.)*

the researchers determined that the SI engine delivers the same power (380 kilowatts) as a diesel engine.

The high compression ratio increases the likelihood of engine knocking. Bromberg says, "We proposed in our modeling to include two fuel tanks in the hybrid heavy-duty truck. One fuel tank would be gasoline while the second fuel is an alcohol that exhibits a high-octane value. The two fuels can be blended to the desired ratio to minimize knocking without adding too much weight."

Pre-chamber jet ignition also is proposed by the researchers to maintain high efficiency. Bromberg says, "This approach can increase the combustion rate while minimizing engine variability from cycle to cycle."

An intriguing option offered by the researchers is to use the flexible fuel option built into their modeling to propose alcohol enabled high performance exhaust recovery. Bromberg says, "Alcohols have the property when exposed to temperatures between 200-300 C and in the presence of a catalyst to decompose into hydrogen and carbon monoxide. The process is endothermic and can readily be conducted under the high temperature engine operating conditions. The hydrogen-rich gas can be reintroduced into the engine leading to potentially a 10%-15% increase in efficiency."

The inefficiencies of the generator/motor can be compensated by the increased energy recovery using the endothermic reforming of the alcohols.

In contrast, the engine gas recirculation (EGR) system present in a diesel engine will not be necessary with the SI engine and its absence also improves efficiency.

From the battery perspective, Bromberg is not as concerned about the type as the size. He says, "We developed our approach with the feeling that a 200-kilowatt sized battery will be required."

The researchers are conducting further modeling to optimize the engine size and the battery. Bromberg says, "We hope to propose this idea to the automotive industry as an approach for introducing electrification to heavy-duty trucks."

Additional information can be found in a recent presentation[2] or by contacting Bromberg at **brom@psfc.mit.edu**.

REFERENCES

1. Canter, N. (2016), "Improving the Efficiency of Plug In-Hybrid Electric Vehicles," TLT, **72** (5), pp. 16-17.
2. Cohn, D. and Bromberg, L. (2019), "Flex Fuel Gasoline-Alcohol Engine for Near Zero Emissions Plug-In Hybrid Long-Haul Trucks," Presented at the SAE World Congress & Exhibition in Detroit, Mich., on April 11, 2019.

New thermoelectric material based on cobalt

A theoretical study is underway to use spin caloritronics to identify an oxide based on cobalt, nickel and zinc.

KEY CONCEPTS

A theoretical study is being conducted to identify superior thermoelectric materials based on cobalt, nickel and zinc oxides.

The objective is to find a transition metal oxide that combines the benefits of the conventional thermoelectric effect with a contribution from the spin thermoelectric effect.

Initial work found that a combination of 25% zinc and 75% nickel in the tetrahedral configuration of the transition metal oxide produced superior performance.

The inefficiency of machinery such as automobiles is continuing to lead researchers to identify materials that can convert waste heat into electricity. Automobiles are a prime example because 60% of fuel efficiency is lost due to waste heat *(see Figure 2)*.

Thermoelectric materials are known to convert heat into electricity by using a temperature difference such as observed at the tailpipe of an automobile where there is a significant difference in the temperature of the automotive exhaust and the ambient temperature. The challenge is to improve the efficiency of thermoelectric materials to enable the process to be commercially viable.

In a previous TLT article,[1] researchers developed a new approach for producing a thermoelectric material than taking advantage of a temperature gradient. A new thermoelectric material containing randomly dispersed platinum nanoparticles in a nickel matrix utilized the inverse spin Hall effect to create an electric voltage. Electricity was generated by taking advantage of the difference in the magnetic properties between the ferromagnetic material, nickel and a normal metal, platinum.

'Cobalt oxide is an appealing material to work with because other transition metals such as nickel can be substituted without an issue.'

Dr. Anveeksh Koneru, senior lecturer in mechanical engineering at the University of Texas Permian Basin in Odessa, Texas, is focused on trying to determine how to increase the figure of merit (ZT) for a thermoelectric material. He says, "ZT is a unitless, non-dimensional parameter that is directly related to the efficiency of a thermoelectric material. A higher ZT directly correlates to a better performing thermoelectric material."

ZT is directly proportional to the Seebeck coefficient and the electrical conductivity of the material while inversely propor-

Figure 2. **Theoretical studies are underway to develop a superior thermoelectric material that could potentially convert waste heat produced during internal combustion into useful electricity.** *(Figure courtesy of The University of Texas Permian Basin.)*

tional to the thermal conductivity. Koneru says, "Most materials encountered exhibit both strong electrical and thermal conductivity. Finding a material with strong electrical conductivity but weak thermal conductivity is very challenging. One other factor is that the temperature of the system can impact the efficiency of the thermoelectric material. In moving from a temperature of 300 K to 700 K, the efficiency of the thermoelectric device can exhibit a five-fold improvement in efficiency."

Koneru believes that ZT can be increased further by incorporating the spin of electrons in polarized materials through the use of the inverse spin Hall effect. This is known as spin caloritronics. He says, "The spin Seebeck effect should allow the harnessing of extra voltage in addition to the conventional voltage generated by the thermoelectric material. A key factor is that any change in the Seebeck coefficient leads to a four-fold improvement in ZT."

The spin Seebeck effect is derived from the difference in the number of electrons with their spins in the upward direction compared to the number with their spins in the downward direction. Koneru envisions a model for a thermoelectric material that combines the conventional thermoelectric effect with a contribution from the spin thermoelectric effect.

Koneru is in the process of conducting theoretical studies using supercomputers to identify a superior thermoelectric material.

Oxides of cobalt, nickel and zinc

In a recent presentation[2] where their initial results were shared, Koneru and his colleagues discussed the use of spin caloritronics to develop an oxide based on cobalt, nickel and zinc that displays superior thermoelectric properties. Koneru says, "Cobalt oxide is an appealing material to work with because other transition metals such as nickel can be substituted without an issue. Our objective is to work with different percentages of cobalt, nickel and zinc in order to optimize the characteristics of the thermoelectric material."

The three metals have different properties with respect to magnetism and electrical conductivity. Cobalt and nickel are both magnetic and conductive while zinc is neither magnetic nor conductive. Differences in the magnetic properties may enable the band gap between electron states to increase leading to better thermoelectric properties.

The researchers are devising between 1,000 and 1,500 configurations of cobalt, nickel zinc oxides that are evaluated theoretically for band gap, lattice parameter, the effective mass of conduction electrons and spin polarization. The challenge is to find a material that maximizes the difference in the population densities of electrons in the upward spin state compared to the lower spin state. Koneru says, "A perfectly symmetric system with equal number of electrons in both states is not desired. The more asymmetry between the two electron spin states will lead to a better spin thermoelectric effect."

The researchers are substituting nickel and zinc atoms for one of the three cobalt atoms in the transition metal oxide. Koneru says, "We found that a combination of 25% zinc and 75% nickel in the tetrahedral configuration of the transition metal oxide produced optimum performance in our initial calculations."

Koneru considers this to be a sweet spot but is looking at other configurations in the future, including those based on manganese and iron. He says, "We also are going to take a close look at how the thermal conductivity parameters can be minimized to also increase ZT."

Additional information can be found in the recent presentation and by contacting Koneru at **anveeksh.koneru@utpb.edu.**

REFERENCES

1. Canter, N. (2017), "Transverse Thermoelectric Device," TLT, **73** (3), pp. 12-13.
2. Hines, N., Resende, G., Girondi, F., Boadi, S., Musho, T. and Koneru, A. (2019), "Substitutional Effects of Bivalent Zn and Ni Cations on Spin Thermoelectric Properties of Co_3O_4," Presented at the Materials Research Society Meeting in Phoenix, Ariz., on April 22, 2019.

Redox flow batteries: New approach may boost performance

A newly developed electrolyte known as CVBH shows promise in redox flow batteries.

KEY CONCEPTS

A close analogue to a natural material known as Amavadin holds promise as a non-aqueous electrolyte for redox flow batteries.

The analogue known as CVBH displayed excellent stability in cyclic voltammetry and static cell testing.

Better solubility was achieved in polar solvents by reacting CVBH with other cations.

A good deal of attention has been paid to the development of batteries for use as a power source in machinery such as automobiles. This column has focused on providing updates on efforts to commercialize lithium-ion and other battery types.

The steady development of renewable and carbon-neutral energy sources such as wind and solar power has been ongoing at the same time. One challenge in working with these technologies is to figure out how to continue to supply energy when the wind is not blowing and the sun is obscured by clouds. Storing energy when excess electricity is generated for use during downtimes is a feasible option.

Redox flow batteries have been identified as a potential energy-storage device. In a previous TLT article,[1] a new type that uses a non-aqueous electrolyte was discussed. The electrolyte is based on a series of multimetallic clusters known as polyoxometalates with a hexavanadate core. In evaluation testing, the researchers found that this electrolyte enabled the redox flow battery to exhibit superior stability without a reduction in charge carrier performance.

In contrast to a lithium-ion battery, the charge-carrying species in a redox flow battery are in solution. Patrick Cappillino, assistant professor of chemistry and biochemistry at University of Massachusetts Dartmouth in Dartmouth, Mass., says, "The potential of a redox flow battery to act as a storage device is based on the ability to increase the size of battery's storage tank to boost energy storage. This compensates for redox flow batteries having only 20% of the charge density of a lithium-ion battery but shows there is a need for improvement."

As mentioned in the previous TLT article,[1] non-aqueous redox flow batteries (NFRB) are desired because of a limitation on the voltage potential for aqueous electrolytes. Cappillino says, "Water has a thermodynamic limit of 1.23 volts because at that point oxidation will generate oxygen creating operational problems. A similar scenario occurs below 0 volts where hydrogen is generated and occasionally needs to be bled off. Moving to a non-aqueous solvent provides much more flexibility as there are a wide variety of options to choose from including gamma valerolactone which has an electrochemical window of 8 volts, which is more than six times higher than the thermodynamic limit of water."

CVBH does not become unstable in comparison to other vanadium-based species.

Another important factor in working with a NFRB is the use of vanadium. Cappillino says,

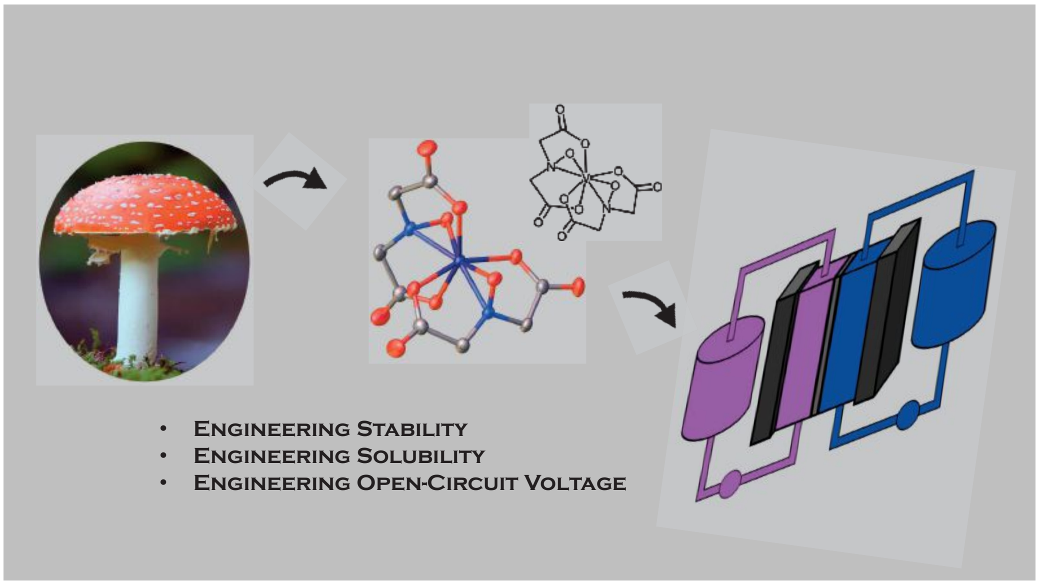

Figure 3. **A new non-aqueous electrolyte that has a high affinity for vanadium was developed based on a natural material found in a mushroom and displays potential for use in redox flow batteries.** *(Figure courtesy of the University of Massachusetts Dartmouth.)*

"This element is used because of its many stable oxidation states. In the operation of a redox flow battery, during charging, vanadium (3+) is converted to vanadium (2+) in one half-cell and vanadium (4+) is converted to vanadium (5+) in the second half cell."

A new vanadium-based species inspired by a natural product has now been synthesized and shows superior stability for use in a NFRB.

CVBH

Cappillino and his colleagues have developed a new vanadium based non-aqueous electrolyte that is inspired from a natural material found in the poisonous Amanita mushrooms. The material is known as Amavadin and exhibits an extremely strong affinity to chelate vanadium for an unknown biological function.

Cappillino says, "Our interest in Amavadin originated because one of the precursors of this material is vanadyl $(acac)_2$ which exhibits interesting electrochemical properties and has been implemented as a NFRB active material but has experienced challenges with instability. In evaluating Amavadin, we modified a synthetic process for making a close analogue known as calcium (II) vanadium (IV) bis-hydroxyliminodiacetate (CVBH). The process is straightforward, uses inexpensive starting materials and can readily be scaled up."

Figure 3 shows the steps taken by the researchers in developing the idea from the *Amanita* mushroom, synthesizing CVBH and then evaluating it as an electrolyte in a NFRB.

The researchers evaluated CVBH's electrochemical properties by using cyclic voltammetry and in static cell cycling and flow cell cycling. Cappillino says, "CVBH demonstrated excellent stability in cyclic voltammetry over 800 cycles as there was no sign of a decrease in peak current and no changes in reversibility. Even the addition of 20% water (by volume) to the system did not lead to a decrease in performance."

Cappillino noted that other vanadium-based species such as vanadyl $(acac)_2$ exhibit rapid hydrolysis in the presence of water. He says, "These species form vanadyl (V=O) moieties that are readily detected by analytical spectroscopy techniques. Due to their high stability, this decomposition mechanism is shut down in the mushroom-inspired compounds."

In static cell testing, no decomposition was seen over 100 cycles and 95% conversions were achieved with bulk oxidation and bulk reduction. Flow cell cycling was conducted in collaboration with Ertan Agar, assistant professor of mechanical engineering at the University of Massachusetts Lowell in Lowell, Mass. Cappillino says, "In this process, a 1:1 mixture of vanadium (IV/V) was prepared. During discharging, vanadium (IV) was oxidized at the negative electrode while vanadium (V) was reduced at the positive electrode."

The researchers observed that almost all of the capacity was retained after hundreds of cycles. Further analysis by UV-Vis spectroscopy indicated that the concentration of CVBH remained stable.

Cappillino says, "CVBH appears to be more stable than other vanadium-based electrolytes but its solubility is limited to only a few non-aqueous solvents such as dimethyl sulfoxide (DMSO) which was used in this study."

To improve solubility, Cappillino's group has reacted CVBH with other cations. He says, "We found that these new species display better solubility in polar solvents such as tetrahydrofuran and acetonitrile."

Additional information can be found in an article[2] published in 2017, a recent article[3] that was just published or by contacting Cappillino at **pcappillino@umassd.edu.**

*Neil Canter heads his own consulting company, Chemical Solutions, in Willow Grove, Pa. Ideas for Tech Beat can be submitted to him at **neilcanter@comcast.net.***

REFERENCES

1. Canter, N. (2018), "Non-aqueous Redox Flow Batteries," TLT, **74** (5), pp. 20-21.
2. Huang, H., Howland, R., Agar, E., Nourani, M., Golen, J. and Cappillino, P. (2017), "Bioinspired, High-stability, Nonaqueous Redox Flow Battery Electrolytes," *Journal of Materials Chemistry A*, **5** (23), pp. 11586-11591.
3. Gokoglan, T., Pahari, S., Hamel, A, Howland R., Cappillino, P. and Agar, E. (2019), "Operando Spectroelectrochemical Characterization of a Highly Stable Bioinspired Redox Flow Battery Active Material," *Journal of the Electrochemical Society*, **166** (10), pp. A1745-A1751.

Xiaolan Ai

This Timken scientist discusses bearing fatigue life and the advantages of virtual bearing testing.

By Rachel Fowler
Managing Editor

Xiaolan Ai at the patent wall of the research lab.

Xiaolan Ai
The Quick File:

Dr. Xiaolan Ai received his bachelor's of science and master's of science degrees in mechanical engineering from Tsinghua University, Beijing, China, in 1984 and 1986. He earned his doctorate in mechanical engineering from Northwestern University in Evanston, Ill., in 1993. Ai joined The Timken Co. in 1995 as a principal engineer and later became a research specialist and then a senior product development specialist. He is now in the lead scientist role.

Ai is a prolific inventor and one of the go-to experts of The Timken Co. He has wide research interests in bearing fundamentals, tribology, electromechanical systems, transmissions and powertrains. He is instrumental in broadening and advancing the company's engineering analysis capabilities. He initiated and led the development of a comprehensive virtual bearing life test model which, among other unique and desirable features, established for the first time the ability to quantify the impact of steel cleanliness on bearing performance.

Ai has authored 61 peer-reviewed journal papers and book chapters. He holds 60 patents (38 U.S. and 22 foreign) and has a dozen pending patent applications. Ai's invention covers areas of bearings, sensors, cutting tools, traction drives, gear drives and motor drives.

Ai is a Fellow of the American Society of Mechanical Engineers (ASME). He served as section editor of rolling element bearings for Encyclopedia of Tribology and associate editor for ASME Journal of Tribology from 2012 to 2018.

TLT: Why is modeling such an important tool in bearing useful life prediction, and how does it work?

Ai: The damage mode of rolling element bearings varies widely. It depends on bearing design, manufacturing, handling, installation, maintenance and operating conditions. The ultimate damage mode, however, in a well-designed, quality-built, carefully maintained rolling element bearing is fatigue damage.

For the great majority of applications, rolling element bearings are selected based on their load ratings, which are closely associated with fatigue life performance. Thus, the ability to predict bearing fatigue life is of paramount importance. Physic testing played a very important role in establishing bearing ratings and an equally important role in product quality assurance.

Due to its statistical nature, bearing fatigue testing is a very time-consuming and costly exercise. It requires multiple bearings (usually 24 or more) with essentially identical attributes to be tested under the same load, speed and lubrication conditions. The test may last for several weeks or even months. As bearing size increases, the cost of physical testing quickly skyrockets. For large and ultra-large bearings, such as those used for the main shafts of wind turbines, physical bearing life testing is often cost prohibitive. This creates a pressing need to develop a means to conduct virtual bearing life testing (VBLT). An example of a VBLT model is shown in Figure 1. It can be viewed as a digital representation of an actual physical test where the test bearings and rig are modeled numerically through a layered structure to ensure the required resolution and computational efficiency. The model contains more than a dozen individual modules to describe various aspects of bearing performance attributes.

VBLT starts with finite element (FE) modeling of the test rig from which the loads acting on each of bearings are obtained *(step a in Figure 1)*. Detailed FE models of the test bearings are built with a finer mesh grid where load distribution at the contacts between the rollers and raceways is esti-

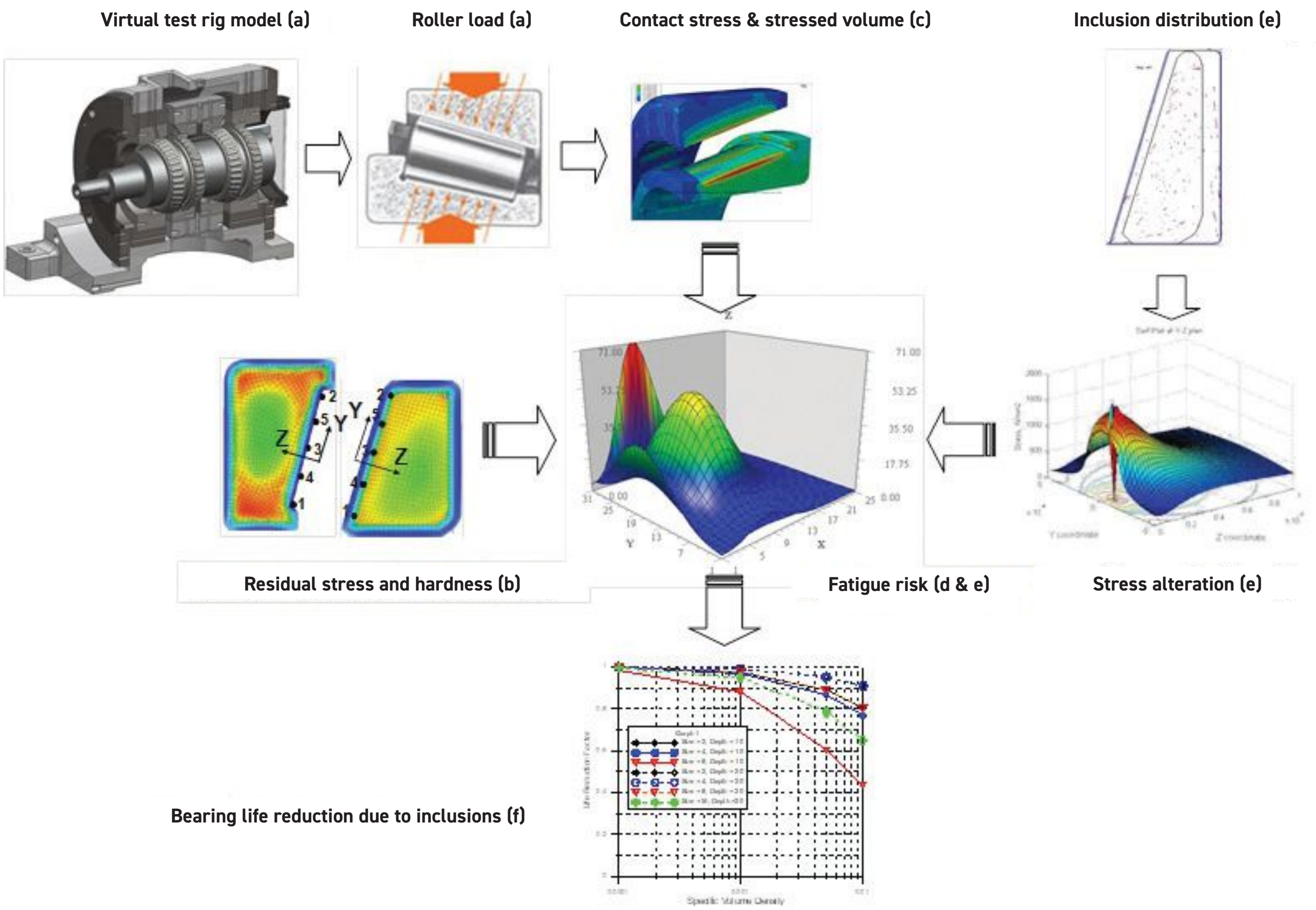

Figure 1. **VBLT model structure and computational work flow.** *(Copyright by ASME: A Comprehensive Model for Assessing the Impact of Steel Cleanliness on Bearing Performance," by Xiaolan Ai, Journal of Tribol. 2014; 137(1).)*

mated *(also step a)*. Roller loads are then passed on to a contact module where detailed contact analysis is performed for surface and subsurface stress distributions at each of the contact locations *(step c)*.

The model includes a heat treatment module to model the material's response to different heat treatment processes. This module provides the resultant residual stress distributions and hardness profiles within the bearing components *(step b)*. A fatigue risk assessment module then combines the contact stresses and residual stresses to generate a critical stress, which is compared to the material strength to establish the risk of fatigue damage at the given point. The fatigue risk assessment module further integrates fatigue risk over the entire stressed volume of the material for all bearing components to derive an estimate of bearing life based on a three-parameter Weibull statistical distribution *(step d)*.

To consider the impact of surface roughness on bearing fatigue life, a rough contact module calculates contact stress fluctuations for a given load level using the measured 3D surface topography of the bearing raceway surfaces. An effective stress correction function is derived based on Miner's Rule of damage accumulation using the resulting stress fluctuations and is subsequently applied to the contact stresses of smooth surfaces subjected to the same load level.

Additional modules have been developed for calculating the stress alterations resulting from inclusions within the material or surface indentations on the bearing raceways. The inclusion module reads in inclusion information—including inclusion size, location, material property and orientation for every inclusion found within the bearing components—and calculates stress alterations within a super cell surrounding the inclusion.

The super cell is usually set at approximately 10 times larger in volume than the inclusion it encapsulates. The original stress field is then modified by substituting the super cells at their respective locations *(step e)*. The fatigue life of the bearing is re-evaluated using the modified stress field. A relative life with respect to nominal life can thus be obtained *(step f)*.

A similar methodology can be applied to the surface indentation module from which a life reduction factor due to the surface indentations is estimated for the dented bearings.

Through careful calibration with test data, VBLT, as a first principle-based model, can be extended to cover different bearing size and types, and to model different test conditions quickly with high fidelity. It not only provides an alternative to large and ultra-large bearing tests but also is a cost-effective means for conducting life tests on conventional sized bearings.

TLT: What are the main advantages and challenges in virtual bearing testing?

Ai: As mentioned, one of the main advantages is cost effectiveness. It allows application engineers anywhere to conduct bearing tests under various application scenarios quickly with minimum cost. In addition, it allows research and design engineers to conduct what-if studies to gain better insight into various factors that affect bearing life performance. This, in turn, could lead to improved bearing designs to achieve application objectives.

Bearing fatigue life modeling is by no means an easy task. The statistical nature of bearing fatigue indicates there are a host of influential variables that affect bearing life performance; some of them are still not yet fully understood or well controlled.

One of the challenges in bearing fatigue modeling is material microstructure response to stress cycles. To a certain extent, our current knowledge is still primarily experimental and phenomenon based. A unified damage mechanism across different material types and microstructures needs to be further explored. A computationally effective material response model applicable to all bearing steel material is yet to be established and validated.

TLT: What's your view on the emerging powertrain technologies and their impacts in the next 10-15 years?

Ai: We are in an era of rapid change. We are currently at a converging point of several mega trends. Cyber-physical systems are a common theme across many industries. They call for product digitization, connectivity, intelligence and flexible automations. Concurrently, the automotive industry is experiencing a major transformation of electrification. This technical trend was originally driven by energy conservation and environmental concerns and more recently has been fueled ▶▶▶

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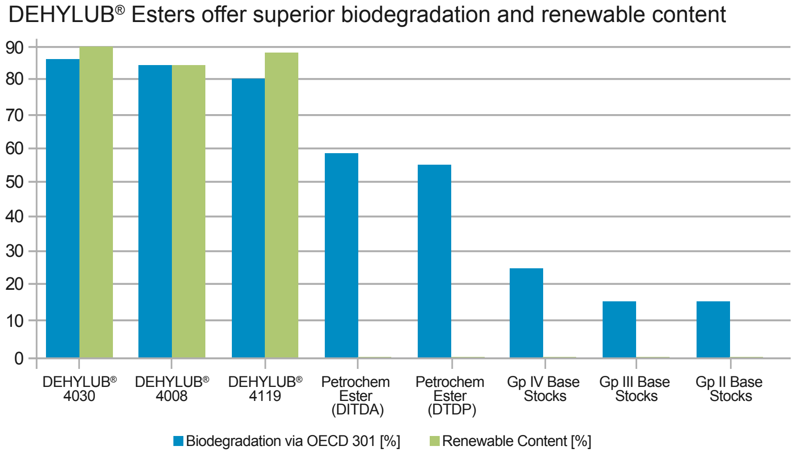

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by the rapid advancements in autonomous and artificial intelligence technologies. It is expected that the process of transformation will last for the next few decades. This transformation is also occurring in other mobile industries.

As we are embracing the new powertrain technologies and enjoy the many benefits they bring to society and end-users, we must also be prepared for the impact they bring upon manufacturing processes and component suppliers. For the bearings industry, this imposes challenges but also creates new opportunities. Bearings in electrified powertrains are required to operate at higher speeds and under thin lubricant film conditions to reduce friction and drag losses. Housing material, lubrication method and operating temperature also are expected to change. System noise, vibration and harshness (NVH) and thermal management become critically important.

> **Cyber-physical systems are a common theme across all industries.**

To meet these challenges, rolling element bearings may need to be specifically engineered to attain the performance attributes of precision, quietness and higher fuel efficiency to support powertrain electrification. Design options for creating such products include bearing material cleanness, bearing macro- and micro-geometries, surface finishing and manufacturing process control. Bearing design engineers may need to push boundaries and establish new design practices to provide cost-effective solutions and competitive products.

TLT: What's your current focus and interests?

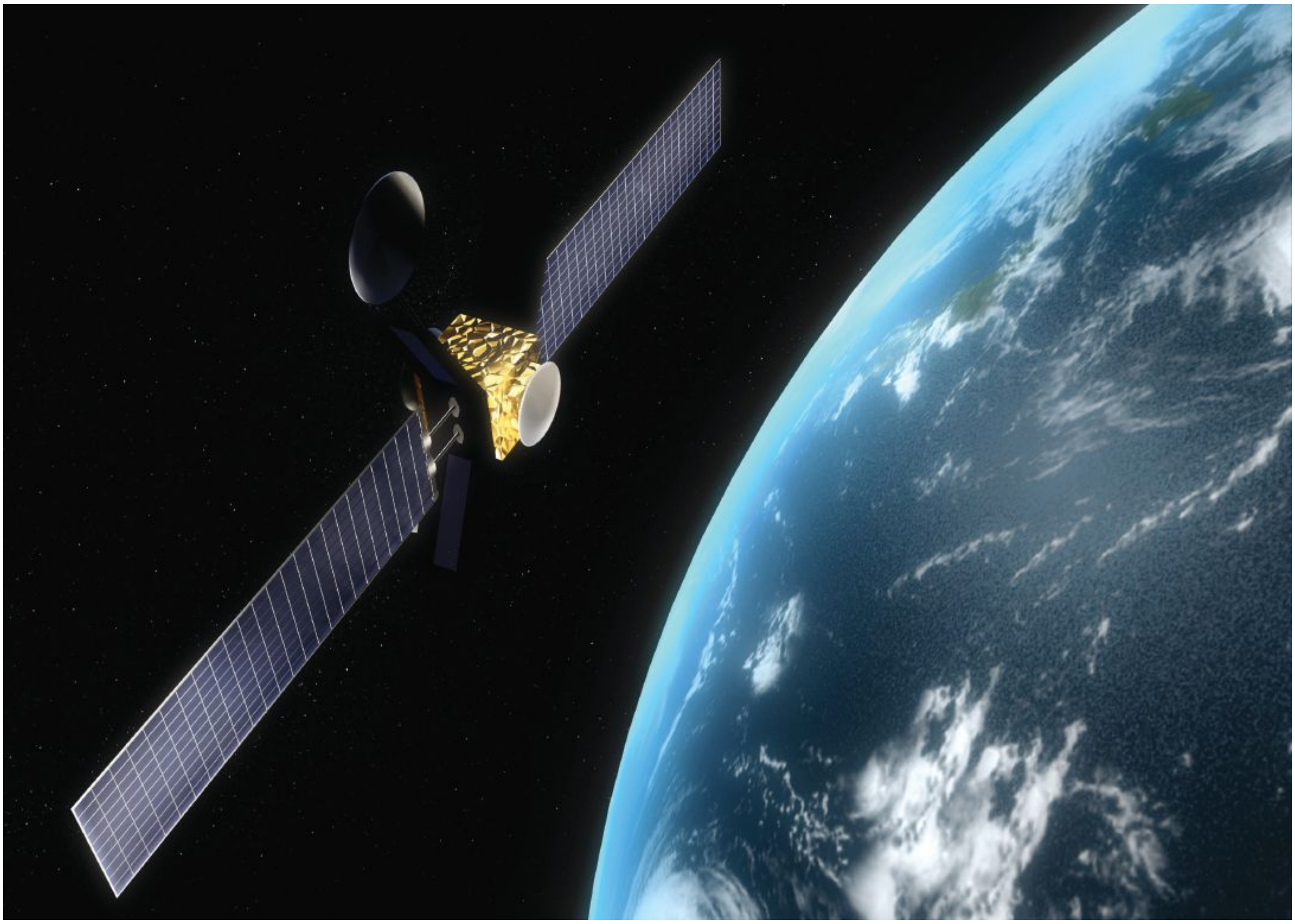
Ai: Virtual bearing life testing, from a higher perspective, is a part of a digital engineering ecosystem. To support and be well prepared for the industry-wide digital revolution, we are currently looking at expending the horizon of virtual bearing life testing beyond fatigue—building a full virtual laboratory to include virtual tests of all performance attributes such as dynamics, noise and vibration, surface wear, scuffing, torque and heat generation for all types of rolling element bearings.

I am currently working closely with a group of talented colleagues toward this ambitious goal. Creating something new and useful has always been my passion, whether it's a piece of software, a product or a process.

You can reach Xiaolan Ai at ***xiaolan.ai@timken.com.***

Solid lubricants

These materials are well suited for extreme conditions where liquid lubricants are impractical.



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KEY CONCEPTS

Solid lubricants are ideal for but not limited to extreme conditions.

They are usually applied as coatings by a variety of methods.

Advances are focused on coatings whose properties can change with operating conditions.

By Jane Marie Andrew
Contributing Editor

Although liquid lubricants are the typical solution for reducing friction, sometimes they are impractical or inadequate, for instance, where there is extreme contact pressure, elevated temperature or a vacuum. Such atypical conditions call for atypical solutions. Fortunately lubrication technology now includes a range of solid lubricants (also called dry or dry-film lubricants) that are well suited for extremes.

Solid lubricants take the form of either a coating applied to a surface or solids added to a composite. Unlike liquids or gases, solid lubricants do not volatilize or decompose in extreme operating conditions. However, they often have specific operation criteria and thus require careful selection or customization to the application.

Most solid lubricants fall into one of four classes:

1. Carbon-based solid lubricants such as graphite, diamondlike carbon (DLC) and nanocrystalline diamond
2. Transition-metal dichalcogenides such as molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2)
3. Polymers and polymer composites, including polytetrafluoroethylenes (PTFEs, e.g., Teflon) and polyimides
4. Soft metals, such as gold, silver, lead and copper.

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Solid lubricants are a good choice for diagnostic imaging machines because the bearings in these tubes operate at high rotational speeds, at high temperature and in a hard vacuum.

First developed for applications in the 1980s, these coating have become more structurally sophisticated as research has advanced. In a review chapter for an ASM handbook,[1] Sandia Laboratories scientist and STLE Past President Michael T. Dugger classified solid lubricants according to their chronological development, moving from single-component structures to multicomponent or multilayer structures, then later to nanostructured, superlattice or functional gradient structures. At the forefront today are adaptive or smart structures.

Application or fabrication

Solid lubricants can be either monolithic or applied as a coating or thin film. Most solid lubricants are applied as a powder that is burnished, thermal sprayed or cold sprayed on a part to form a coating or film. Such methods can be inexpensive and are appropriate for coatings that need to be replaced periodically. For coatings used in environments where replacement is not possible, physical and chemical vapor deposition processes may be required. In these processes, atoms or molecules of the solid lubricant are vaporized from a piece of the solid and deposited on a substrate material. For polymer-based solid lubricants and their composites (e.g., PTFE containing nickel), electrochemical processes are used.

Solid lubricants are at the forefront of adaptive or smart structure.

Although solid lubrication usually requires an application or fabrication step, under some conditions a similar effect is created during operation. Liquid or gas lubricants can sometimes react with the contacting material during operation to form a thin film of solid lubricant, often called a tribofilm. Such a film can function like a solid lubricant as long as the film remains in the moving contact. For example, tribofilms can form on DLC in the presence of liquid lubricants as a result of friction-induced chemical reactions between the DLC and additives in the lubricant. Thus, DLC can be used to mitigate friction and wear in automotive piston rings and cam followers, for example.

Characterization and evaluation

The composition and structure of solid lubricants are studied with a range of spectroscopic and structural microscopy techniques. Their performance is evaluated initially with standard tribological lab tests such as pin-on-disk sliding and high-frequency reciprocating wear. Once a candidate material is identified, larger-scale bench testing, such as engine tests, are conducted.

Lubrication mechanisms

The fundamental lubrication mechanism for a solid lubricant is interfacial sliding between the wear track that forms on the solid lubricant and the transfer film or tribofilm that adheres to the sliding counter face material. When low interfacial shear can be achieved, friction between the contacting surfaces is often very low, extending wear life.

The wear life can be further increased by using a hard, load-bearing underlayer to minimize the contact area. This soft-on-hard combination is often referred to as the Bowden-Tabor concept.[2] The four classes of solid lubricants mentioned previously all provide low interfacial shear at the moving contact.

Properties and operating parameters

In general, the parameters that control friction and wear with solid lubricants are low interfacial shear in the direction of sliding; strong adhesion to the surface; adequate lubricant cohesion; and physical, chemical and mechanical compatibility with the contacting surface. These parameters must be satisfied for the intended operating contact pressure, temperature and chemical environment. Other parameters to be considered include thermal stability, oxidation stability, volatility, chemical reactivity and melting point.

Sliding friction coefficients for solid lubricants are usually <0.1-0.2, and wear rates range between 10^{-6} and 10^{-7} mm^3/Nm, thus somewhat higher than those of liquid lubricants. (See Scharf and Prasad[3] for a summary of friction coefficients for many common solid lubricants.) The latter wear rate equates to an average removal rate of less than 1 atomic layer per 1 cm pass of a counter body loaded at 5 N. A maximum hardness of 5 on the Mohs scale is the practical limit for solid lubricants.

As to operating parameters, in general, solid lubricants do not volatize or evaporate; they are less sensitive to picking up dust or other contaminants, and they can be stored or dormant for long periods of times without lubricant escaping from the contact. Their general advantages and disadvantages are summarized in Table 1. Solid lubricants are available for a wide range of temperatures (cryogenic to approximately 700 C), environments (humid to dry air, ultrahigh vacuum), and contact pressures (megapascals to gigapascals). General characteristics and operating conditions of the main classes of solid lubricants are summarized in Table 2 on Page 28.

Table 1. **Advantages and Disadvantages of Solid Lubricants**

Advantages	Disadvantages
• Very stable in high-temperature, cryogenic, vacuum and high-pressure environments • High heat dissipation (with high thermally conductive lubricants) • High resistance to deterioration in the presence of radiation • High resistance to abrasion in the presence of dust • High resistance to deterioration in corrosive environments • High resistance to deterioration in storage • More effective than fluids at high load and high speeds • Lighter and less complex operation—lubrication distribution systems and seals are not required • Reliable—suitable for applications where servicing is difficult or impossible.	• Higher coefficients of friction and wear than liquid lubricants • Poor heat dissipation with low thermally conductive lubricants such as polymer-based films • Poor self-healing properties (a broken solid film may shorten the lubricant life) • Possibly undesirable color (i.e., graphite).

Table adapted from Van Rensselar, J. (2009), "Aerospace Lubricants: Solid is essential in every sense," TLT, ***65*** *(6), p. 44.*

Typically, solid lubricants are used at extremes of temperature and pressure at which liquid lubricants are not feasible *(see Figure 1)*. For example, coatings on satellite components must function in an ultrahigh vacuum atmosphere in low Earth orbit, resist exposure to radiation and atomic oxygen and cycle between extreme temperatures (cryogenic to about 100 C). Such applications usually use an MoS_2-based coating. Increasingly, however, designers are choosing solid lubricants even within the traditional liquid lubricant regime. For some cases, solid lubricants are cheaper and easier to implement than liquid or gas-phase lubricants.

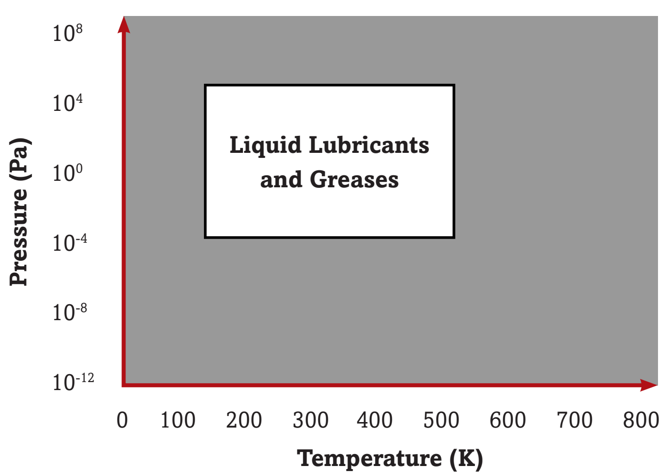

Figure 1. **Typical operational and temperature range of liquid lubricants and grease. Traditionally solid lubricants have been used in the region outside the box, but increasingly they are used throughout the entire pressure/temperature space.** *(Adapted from Doll, G.L., (2017), "Lubricant strategies for challenging environments," ASM Handbook, Vol. 18: Friction, Lubrication, and Wear Technology, edited by G.E. Totten. Materials Park, Ohio: ASM International, pp. 213-219. Reprinted with permission of ASM International. All rights reserved.* ***www.asminternational.org****.)*

These operating ranges can be tailored to a degree, but no single solid lubricant material can function over the entire range of extremes. Attention has thus turned to composite solid lubricants in which each phase in the composite can target given operational range(s). For example, a composite coating consisting of CaF_2/BaF_2 (for high temperatures), silver (for low temperatures) and CrO_x (for wear resistance) has been developed for use to ~900 C. Other composites that have been qualified for applications include $MoS_2/Sb_2O_3/C$ for space coatings and WC-doped DLC for rolling elements.

In addition to the main categories listed in Table 2, a variety of other materials ►►►


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can function as solid lubricants under certain conditions. Fluoride coatings (e.g., CaF_2 and BaF_2) and oxide coatings (e.g., B_2O_3) are lubricating at high temperatures (i.e., over 500 C) where their shear strengths are small. PbO has good lubricating properties from about 450 C-700 C but is limited by its shear strength at low temperatures and by phase change, reactivity and melting at high temperatures. Other materials that are sometimes desirable for their high-temperature lubricating properties include oxygen-deficient $TiO_{(2-x)}$ materials with mechanically weak shear planes, oxides and double oxides, and Cs-based compounds.

Table 2. **Operating Parameters of Solid Lubricants**

Lubricant	Mechanism	Operating conditions
Carbon-based materials • graphite • diamondlike carbon (DLC)	• *Graphite:* Interlamellar shear between covalently bonded hexagonal basal planes. (Hexagonal crystal structure has the intrinsic property of easy shear.) • *DLC:* Both high hardness and low friction through an amorphous structure that combines diamond and graphitic phases. Can be doped with hydrogen, nitrogen and other elements for tailored properties.	• Thermal range: –200 C to 350 C • Require oxygen and/or moisture (except highly hydrogenated DLC)
Transition-metal dichalcogenides • crystalline MoS_2 • crystalline WS_2	• Interlamellar shear between covalently bonded hexagonal basal planes. • Coating density and oxidative stability improve when produced as a composite with a soft metal or a binder material (e.g., Sb_2O_3)	• Thermal range: –150 C to 350 C • Best performance in vacuum or dry environments • Performance in humidity improves with modified composition
Polymers (e.g., polytetrafluoroethylene [PTFE])	• Highly linear molecules provide low-friction surfaces. • PTFE: - Long-chain fluorocarbon - Low chemical reactivity - Does not rely on adsorbed vapors or moisture - Low surface energy	• Thermal range: –70 C to 200 C • Vacuum and air • Performs best at low contact loads/pressures • Fails at higher contact loads/pressures; additives required to support higher loads
Soft metals (e.g., lead, tin, indium, silver, copper, gold)	• Shear accommodation (solid state) • Liquid film (molten state)	• Rapid thermal degradation typically occurs above ~600 C to 700 C • Improved thermal behavior above 400 C may be possible with layered binary oxides

Applications

An application that illustrates the value of solid lubricants is coatings for rolling bearings in rotating anode X-ray tubes used in diagnostic imaging. Bearings in these tubes operate at high rotational speeds, at high temperature and in a hard vacuum. In addition, electrical current must pass from the bearing housing to the shaft, which is connected to the anodic material. Some of the important criteria for solid lubricants used in this application include high electrical and thermal conductivities, low wear rates and high lubricity at operating temperatures. These criteria limit the solid lubricants to materials such as lead, gold and silver. Additional application requirements limit the thickness and deposition processes that can be used to deposit these materials.

In general, solid lubricants are highly valued for mechanical devices that operate in vacuum, high temperatures or inert atmospheres, and they are essential for components operating in space.[4] They also are used to mitigate fretting-type wear in mechanical components that experience low-amplitude, oscillating motion. Rolling bearings used in high-speed turbine engines employ silver coatings on steel cages to lubricate the ball/cage and cage/land contacts. Foil bearings used in gas turbines now employ a specially developed solid lubricant coating.[5] Diamondlike carbon lubricants are now being used on rolling bearings and gears that are normally oil-lubricated but experience periods of interrupted oil flow.[6] During these interruptions, the DLC coatings function as solid lubricants.

Customization

For some applications it is advisable to customize solid lubricant coatings to meet the demands of the contact environment. For example, when the operational lifetime of the component depends entirely upon the durability of the coating, the solid lubricant must have adequate wear resistance and/or a stable tribofilm. In contrast, where the goal is to minimize frictional heating from intermittent contact, a low friction coefficient is more critical than good wear resistance. It is sometimes possible to meet conflicting tribological demands with a composite. Some composites are self-lubricating—that is, the contact surface material incorporates a solid lubricant (such as graphite or MoS_2). In other composites, different components provide the necessary properties at different conditions. ▶▶▶

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Lexolube IPO	Oleate	5	2	n/a	175	-25
Lexolube NBS	Stearate	6	2	200	195	20
Lubricit 5399	Polyol	21	5	140	285	-30
Lexolube FG-22 HX1	Polyol	22	5	140	250	-50
Lexolube FG-46 HX1	Polyol	46	8	135	270	-45
Lubricit TMP C18 VEG	Oleate	46	9	190	325	-45
Lubricit GMO	Oleate	50	9	145	290	0
Lexolube FG-68 HX1	Polyol	68	10	125	290	-45
Lexolube FG-220 HX1	Polyol	220	19	95	300	-25
Lexolube CG-3000	Complex	3000	290	230	320	-20

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Future approaches

The next step beyond composites, in terms of broadening the operating range of solid lubricants, appears to be adaptive lubricants. Adaptive lubricants are materials that react with the environment to form new lubricious phases as temperature increases. Adaptive lubricants have a low-friction surface at room temperature, and as temperature increases, the components react with each other and with oxygen to form a high-temperature lubricious phase. Examples of adaptive lubricants include

- Transition-metal dichalcogenides strengthened with oxides and doped with soft metals
- Nanocomposites with diffusion barriers
- Dichalcogenide composites with phosphates and soft metals
- Fullerene-like nanoclusters of transition-metal dichalcogenides in metal nitride matrices.

Adaptive solid lubricants may enable machine elements to operate more effectively in changing and/or demanding application environments.

About the experts

This article is based in large part on contributions by STLE-member Thomas Scharf, professor, department of materials science and engineering, University of North Texas (**scharf@unt.edu**), and STLE-member Gary Doll, Timken professor of surface engineering, chemical and biomolecular engineering department, University of Akron (**gdoll@uakron.edu**).

Jane Marie Andrew is a free-lance science writer and editor based in the Chicago area. You can contact her at ***jane@janemarieandrew.com***.

Further reading

- In addition to a general review, Tribology and Applications of Self-Lubricating Materials[7] (CRC Press, 2017) focuses on composites and self-lubricating materials.
- ASM Handbook, Vol. 18: Friction, Lubrication, and Wear Technology (2017) includes an overview of the history, characteristics, processing methods and qualification of solid lubricants[1] and a discussion of lubrication in challenging conditions.[8]
- Scharf and Prasad[3] provide an overview of research on lubrication mechanisms in solid lubricants as well as a detailed listing of 20 solid lubricants with their characteristics and applications.
- A classic resource on the mechanisms of solid lubrication is the 1942 Nature article Mechanism of Metallic Friction by Bowden and Tabor.[2]

REFERENCES

1. Dugger, M.T. (2017), "Solid lubricants," in *ASM Handbook, Vol. 18: Friction, Lubrication, and Wear Technology*, edited by G.E. Totten. Materials Park, Ohio: ASM International, pp. 191-206.
2. Bowden, F.P. and Tabor, D. (1942), "Mechanism of Metallic Friction," *Nature*, August 15, pp. 197-199.
3. Scharf, T.W. and Prasad, S.V. (2013), "Solid Lubricants: A Review," *Journal of Materials Science*, **48**, pp. 511-531.
4. Van Rensselar, J. (2009), "Aerospace Lubricants: Solid is Essential in Every Sense," TLT, **65** (6), p. 44.
5. DellaCorte, C. (2000), "The Evaluation of a Modified Chrome Oxide Based High Temperature Solid Lubricant Coating for Foil Gas Bearings," *Tribology Transactions*, **43** (2), pp. 257-262.
6. Mutyala, K.C., Singh, H., Evans, R.D. and Doll, G.L. (2016), "Effect of Diamond-Like Carbon Coatings on Ball Bearing Performance in Normal, Oil-Starved, and Debris-Damaged Conditions," *Tribology Transactions*, **59** (6), pp. 1039-1047.
7. Omrani, E., Rohatgi, P.K. and Menezes, P.L. (2017), *Tribology and Applications of Self-Lubricating Materials*, 1st ed., Boca Raton, Fla.: CRC Press.
8. Doll, G.L. (2017), "Lubricant Strategies for Challenging Environments," *ASM Handbook, Vol. 18: Friction, Lubrication, and Wear Technology*, edited by G.E. Totten. Materials Park, Ohio: ASM International, pp. 213-219.

Fundamentals of wind turbines

Global capacity has grown continuously since 2001, including a 9% increase in 2018.

KEY CONCEPTS

As an industry, wind energy is growing fast; both total capacity and individual turbine output have increased steadily over the last decade.

The wind characteristics change with geographical location, terrain, season, height, direction and time of day.

The power output of a turbine depends primarily on the blade length and the wind speed.

By Jane Marie Andrew
Contributing Editor

The rising concerns over climate change, environmental pollution and energy security have increased interest in developing renewable energy. We are seeing unparalleled enthusiasm, demand and growth in renewable energy production, with wind energy being at the forefront. Wind energy is expanding both onshore and offshore with bigger, more powerful turbines, creating new demands and markets.

Market

The global capacity for generating power from wind energy has grown continuously since 2001, reaching 591 GW in 2018 (9% growth compared to 2017), according to the Global Wind Energy Council.[1]

In the U.S., capacity figures are reported by the American Wind Energy Association.[2] According to this trade association, the total wind power capacity in the U.S. was 96,488 MW at the end of 2018, an 8% increase from the 88,964 MW installed at the end of 2017 *(see Figure 1)*. (Generation capacity means the

Dr. Harpal Singh

MEET THE PRESENTER

This article is based on a Webinar originally presented by STLE Education on Feb. 27. **Fundamentals of Wind Turbines** is available at **www.stle.org**: $39 to STLE members, $59 for all others.

Dr. Harpal Singh is a senior scientist at Sentient Science where he is engaged in wind turbine and aerospace-related mechanical and materials science research involving tribology, materials characterization and failure analysis.

Singh has more than six years of experience in the field of tribology and metallic materials. He holds a patent, several peer-reviewed publications and two best paper awards from STLE in the field of solid lubricants. He earned his doctorate in mechanical engineering from the University of Akron, Ohio. His research was focused on the mechanical, material and tribological properties of materials and coatings used in wind, automotive and aerospace applications. His expertise includes materials characterization, tribological testing, coatings and failure analysis.

You can reach Singh at **hsingh@SentientScience.com**.

output of a wind turbine when running at rated power.) New installed capacity grew steadily from 2000 to 2012. After a spike and a trough in 2012 and 2013, new installations recovered in 2014 and have leveled out at about 7,000-8,500 MW annually since 2015.

Capacity growth in the U.S. in 2018 was concentrated in the central states (the "wind belt"), the West Coast states and, to a lesser extent, the tier of states along the northern border. Texas leads in overall installed capacity, followed by Oklahoma and Iowa. Similar trends are observed in new capacity installations, with Texas far outstripping any other state, followed at a distant second by Iowa *(see Figure 2 on Page 34)*. Five central states were in the next tier in 2018: Colorado, Oklahoma, Nebraska, Kansas and Illinois. This growth has resulted in strong employment growth. In the decade from 2008 to 2018, the number of full-time equivalent jobs in the wind industry grew from about 50,000 to more than 110,000. Texas has the most wind-related employment, with 25,000-26,000 jobs, distantly followed by 10 other states with 3,000-10,000 jobs by the end of 2018.

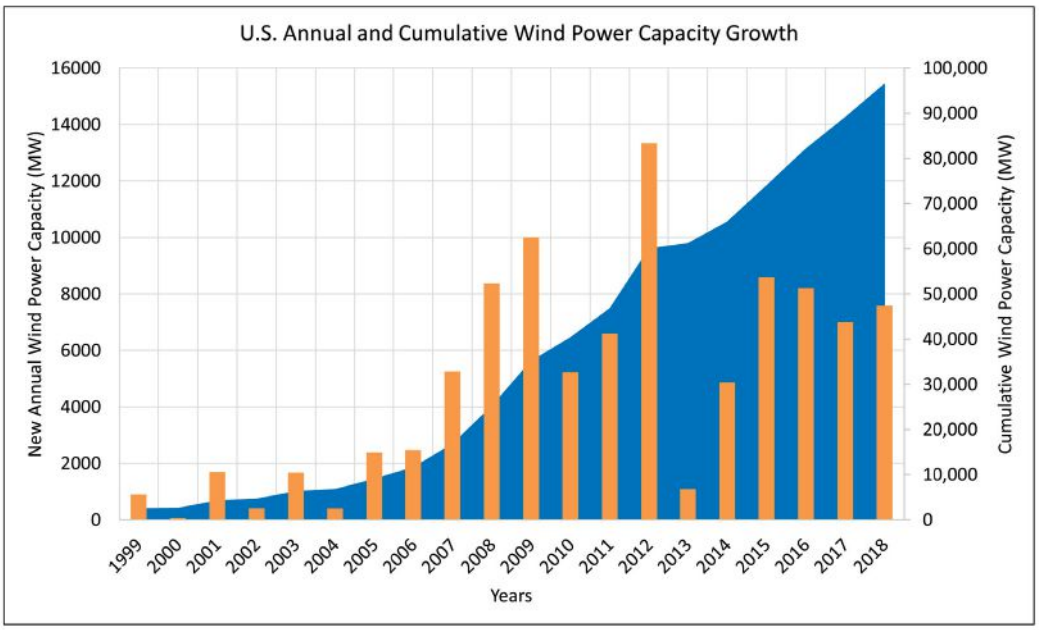

Figure 1. **Trends in U.S. wind energy growth.** *(Figure courtesy of the American Wind Energy Association's U.S. Wind Industry Fourth Quarter 2018 Market Report.)*

In addition to exploiting interior wind belt regions, many countries with ocean coastlines are developing offshore wind power generation. The trends in offshore capacity mirror those for land-based capacity, showing steady growth. The global offshore capacity as of 2018 was 23,140 MW or about 4% of the global 2018 capacity of 591 GW, according to the Global Wind Energy Council.[1]

The cost of onshore wind energy has become competitive with utility-scale solar photovoltaics and gas combined-cycle generation joining them as the three least expensive sources of energy. According to Lazard, a financial advisory and asset management firm, the cost of wind energy dropped 69% from 2009 to 2018, and the mean levelized cost of energy for wind power is now $29 to $56 per megawatt-hour.[3] Coal is the only other technology that approaches the same range.

In a growing trend, large corporations are including wind power in their power purchase strategy, either through direct ownership of wind projects or purchase agreements. Among commercial and industrial (C&I) purchasers, Walmart made an early mark in this area with a purchase announced in 2008. Google Energy has announced purchases each year since 2010 and is currently the largest C&I wind customer, with total contracted capacity of 1,096 MW. AT&T contracted the most new wind power in 2018, a total of 820 MW.[2] Other major purchasers include not only large technology companies and manufacturers but also a municipality, a regional transit system and a government agency.

As the market has grown, turbine models have proliferated; in 2018 there were more than 30. According to the American Wind Energy Association, three manufacturers hold over 85% of the U.S. market: GE Renewable Energy (41.4%), Vestas (24.2%) and Siemens Gamesa Renewable Energy (19.7%). Smaller players are Mitsubishi, Suzlon, Clipper and Senvion. In terms of capacity, GE Renewable Energy and Vestas are the clear leaders at 39,912 and 23,318 MW, respectively.[2]

The products created by these companies are growing ever larger in both generating capacity and physical size. For turbines installed in the U.S. from 2000 to 2018, average generating capacity roughly quadrupled from 660 kW to 2.43 MW. For a sense of scale, the average U.S. household uses 2 kW of electricity annually. A 2.5-MW turbine running at peak capacity all year round would power about 1,250 homes.

In the same period, the average height of the turbine hub increased from 190 feet (58 m) to 288 feet (88 m)—approaching the height of the Statue of Liberty—and rotor diameter has more than doubled from 160 feet (49 m) to 380 feet (116 m), about the length of a soccer field. The majority of turbines installed in the U.S. in 2018 had capacity ratings in the range of 2-3 MW, followed by units rated for 3-3.5 MW. Sixteen models dominated the 2018 installations, as shown in Figure 3.

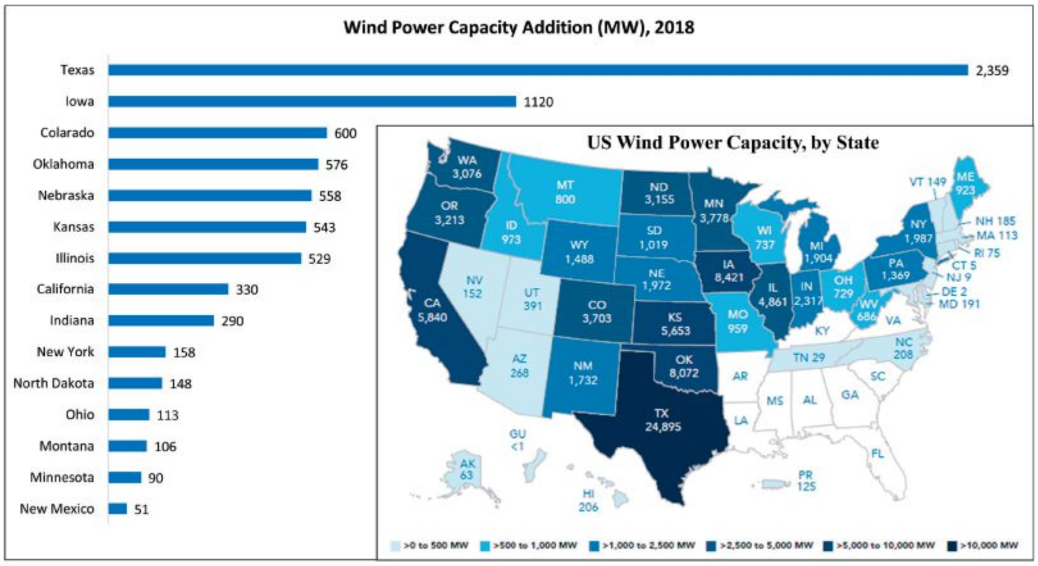

Figure 2. **New U.S. capacity installed in 2018 and (inset) cumulative installed capacity by state.** *(Figure courtesy of the American Wind Energy Association's U.S. Wind Industry Fourth Quarter 2018 Market Report.)*

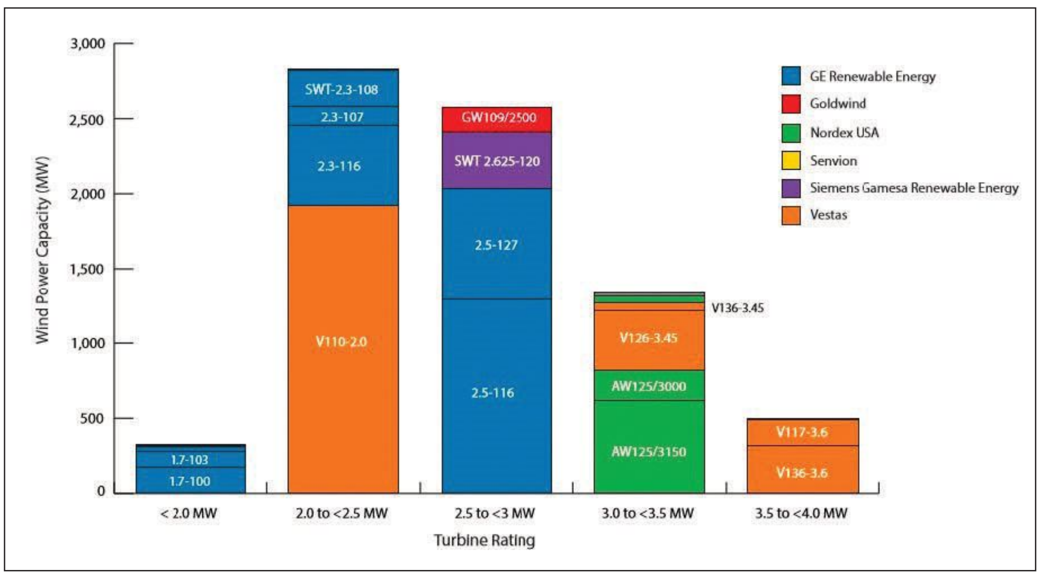

Figure 3. **Turbine models installed in 2018.** *(Figure courtesy of the American Wind Energy Association's U.S. Wind Industry Fourth Quarter 2018 Market Report.)*

Wind physics fundamentals

Wind arises from processes driven by solar energy. The sun's energy creates temperature differences that drive air circulation. Hot air rises, reducing the local atmospheric pressure; nearby cooler air flows into this region of lower pressure; this air flow is wind.

Wind is shaped by both global and local forces. Global patterns are in part the result of the Coriolis force, which arises from the Earth's rotation. As cool air flows from higher to lower pressure areas, it is deflected by the Coriolis force; the direction of deflection depends on latitude. As a result, different regions of Earth ▶▶▶

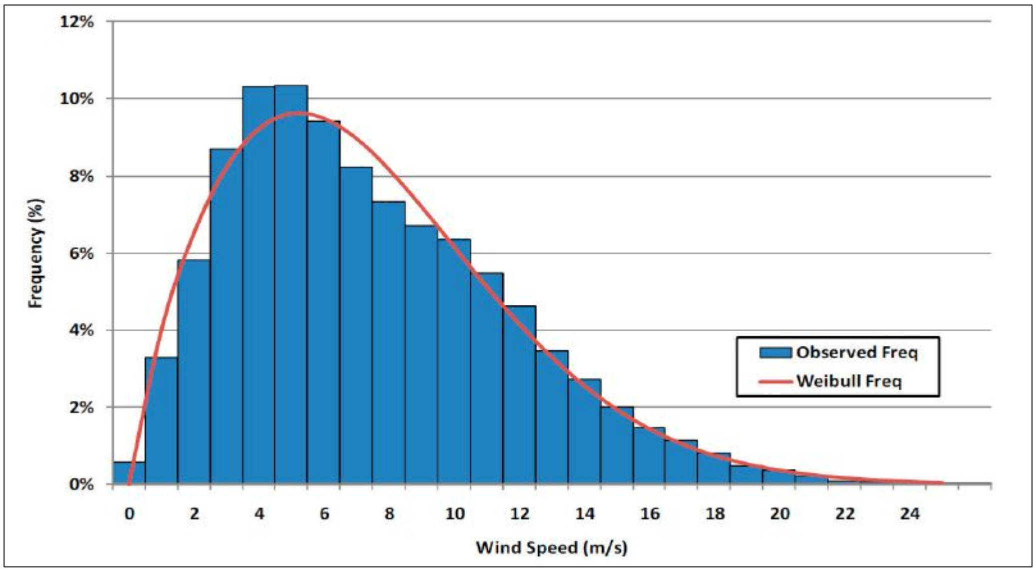

Figure 4. **Plot of the frequency of occurrence of different wind speeds over a period of a year.** *(Figure courtesy of Sentient Science Corp.)*

have different prevailing wind directions.

At the other end of the spectrum, local geographical features can have very specific effects. One such effect, familiar to anyone living near the ocean, is the land breeze. At night, the water is warm relative to the land, so air is warmed over the water and rises; the resulting low pressure draws cool air from land out to sea: the land breeze.

Although there may be a *prevailing* wind direction, it is not the *only* wind direction. Both direction and speed are highly variable with geographical location, season, height above the surface and time of day. Understanding this variability is key to siting wind power generation, because higher wind speeds mean higher duty cycles (i.e., longer periods of active power generation). It is necessary to measure the characteristics of the wind in great detail, including how often winds of certain speeds occur *(see Figure 4)* and how the surrounding terrain affects the stability of wind flow.

A stable flow with a consistent speed is very important for both generating efficiency and structural integrity. Variability leads to wind shear and wake forces. Wind shear is a function of wind speed, which increases with height above the surface. Thus, the shear forces on the rotor blade are greater when it is in the top position *(see Technical Note: Equations for Wind Turbines)*.

Wake forces are created because the wind slows down and becomes turbulent as it passes the wind turbine rotor blades. This is why turbines are widely spaced, usually five to nine rotor diameters in the direction of the prevailing wind and three to five rotor diameters in the perpendicular direction.

Wind speed also changes as a result of turbulence, which can be caused by nearby rough terrain, including trees and buildings; these can cause wind speed to vary greatly even within several hundred yards or meters. This effect, called turbulence, decreases efficiency and causes fatigue loading.

Wind power fundamentals

Energy is captured from wind through the lift phenomenon—the same phenomenon that allows birds and airplanes to fly. (Turbine blades are, in essence, captive wings.) The lift generated as wind passes over the blade causes it to move, thereby rotating the main shaft. The rotation is transmitted through a gearbox to a generator, which converts it into electricity. The magnitudes of the lift and drag on the turbine blade are dependent on the angle of attack between the apparent wind direction and the chord line of the blade.

Several different factors influence the power output of a wind turbine. Among other factors, wind speed and rotor diameter are the two primary parameters *(see Technical Note: Equations for Wind Turbines)*.

- Turbine power increases with the square of blade length. For example, increasing the rotor diameter from 262 feet (80 m) to 394 feet (120 m) allows power to increase from 2 MW to 5 MW (a factor of 2.5).

Technical Note: Equations for wind turbines

Wind Shear

An important consideration for turbine siting and operation is wind shear when the blade is at the top position. Wind shear is calculated as

$$V = V_{ref} \ln\left(\frac{H}{H_0}\right) / \ln\left(\frac{H_{ref}}{H_0}\right)$$

V = wind speed at height H above ground level
V_{ref} = reference speed
H_{ref} = reference height
H = height above ground level for the desired velocity, V
H_0 = roughness length in the current wind direction.

For instance, assume we know that the wind is blowing at 8 m/s at a height of 20 m. We want to calculate the wind speed at 70 m. If the roughness length is 0.1 m, then

V_{ref} = 8
H = 70
H_0 = 0.1 and
H_{ref} = 20, hence,
V = 8 ln(70/0.1) / ln(20/0.1) = 9.8915 m/s.

Turbine power increases with the cube of wind velocity.

- Turbine power increases with the cube of wind velocity. For example, a turbine at a site with an average wind speed of 16 mph would produce 50% more electricity than the same turbine at a site with average wind speeds of 14 mph.

These two fundamental physical relationships are behind the drive to scale up the physical size of turbines. A larger rotor diameter allows a single turbine to generate more electricity, providing better return on installation cost. And because wind speed and consistency both increase with height, taller turbines produce a higher and more consistent supply of electricity.

A given design operates with a range of wind speeds. Below the cut-in wind speed, the turbine cannot produce power because the wind does not transmit enough energy to overcome the friction in the drivetrain. At the rated output wind speed, the turbine produces its peak power (its rated power). Below the cut-out wind speed, the turbine must be stopped to prevent damage. A typical power profile for wind speed is shown in Figure 5.

In addition to an operating range, an installed turbine has a capacity factor that reflects its actual power generation. The capacity factor is the annual average of power generated divided by the rated peak power. For example, if a turbine rated at 5 MW produces power at an average of 2 MW, then its capacity factor is 40%. In general, a higher capacity factor is preferred, although it may not be advantageous economically. For instance, in a windy location, it will be advantageous to use a large-size generator with the same rotor diameter. This would tend to lower the capacity factor, but it will lead to substantially larger annual production.

Turbine Power

The energy contained in a mass m of moving air with velocity v is

$$E = \frac{1}{2}mv^2 \,.$$

The mass flow rate of moving air with a density ρ through a cross-section area A is

$$m = \rho v A \,.$$

The power contained in a flowing mass of air through area A is

$$P = \frac{dE}{dt} = \frac{1}{2}mv^2 = \frac{1}{2}\rho v^3 A \,.$$

The power extracted by blades of diameter d is

$$P = \frac{\pi}{8}c_p \rho v^3 d^2 \,,$$

where the power coefficient c_p has a theoretical limit of ~0.6; this is referred to as the Betz limit, which defines the maximum amount of wind kinetic energy that can be converted to kinetic energy.

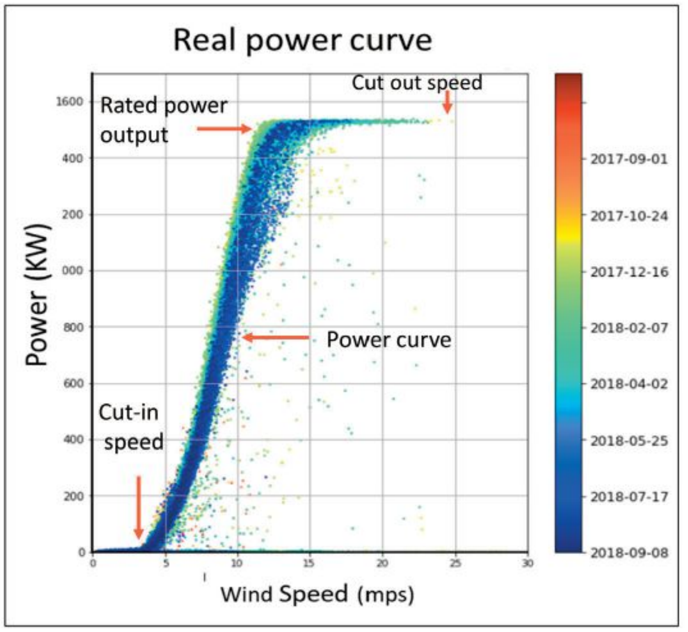

Figure 5. **Profile of power output from a wind turbine over a year.** *(Figure courtesy of Sentient Science Corp.)*

Wind turbine technology

Turbines come in several general categories based on orientation and drivetrain type.

The turbine blades can be oriented around either a vertical or horizontal axis. An advantage of the vertical axis is that blades do not have to be mechanically reoriented when the wind direction changes. Horizontal-axis turbines come in two general designs. In a downwind design, the blades face away from the incoming wind; in an upwind design, the blades face into the wind *(see Figure 6 on Page 38)*. More than 90% of currently installed turbines are of the upwind type, as this design does not create wind shade behind the tower.

For the drivetrain, in a gearbox-drive design, a gearbox is used to increase the speed transmitted from the rotors to the generator. In a direct-drive design, the speed is transmitted directly to an annular generator. Aside from the gearbox, the components are generally similar; however, in a direct-drive turbine the generator diameter is much bigger to increase generator torque as it rotates at the same speed as the turbine blades.

The wind turbine components that experience friction and wear and require lubrication are the following:

- Pitch bearing (grease)
- Main shaft bearing (grease)
- Gearbox if any (oil)
- Yaw drive (grease)
- Generator bearing (grease).

The pitch drive is used to adjust the angle of the blades. This adjustment is made for two reasons: 1.) to capture maximum power from winds below the rated output wind speed or 2.) to slow the blades for safe operation at winds above the rated speed. The yaw drive moves the blade and housing assembly (the nacelle) to the optimum wind direction in relation to the wind. An animation prepared by the Union of Concerned Scientists is helpful in visualizing the action of these drives.[4]

Figure 7 shows a typical three-stage wind turbine gearbox. A planetary stage (bottom left) transfers the torque first to a low-speed intermediate stage (bottom right) and then to a high-speed intermediate stage (middle), which drives a high-speed stage (top) that feeds the generator. Such a design might, for example, convert 14 RPM input from the rotors into 1,500 RPM to the generator; the exact conversion of course depends on the gear ratio. Different bearing types are used in these various components, as shown in Table 1 on Page 40.

Some technical differences should be noted between land-based and offshore turbines. Offshore installations account for more than 3% of global capacity. Offshore construction presents different challenges, the most obvious being how the structure is anchored. The strategy differs depending on the water depth. For depths less than about 100 ft (30 m), monopile construction is used. For transitional waters (100-200 ft or 30-60 m), a cross-braced "jacket" foundation is used. For deeper waters, prototype floating platforms are being tested. The transformer design also is different for different water depths, and in general offshore installations are moving from gearbox to direct-drive designs.

Another very significant difference is size. Without the need to limit noise or accommodate terrain-induced turbulence, designers can pursue truly giant scales. GE has built an offshore design rated at 12 MW, significantly higher than the 2017 average of about 2.3 MW. It is indeed a giant: the rotor diameter is on the scale of the towers of the Golden Gate Bridge, and the surface area of the blade sweep is equivalent to seven American football fields. This is a direct drive design where speed is transmitted directly to the generator. Why build such giants? In addition to raising power output, large turbines reduce installation cost. Installing one 12-MW turbine is cheaper than installing six 2-MW ones; thus the final cost per megawatt is lower. For these reasons, and because of the abundance of offshore wind resources, the industry is moving to an emphasis on offshore wind power. ▶▶▶

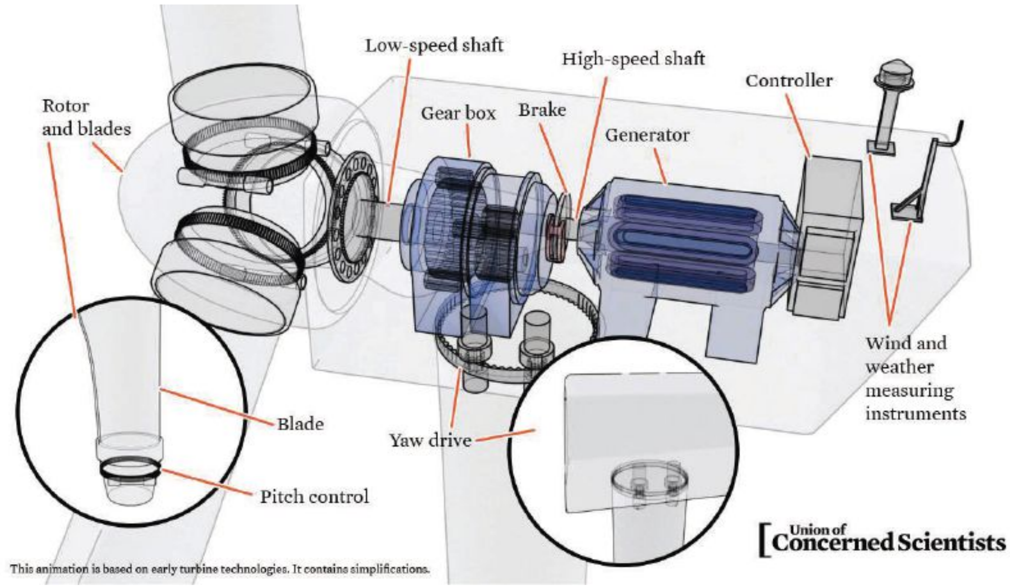

Figure 6. **Simplified view of components of an upwind-facing, horizontal-axis wind turbine with a gearbox drive. An animation is available.[4]** *(Figure courtesy of Union of Concerned Scientists, www.ucsusa.org.)*

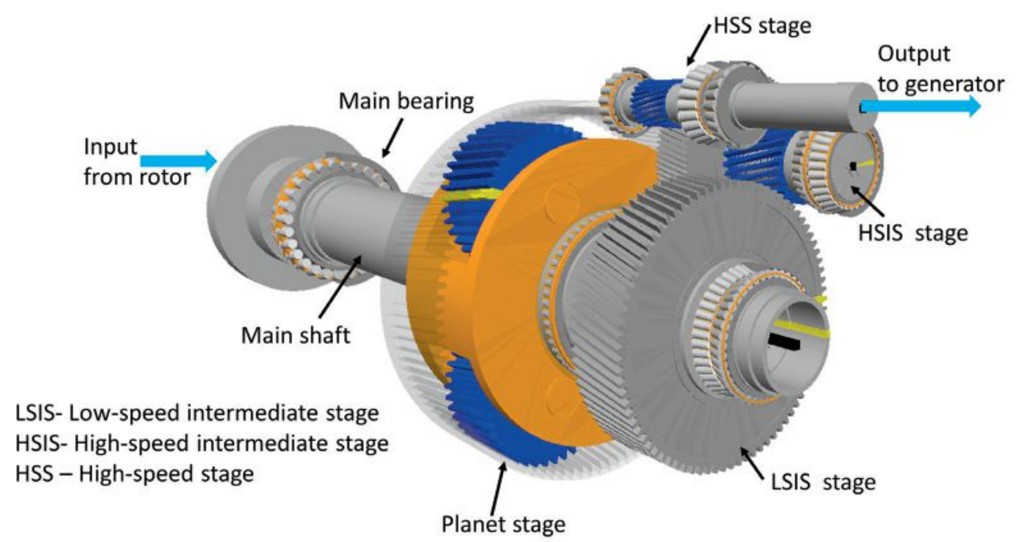

Figure 7. **Power flow diagram of a typical three-stage wind turbine gearbox. The low-speed input from the rotors (far left) is converted into high speed at the output shaft (HSS) to feed the generator (top right).** *(Figure courtesy of Sentient Science Corp.)*

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Offshore construction presents different challenges.

Summary

Wind turbines are the fastest-growing renewable energy source, and wind energy is now cost-competitive with nonrenewable resources. Growth in generating capacity is concentrated in five to 10 states, notably Texas. The field of turbine manufacturers is crowded, but GE Renewable Energy and Vestas are leaders in the U.S. wind market. Increasingly, capacity is being purchased by entities other than utilities, and offshore installations are becoming more attractive and viable.

Table 1. **Application of Different Bearing Types in Wind Turbine Drivetrains**

Bearing Type	Wind Turbine System
Ball	· Yaw system · Pitch system · Generator
Cylindrical roller	· Gearbox
Tapered roller	· Gearbox · Main shaft · Pitch system
Spherical roller	· Main shaft · Gearbox

In terms of technology, turbine design focuses on optimizing power output by focusing on two key parameters: blade length and average wind speed. The latter is affected by surface terrain and varies spatially, directionally and seasonally. The effectiveness of a particular installation is quantified by a capacity factor: the ratio of actual annual energy output to the theoretical maximum output. A number of basic designs are in use, but most commercial installations use a horizontal axis, upwind-facing design. Turbines are becoming ever larger, in both physical size and generating capacity, in order to capture more stable winds and to maximize return on installation costs.

Jane Marie Andrew is a freelance science writer and editor based in the Chicago area. You can contact her at ***jane@janemarieandrew.com.***

REFERENCES

1. *Global Wind Report 2018*, by Global Wind Energy Council. Available at **https://gwec.net/global-wind-report-2018/.**
2. *U.S. Wind Industry Fourth Quarter 2018 Market Report* by American Wind Energy Association, January 30, 2019; public version available at **www.awea.org/resources/publications-and-reports/market-reports/2018-u-s-wind-industry-market-reports/4q2018_public.**
3. *Lazard's Levelized Cost of Energy Analysis – Version 12* by Lazard, 2018, pp. 4 and 8. Available at **www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf.**
4. "How Wind Energy Works," by the Union of Concerned Scientists. Available at **www.ucsusa.org/clean-energy/renewable-energy/how-wind-energy-works.**


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TOP STORIES

ExxonMobil completes Singapore refinery expansion

ExxonMobil has completed an expansion at its Singapore refinery to upgrade its production of EHC™ Group II base stocks, strengthening the global supply of high-quality base stocks and enhancing the integrated facility's competitiveness.

The expansion enables customers to blend lubricants that satisfy more stringent specifications, help lower emissions and improve fuel economy and low-temperature performance. Customers will achieve short-term and long-term cost savings through blending optimization and reformulation.

"The safe, on-schedule completion and successful startup of this expansion further enhances ExxonMobil's competitiveness in manufacturing Group II base stocks," says Bryan Milton, president of ExxonMobil Fuels & Lubricants. "It further establishes ExxonMobil as a key producer of fuels and petrochemical products and affirms our confidence in Singapore where we operate ExxonMobil's largest global integrated refining and petrochemical complex."

Supply to customers is expected in the third quarter of 2019 and builds upon recent expansions at ExxonMobil's Rotterdam facility, which along with existing production in Baytown, Texas, strengthens the global supply of high-quality base stocks.

Construction of the expansion began in 2017 and was completed safely and on schedule with one million workforce hours. At peak construction, more than 300 workers were employed.

BASF names Quadra Chemicals mining products distributor

BASF enters in an exclusive agreement with Quadra Chemicals Ltd. to represent its mining solutions portfolio of products in Canada and Alaska.

"Quadra's network of supply locations and personnel in the mining industry will enable us to respond to customers' needs quickly and efficiently," says Robert Leary, sales leader BASF's Mining Solutions business for U.S. & Canada. "Partnering with Quadra is a key component of our strategy to bring new innovations to the market place and streamline our supply to efficiently serve our current and future customers."

BASF's Mining Solutions business offers a diverse range of mineral processing chemicals and technologies to improve process efficiencies and support the economic extraction of valuable resources.

"Partnering with a world-renowned producer such as BASF allows us to continue to provide technologies and innovations, which will help to ensure our client's competitiveness in the market," says Rubens Verni, business manager Mining Group ►►►

of Quadra Chemicals Ltd. "We are excited about this new partnership and look forward to working in collaboration with BASF."

Pilot Chemical receives top workplace award

West Chester, Ohio-based, **Pilot Chemical Co.** has been awarded a Top Workplaces 2019 honor by The Cincinnati Enquirer.

The list is based solely on employee feedback gathered through a third-party survey administered by research partner Energage, LLC, a leading provider of technology-based employee engagement tools. The anonymous survey measures several aspects of workplace culture, including alignment, execution and connection, just to name a few.

"Top Workplaces is more than just recognition," says Doug Claffey, CEO of Energage. "Our research shows organizations that earn the award attract better talent, experience lower turnover and are better equipped to deliver bottom-line results. Their leaders prioritize and carefully craft a healthy workplace culture that supports employee engagement."

"This is truly a great recognition and a tribute to all the employees who work hard every day to make Pilot a successful and enjoyable place to work," says Pam Butcher, CEO of Pilot Chemical. "For the past 67 years, Pilot has consistently encouraged a commitment to the interests and welfare of its employees and their families, as well as the communities where it operates."

"Becoming a Top Workplace isn't something organizations can buy," Claffey says. "It's an achievement organizations have worked for and a distinction that gives them a competitive advantage. It's a big deal."

LANXESS expands test capacity for high-performance additives

Specialty chemicals company **LANXESS** has taken a new test bench for additivated hydraulic fluids into operation at its Mannheim site. It is being used to test the additive package Additin RC 9200 N, as well as other fluids. These high-performance additives are used to formulate hydraulic fluids that are utilized in large commercial vehicles such as excavators, combine harvesters or construction vehicles.

As the market requires test runs to be performed using various grades of oil and the test capacity at hydraulic unit manufacturer Bosch Rexroth is only available on a limited basis, the LANXESS additives business unit decided to build its own test bench to conduct these tests. Additin RC 9200 N had already been approved by the mechanical engineering company in March 2018. All end products that pass the test are published in a list of recommended products for high operational safety.

Richard Baker launches TriboTonic

STLE-member **Dr. Richard Baker,** formerly of PCS Instruments, has set up a company to distribute tribology equipment ▶▶▶

across Europe.

Having graduated from Imperial College in London with a bachelor's of science degree in mathematics and attained a doctorate from the same school, Baker worked for PCS for more than 16 years in a variety of positions including international sales and marketing and business development manager.

Dr. Richard Baker

Baker's company, **TriboTonic (www.tribotonic.com)**, distributes tribology products within Europe. Based in London, TriboTonic will be the exclusive distributor for both PCS Instruments and Falex equipment, supplying sales, support and service for these instruments in Europe.

STLE LOCAL SECTIONS

The STLE Louisiana Section held its quarterly meeting on May 9. Louisiana Tech University in Ruston, La., hosted the event, and many engineering students were in attendance. A technical topic was presented by Amanda Nicholas Hall of International Paper and STLE-member Wade Stephens of Lard Oil Co. ▶▶▶

Call for Presentations

75th STLE Annual Meeting & Exhibition
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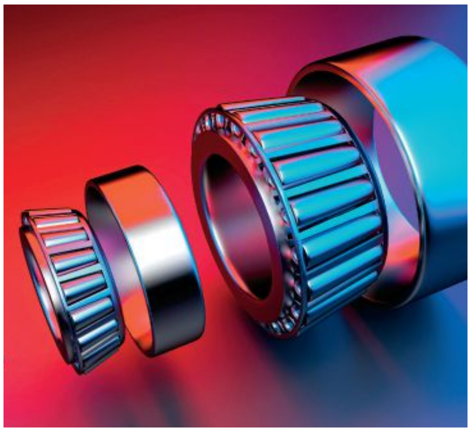

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- Nonferrous Metals
- Power Generation
- Rolling Element Bearings
- Seals
- Surface Engineering
- Synthetic and Hydraulic Lubricants
- Tribotesting
- Wear
- Wind Turbine Tribology

Abstract Submission
If you are interested in presenting at STLE's 2020 Annual Meeting & Exhibition, submit a 100-150-word abstract at **www.stle.org**. Abstracts are due **Oct. 1, 2019.** Notification of acceptance will be sent in December 2019. While you do not need to prepare a full manuscript to be included on the meeting technical program, you are invited and encouraged to submit a manuscript for review and possible publication in STLE's peer-reviewed journal, Tribology Transactions.

For more information, please contact:
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Society of Tribologists and Lubrication Engineers, 840 Busse Highway, Park Ridge, IL 60068, info@stle.org, www.stle.org.

NLGI honors Wayne Mackwood for meritorious service

LANXESS global head of detergent and grease technology and STLE-member **Wayne Mackwood** was recently honored by the National Lubricating Grease Institute (NLGI) with the esteemed John A. Bellanti Sr. Memorial Award during the 2019 Annual Meeting in Las Vegas.

The award acknowledges meritorious service on the NLGI Board, on technical committee projects or to the industry in general.

NLGI president and STLE-member Joe Kaperick states: "Wayne is richly deserving of this tremendous recognition for his tireless work on behalf of the NLGI and within the lubricating grease industry. He has served on the NLGI board of directors for eight consecutive years and contributed mightily in several committee and technical roles. Wayne's acumen and leadership capabilities also were recently validated by his elevation to the position of treasurer and appointment to the NLGI executive committee in 2018."

Mackwood is recognized as an expert in the design, manufacture and use of calcium sulfonate complex grease. He has developed more than 150 grease formulations and continues to be active in the development and introduction of new detergent formulations and technology. Although he has spent the majority of his 25-year career as a scientist, Mackwood has held roles in marketing and asset management. His contributions to the field include authoring more than a dozen technical papers, holding two patents and giving more than 20 technical presentations at leading industry conferences and seminars around the world.


Wayne Mackwood

In addition to his NLGI service, Mackwood also has served on the STLE board of directors and remains active at the local level. He holds a master's degree in materials engineering science with a focus on tribology from the University of Western Ontario.

Want to be recognized in TLT? If you have news about a new employee or if someone in your company has been recognized with an award or any other interesting items, let us know. Please send us your news releases and photos for publication in Newsmakers to TLT Magazine, Attn: Rachel Fowler, 840 Busse Highway, Park Ridge, IL 60068, **rfowler@stle.org**.

OLOA® 55600

Chevron Oronite is ready for the May 2020 launch of GF-6 with the introduction of **OLOA® 55600**, which has been thoroughly tested in real-world conditions, is compatible with hybrids and incorporates the company's latest passenger car motor oil technology. OLOA 55600 delivers the increased engine protection and improved fuel economy required by the new ILSAC GF-6 standard at an efficient treat rate and will provide coverage for dexos1, API SP and ILSAC GF-6 A & B all through one additive package. In addition, it protects against low-speed pre-ignition, provides robust turbocharger protection and is compatible with cars fitted with gasoline particulate filters. Customers also will enjoy the flexibility of wide-ranging base oil and viscosity modifier coverage in blending their finished oil packages. OLOA 55600 is formulated with the award-winning OLOA 55516 technology in mind. Oronite plans to offer additional flexibility to customers by making OLOA 55516 API SP and ILSAC GF-6 A & B capable. Oronite also will offer this technology with an embedded pour point depressant to interested customers.

Chevron Oronite
San Ramon, Calif.
(713) 954-6060
www.oronite.com

Photo courtesy of Chevron Oronite.

ST100 gas flow meter

Fluid Components International LLC introduces **ST100**, an all-new thermal dispersion technology gas flow meter that combines the most feature- and function-rich electronics with the industry's most advanced flow sensors to achieve a truly state-of-the-science flow metering solution for industrial processes and plant applications. The ST100 series transmitter is unsurpassed in meeting current and future need for outputs, process information and communications. ST100's bus communications have been certified by and are registered devices with HART and Foundation fieldbus. In addition, Emerson Process (Delta V), Yokogawa and ABB (800xA) have tested and verified ST100 Series' Foundation Fieldbus interoperability with their systems. ST100 also can be converted to any of these outputs with a simple card change in the field. To complete the solution, ST100 flow elements and process connections ensure the best possible measurements and effective installation. FCI flow element designs have been perfected and optimized through six decades of R&D and real-world experience in thermal dispersion technology and flow metering applications. With thermal dispersion there are no moving parts to foul or clog. This results in the greatest reliability and valuable savings on maintenance.

Fluid Components International LLC
San Marcos, Calif.
(760) 744-6950
www.fluidcomponents.com

Photo courtesy of Fluid Components International LLC.

Automated solution for endotoxin detection

Lonza introduces the **PyroTec™ PRO**, the first-ever fully automated, plate-based robotic solution for endotoxin detection. Integrated with the latest version of Lonza's proprietary dynamic control WinKQCL™ 6.0 software platform, the new system has been designed to meet the needs of rapidly changing requirements of QC testing laboratories for fully automated processing of simple to complex sample matrices. As a powerful combination of robotic liquid-handling technology with an automation software module, the system improves data integrity organically with the capture of new metadata from the automated preparation, adding traceability into tracking, trending and audit controls. It enhances assay robustness and reproducibility for increased confidence in the accuracy and precision of results and significantly reduces manual intervention, simplifying QC testing workflows and eliminating the human error potential. It also reduces re-test rates as well as out-of-specification and out-of-trend deviations, thereby improving the laboratory's performance. It offers considerable cost savings compared with conventional cartridge-based systems, which require the use of expensive reagents.

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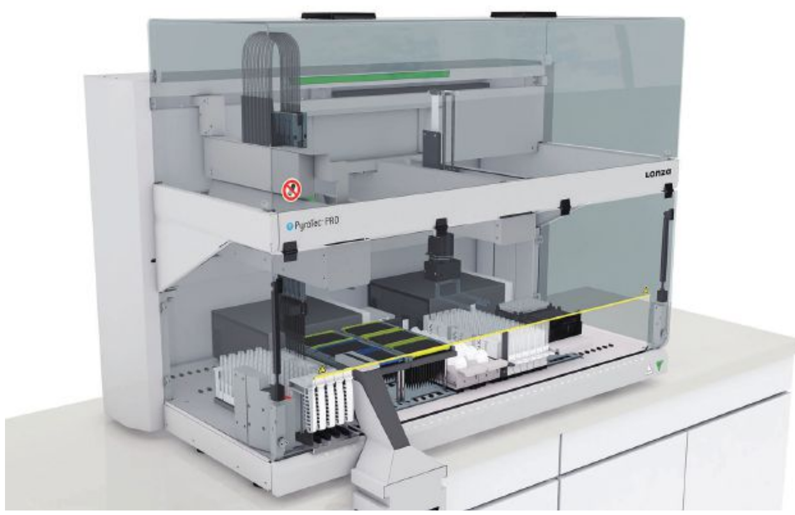

Photo courtesy of Lonza.

Tribology Encompassed

An education event hosted by the STLE Chicago Section

When: Oct. 16 and 17
Where: River Forest Country Club, 15W468 Grand Ave., Elmhurst, Ill.
Price: Both days: $295 STLE member, $375 nonmember
Day 1: $149 STLE member, $189 nonmember
Day 2: $149 STLE member, $189 nonmember
TBD discounted student rates

Schedule:

Day 1: Lubrication Basics
The event begins with tech talks based on the fundamentals of lubrication. Topics include base oils, lubrication fundamentals, lubrication additives, lubrication testing and synthetic lubricants.

This is followed by a session of STLE expert speed dating! It's exactly what you think. Maybe this is the technical expert you've been looking for, maybe not. Either way, you'll have five minutes with each industry expert, and after five minutes…SWITCH! If you can't imagine yourself speed dating, then think of it as networking in high speed.

Day 2: Tribology in Life
The second day focuses on a variety of topics that get away from the basics of lubrication. It's a day filled with presentations casting a wide net on the world of tribology. Topics include medical tribology, engine lubrication, biobased lubricants, marine lubrication, grease, food grade lubricants and dry film lubricants.

All leading into the October STLE Chicago Section dinner.

For more information and to register, visit **www.chicagostle.org.**

A global view of tribology education

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Executive Summary

If the world is looking for a cause to bring all nations together, the lack of quality tribology education globally might be a good place to start. That was the message delivered by TLT readers responding to this month's Sounding Board survey. TLT heard from tribologists from Canada to Ecuador, from Germany to Nigeria, and the story was universal—little or no tribology education or training at virtually all levels of education. Despite claiming Auburn University, the only school nationwide to offer a tribology minor, the U.S. fared no better than other countries and received more than its share of criticism. "99% of people in the U.S. think tribology is the study of dinosaurs; they are clueless," opined one STLE member. The survey's numbers supported the anecdotal reports—only 18% of TLT readers, regardless of nationality, have taken a formal course in tribology.

Q.1

What is the current state of tribology education in your country and how could it be improved?

Low. Almost any type of educational programs would help.

In Germany the tribology education of engineers differs from university to university. Sometimes tribology is just a side issue of machine components.

Turkey. Actually nothing—no networking for between related academics and no tribology-specific departments.

Trinidad & Tobago. Almost non-existent.

These are very interesting times for young tribologists. We need to train and pay the next generation appropriately.

U.S. We are not too bad, but there is definitely room for more education at the college level and even trade schools.

It is 25% in Nigeria.

In the Netherlands we have three universities of technology where some tribology is present, but currently there is only one very active one: Twente University. This is the only university with a full-time chair in tribology and surface modifications. In addition, there is a full-time chair in fluid mechanics who also is teaching advanced tribology stuff, and there are three part-time professors from industry and some associate and assistant professors.

Canada. Very little except in the workforce. Universities have too much to cram into four years already, but perhaps a five-year specialist's program.

U.S. Deficient. In chemical curriculums there is not much attention paid to friction and wear or their molecular basis. Likewise, I'm not sure how common screening techniques correlate with real world. For most students this is not that relevant, so an online approach would magnify the benefit.

U.S. Many in sales have minimal training.

There are not enough courses or programs concentrating on tribology topics. The increasing demands of precision machining and other technological requirements call for the education of more tribology specialists.

South Africa. It does not get enough focus at tertiary level. Should be made a compulsory module for bachelor's of science chemical and mechanical engineering degrees.

In Lithuania, tribology education is available only for graduate students or researchers.

South Africa. Outside of the universities, there are a few organizations that provide general courses on tribology.

In India the tribology education varies from mediocre to very good. It is mostly driven by the grease/oil manufacturing companies. So any tribology education/seminar is mixed with product promotion and paper presentation. Pure research is limited.

During your university studies, did you take a specific course focusing on tribology?	
Yes	**18%**
No	**82%**

Based on responses sent to 15,000 TLT readers.

Restore tribology courses even if they are embedded in subjects such as safety and reliability. Australia.

Is the U.S. tops?

In our country, tribology studies related to automotive components, bio-tribology of implants, surface coatings, etc., can be improved by surface-modification techniques.

Setting up the tribology department in the college or university level as the chemistry, chemical engineering and mechanical engineering departments.

In the U.S. it is growing as many companies are understanding that correct lubrication is an asset to their bottom lines.

Some online courses, but they are not helping me to improve.

U.S. Good.

Specialized training for graduate students.

U.S. Subject matter is mostly overlooked in most standard mechanical engineering programs.

U.S. Lubrication education needs to be a course at the undergraduate level in college. STLE needs to take more action in getting lubrication education available at colleges as well as other venues (outside of STLE activities).

U.S. It is moderately promoted.

Canada. Very little. Some courses at the Universities of Waterloo and Toronto.

Not high. We don't tend to focus on things of practical value in education.

In my country (Ecuador, South America) tribology education is really poor. I think it is highly important that we improve it. Influence of industries and companies could be important to obtain progress.

U.S. Needs to be more broadly spread across all industries.

U.S. The company I work for includes ongoing training. We also attend training outside the company for such things as refrigeration and refining.

U.S. Poor. I know only Auburn University offers a tribology undergraduate degree.

U.S. Minimal.

UK. Generally good. Needs more interdisciplinary teaching, e.g., lubricant chemistry for mechanical engineers and vice versa.

Sweden. Tribology courses are given at several major universities. There also is a joint national research in tribology for doctoral students.

In the Netherlands only one university is providing a master track dedicated to surface engineering and tribology. Student interest is generally low. Somehow the perception is that tribology is complex and not so interesting or relevant. It should start with changing the perception. Second, time is mostly spent on theoretical parts. I would opt for a better balance between theory and experiment by adding more practical exercises to the curriculum. This should already start in the bachelor phase to also increase the interest of the students.

Re-establish STLE. The organization is not credible.

OK. Not a lot of people know what it is and how it directly affects their lives. Not readily seen as an option for a career path. Start earlier. It is not really discussed at entry-level chemistry classes. I have a bachelor's of science degree in professional geology. In my undergrad classes, I wasn't exposed to tribology.

It's beginning to happen. Very focused on engineering, not chemistry.

Latin America. Either regular or bad. STLE needs to turn toward Latin America and focus in the region, invest time and funds to develop short courses, seminars, congress, etc. I live in Bolivia.

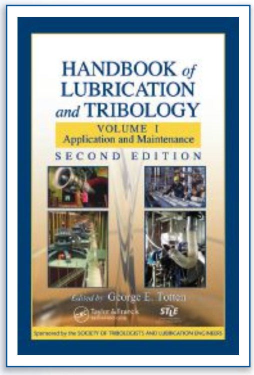
There's a small number of universities that specialize in some aspects of tribology (e.g., automotive engine wear, bearings, aerospace, medical, knee/hip replacements); however, very little is done regarding metal machining, metal forming, etc., regarding the tooling required to make those parts in the first place.

99% of people in the U.S. think tribology is the study of dinosaurs; they are clueless. Very few understand what it is. Those that do seem to take it to extremes.

In Western Canada tribology training is hard to get unless you are affiliated with a major oil marketer. ▶▶▶

Must-Have Resources for Your
Tribology Research

Exclusive Discount for *STLE TLT Magazine* Subscribers:



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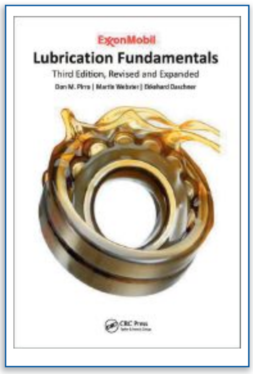

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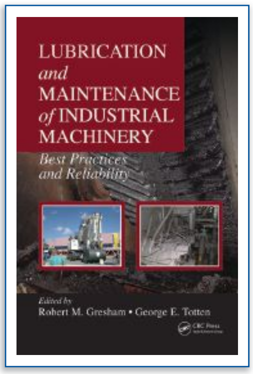

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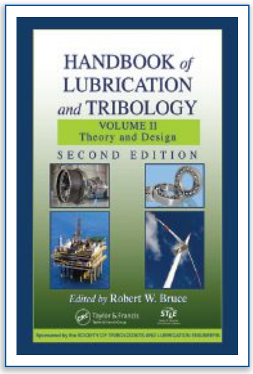

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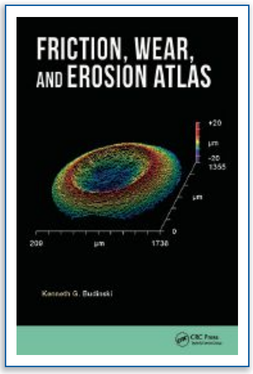

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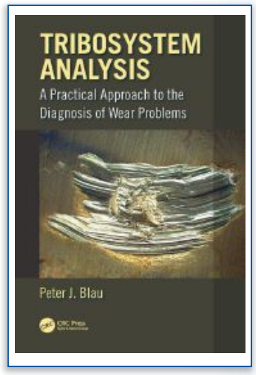

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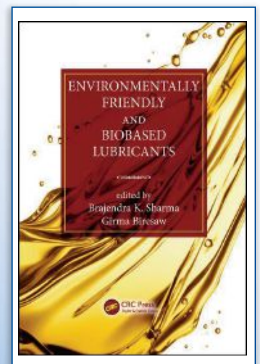

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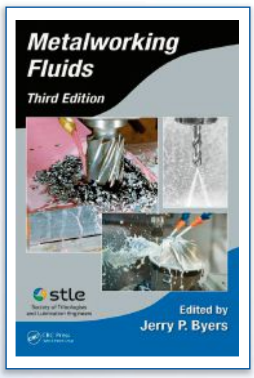

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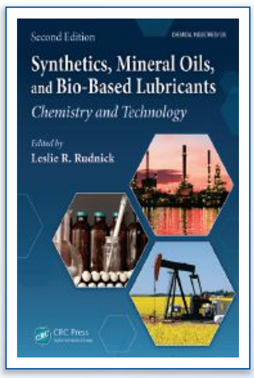

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Tribology education in the U.S. is fragmented, but some areas are making progress by doing such things as offering new graduate majors in tribology. The range of tribology educational content varies widely in short courses (days to 1-2 weeks), college term-length courses and courses given by consultants to private companies. The shorter the course, the more likely it will have a bias either toward lubrication, materials, coatings, mechanical designs, contact mechanics or trouble shooting. Therefore, there is a wide diversity and unevenness in the type and depth of available courses. Students will be presented with potentially incomplete or biased views of the subject depending on the duration of the courses and the specific experience of the speakers. This is true especially in team-taught courses in which instructors may change from year to year.

Formal curriculum-based education within the U.S. is limited and focuses on select areas of study.

Very labor intensive. Look at A.I. for better, more accurate analysis.

Does not exist (Ecuador).

U.S. and the state of tribology is marginally acceptable. I'm from the U.S., and I believe that most universities do not offer tribology as a course of study. All of my training came from on the job or from organizations like STLE, ILMA, NLGI, etc.

UK. Introduce tribology to undergraduates.

Canada. Not many courses that I have seen or found. Most of my learning has been through STLE avenues.

U.S. I believe it is and has been informative in the professional world; however, I am not sure of its application in academia or if there is a formal way to introduce it to the world of chemical engineers at the college level. Admittedly, it is not clear if higher education is incorporating lubrication technology.

Q.2 Machine learning is defined as the ability of artificial intelligence to learn from data without additional programming. How could that concept be applied to tribology?

Machine learning could be used to evaluate measurement data from tribological tests.

Actually, bearing manufacturers are into it. But surface hardness and stress online monitoring may contribute into power drives to set the thresholds for real-life conditions.

Directly tying AI to real-time lube analysis and operational data will perfect predictive programs.

It can be applied in the area of monitoring the wear rate, lubrication efficiency and frictional process in any mechanical machines.

It would be good to examine results of laboratory and bench simulations, e.g., engine oil approvals.

It can be applied through the parameters observed for various used oil analysis tests regarding limits for copper, silicon, etc., but based on OEM requirements for various machines and components.

AI could be used to determine the remaining useful life of a mechanical system based on wear profiles and historical data on specific makes and models of machines and also to auto-diagnose condition monitoring data like oil analysis and vibration data.

The vast array of data available from past and present tribology studies is well-suited for AI applications.

In tribology we have to ensure that the optimum life of the lubricant is obtained to keep costs and environmental effects low. By closely monitoring the operating temperature, we can develop models that ensure more accurate quantity of refill and re-lube intervals for the grease/lubricating oils.

Collating data from trends in lubricant analysis from various applications would make it possible to predict possible failures.

By using data acquisition, we can predict the current state of object. For example, wearable parts can be monitored by ML techniques, and we can optimize or predict the outcomes.

Micro analysis inline and react to real-time data.

Sensors for lubricant quality, torque, temperature, etc., would feed their recordings to AI processing, hoping that AI can predict onset of wear or other failures.

Condition monitoring; formulation improvement; non-lubricant solutions in design to reduce friction and wear. ▶▶▶

I am not sure we can utilize AI in tribology in the near future with tons of data. The development of a computer that powerful is the immediate problem.

Data from equipment in real time will have users be able to correct any problems with vibration, incorrect lubrication and others.

Determine acceptable operation and maintenance ranges, monitor machine operation parameters and trigger alert or corrective action when operation is out of acceptable range.

Used oil analysis would be a good start.

Tribology is not a key area for this technology. It is overkill.

Artificial intelligence should include tribology training.

Ongoing reading by machines of temps, viscosity, pressures, etc.

Yes, it could but would put people out of jobs in tribology.

Depends on what we are looking to find. This will likely require additional hardware and might not be economically viable.

In industries with a high focus on uptime, reliability and energy consumption, the ability to analyze, interpret and apply data from many systems in a complex production environment.

The concept of mass loss in a material can be monitored.

Several ways from formulating to independent testing of all raw materials and finished products to surface technology.

Precisely controlling where and when oil or friction reduction treatment fluid can be applied.

Predictive maintenance, predicting complex tribo-system behavior by deriving black box friction and/or wear models from data, finding proper interaction potentials for molecular dynamics with the aim of modeling sliding interfaces, understand how extensive the tribo-system is by being able to correlate seemingly unimportant influences.

Oil analysis would be a good start.

Lubrication analysis in real time. Oil analysis and condition monitoring seems a scam to suck money. When I take oil samples and there is water and drilling fluid in them, it would be good to know now and not in 45 days when the results are sent to corporate.

Used oil diagnosis.

This is predominantly used in oil analysis already and will be continued in other aspects of tribology.

Evaluating big data from tribology tests in literature.

How much potential do you think online courses can have on exposing people to the fundamentals, challenges and impact of tribology?	
Great potential	57%
Some potential	40%
Little potential	3%

Based on responses sent to 15,000 TLT readers.

Onboard analysis to change telemetry on the move.

AI-designed systems.

With proper programming, oil analysis and the recommendations and trends that follow could be performed by artificial intelligence.

More data needs to be captured.

This sounds good in principle, but I think it works better in some fields (manufacturing/machining/production engineering) than in others where the content is very broad and interdisciplinary. What works in one tribo-system may not necessarily work in the general case or for other tribo-systems that might superficially seem to be similar.

Determine origin of wear material/metal, i.e., what component might be generating it, more specific metallurgy.

It seems that the understanding of lubrication concepts within a process have diminished as technological advancements have been made with the process. When something goes wrong, but the data shows everything is OK, no one understands how to correct the situation.

Courses online.

AI would be able to define the fluid's type and condition, the application, the time in operation, the susceptibility factors, real-time vibration analysis, real-time particle analysis to provide recommended service intervals and to what extent.

First, industry needs to better understand AI's value to their world and appreciate it potential. I am not sure if it is widely understood. In my world of consultancy, it has not come up with great regularity. Looking at other liquid technologies to see how AI is being used might help. Having universities promote its use in tribology would foster downstream greater use or testing in lubrication and metalworking fluids.

One would need a huge amount of data for machine learning. If there are instances where large amounts of good data can be obtained to predict friction and wear, that might work.

I am not sure. I learned the fundamentals of tribology by running friction and wear testers.

Editor's Note: *Sounding Board is based on an informal poll of 15,000 TLT readers. Views expressed are those of the respondents and do not reflect the opinions of the Society of Tribologists and Lubrication Engineers. STLE does not vouch for the technical accuracy of opinions expressed in Sounding Board, nor does inclusion of a comment represent an endorsement of the technology by STLE.*

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AUGUST 2019 • VOL. 75, NO. 8

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Materials: Aug. 1

(Bonus Distribution: ILMA Annual Meeting, Sept. 21-24, Colorado Springs, Colo.)

- Additives
- Seals
- Oil Analysis
- Surface Engineering
- Wind Turbine Special Series: Part II

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October
Ad close: Aug. 23
Materials: Aug. 30

- Synthetic Lubricant Base Stocks
- Marine Tribology
- Computer-aided Tribology
- Automotive Tribology
- Wind Turbine Special Series: Part III

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November
Ad close: Sept. 24
Materials: Oct. 1

- Metalworking Fluids
- Oil Analysis
- Lube Fundamentals
- Wear
- Market Trends

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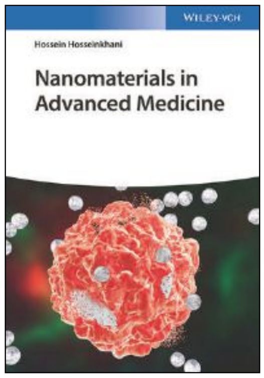
December
Ad close: Oct. 25
Materials: Nov. 1

- Additives
- Oil Analysis
- Metalworking Fluids
- Automotive Tribology
- Lube Fundamentals

Technical Books

Nanomaterials in Advanced Medicine

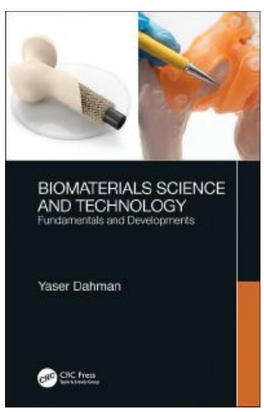
Author: Hossein Hosseinkhani
Publisher: Wiley



A comprehensive and multidisciplinary review of the fundamental concepts and medical applications of nanomaterials development technology, nanomedicine offers a range of multi-interdisciplinary approaches and brings together the field of chemistry, pharmaceutical science, biology and clinical medicines by focusing on design and preparation of biodegradable or non-biodegradable biomaterials for their biological, medical and pharmaceutical applications. Nanomaterials in Advanced Medicine reviews the concepts and applications of the combination of the technology of biology and engineering that are emerging as an integral aspect of today's advanced medicine. Nanomedicine provides the technology for imaging, cancer treatment, medical tools, bone treatment, drug delivery, diagnostic tests, drug development and angiogenesis and aims to exploit the improved and often novel physical, chemical and biological properties of materials at the nanometer scale. Available at **www.wiley.com**. List Price: $124 (USD), hardcover.

Biomaterials Science and Technology: Fundamentals and Developments

Author: Yaser Dahman
Publisher: CRC Press



Biomaterials Science and Technology: Fundamentals and Developments presents a broad scope of the field of biomaterials science and technology, focusing on theory, advances and applications. It reviews the fabrication and properties of different classes of biomaterials such as bioinert, bioactive and bioresorbable, in addition to biocompatibility. It further details traditional and recent techniques and methods that are utilized to characterize major properties of biomaterials. The book also discusses modifications of biomaterials in order to tailor properties and, thus, accommodate different applications in the biomedical engineering fields and summarizes nanotechnology approaches to biomaterials. This book targets students in advanced undergraduate and graduate levels in majors related to fields of chemical engineering, materials engineering and science, biomedical engineering, bioengineering and life sciences. Available at **www.crcpress.com**. List Price: $159.95 (USD), hardcover.

STLE Local Section Meeting Calendar

Events listed here are local section programs. For further details and a full listing of other upcoming section events in your area, visit **www.stle.org**. Meeting announcements can be sent to TLT Magazine, Attn: Rachel Fowler, **rfowler@stle.org**.

August

STLE Cleveland Section Golf Outing, Aug. 12, 10 a.m. (check in), 10 a.m. (putting contest), 11 a.m. (modified shotgun start), 4 p.m. (dinner), Shale Creek Golf Club, 5420 Wolff Rd., Medina, Ohio. Contact: Buck Evans, **buck.evans@sealand-chem.com**.

STLE Certification Exams

STLE is offering certification exams in the coming months. Here is the information on each exam:

- Aug. 16 from 8-11 a.m. at the Hampton Inn & Suites Cleveland-Airport/Middleburg Heights, 7074 Engle Rd., Middleburg Heights, Ohio.
- Sept. 27 from 8:30-11:30 a.m. at Lubrication Engineers Inc., 1919 Tulsa St. E, Wichita, Kansas.

For the online registration form, go to **www.stle.org**; click on the professional development tab at the top. Then go to certification, then registration. Online registration closes two weeks prior to the exam date. Onsite registration may be available on a first come, first serve basis. For more information and for other methods of registering, you may contact STLE headquarters by emailing **certification@stle.org** or calling (847) 825-5536.

COMADEM 2019

The 32nd International Congress and Exhibition on Condition Monitoring and Diagnostic Engineering Management (COMADEM 2019) is Sept. 3-5 in Huddersfield, UK. The University of Huddersfield is working in close collaboration and partnership with COMADEM International and aims to be the premier international event for industrialists, scientists and exhibitors worldwide. The congress will give you a unique opportunity to compare scientific and technical achievements with each other to determine how good they are internationally. For more information, visit **www.comadem2019.com**.

Tribochemistry Hakodate 2019

The 8th International Forum on Tribochemistry (Tribochemistry Hakodate 2019) is Sept. 12-14 at the Hotel Takubokutei in Hakodate, Hokkaido, Japan. The forum is organized by the Tribochemistry, Technical Committee, Japanese Society of Tribologists (JAST). The forum will discuss the basic mechanisms, applications and future prospects of tribochemistry based on the most recent results of research. All fields concerned with tribochemistry are welcome. Presentations will be on mechanism of tribochemical reactions, tribophysics related to tribochemistry, static and dynamic in situ surface analysis, additive tribochemistry and more. For more information, visit **www.tribology.jp/Tribochemistry_Hakodate_2019/index.html.**

ITC Sendai 2019

The International Tribology Conference (ITC Sendai 2019) is Sept. 17-21 at the Sendai International Center. The conference was founded by JAST. The ITC was first held in Tokyo (1985) following the JSLE-ASLE International Lubrication Conference (1975). Following successful conferences in Nagoya (1990), Yokohama (1995), Nagasaki (2000), Kobe (2005), Hiroshima (2011) and Tokyo (2015), ITC 2019 is held in Sendai, Japan. Tribology is the interdisciplinary study encompassing surface physics and chemistry, material science and fluid dynamics. For this reason, an integrative approach is imperative to clarify issues related to tribology. Interdisciplinary studies and discussion on the future direction of various fields is heavily promoted. Active participation of young researchers, specifically students, is strongly encouraged. For more information, visit **www2.convention.co.jp/itc2019**.

ESMATS 2019

The 18th ESMATS is Sept. 18-20 at the Gasteig Cultural and Conference Centre in Munich, Germany, and is hosted by OHB. The Space Tribology Course and Advanced Mechanism Design courses will be held on the Monday and Tuesday prior to ESMATS 2019. Full details will be released soon. Delegates will have the opportunity to tour the OHB Centre for Optics and Science in Oberpfaffenhofen. For more information, visit **www.esmats.eu/esmats2017/home/esmats-2019**.

ROTRIB'19

ROTRIB'19 is Sept. 19-21 at the Technical University of Cluj-Napoca in Romania. It is the 14th conference organized in a series of international scientific events on tribology. The general objective of this conference is to bring scientific contributions to fundamental and applied tribology. The event will provide an interdisciplinary forum for discussions and networking and will also aim to initiate collaborations among specialists. These collaborations will be focused on materials in tribology and their real-life applications in product design and reliability. Another key goal of this conference is the exchange of ideas and theories on new research methods and future trends. This will be achieved by bringing together specialists from various industries and academic backgrounds and leading researchers from diverse environments and scientific fields. For more information, visit **https://minas.utcluj.ro/rotrib2019.html**.

Gearboxes and battery electric vehicles

Multi-speed transmissions offer substantial advantages—plus a few drawbacks.

By Dr. Edward P. Becker

I've taken some heat for referring to the reduction gear assembly in battery electric vehicles (BEV) as a gearbox. While it is true that all production BEVs to date have used a single-speed reduction gear contained in a structure (i.e., a box with gears), the popular definition of gearbox generally seems to require gears of various ratios, able to be connected and disconnected by a shifting mechanism. A flurry of activity by transmission suppliers, however, suggests the single-speed gearbox may be about to go the way of the carburetor, inner tube and mechanical brake.

Multi-speed transmissions for BEVs are now available, and they offer substantial advantages.

A reduction gear is required in the first place as modern electric motors for vehicles typically have top speeds around 20,000 rpm, while the wheels of a typical passenger car rotate at less than 1,000 rpm at 100 kph (62 mph). Since electric motors have poor efficiency at low speed, the reduction gear allows the engine to turn much faster than the wheels (typically 7-10 times faster) so the motor is running near peak efficiency while cruising, thus increasing range.

Since electric motors provide little torque at high speed, little power is available for acceleration or hill climbing. One way to remedy this situation is a multi-speed gearbox, which would allow the engine to turn slower when the vehicle is at high speed, thus increasing the power available.

There are downsides to a multi-speed transmission for a BEV, however. Most obvious are additional cost, weight and mechanical complexity. Transmission suppliers point to increases in efficiency, as much as 15%, as offsetting these considerations. One remaining problem, however, is primarily tribological.

The reduction gears in current BEVs are usually lubricated with conventional automatic transmission fluid (ATF), which is optimized to manage friction and wear on gears that operate at high load only at high engine speeds. The electric motor, as previously noted, generates maximum torque at zero speed. While research into an ideal BEV gear fluid is ongoing, adding additional speeds further complicates the issue. Now the gears must be able to mesh and unmesh smoothly and without excessive wear under high-load, low-speed conditions as well as low load, high speed.

Downsides include additional cost, weight and mechanical complexity.

The automotive industry should recognize the need for intensive research into new ATFs for electric vehicles, perhaps modeled after the way engine oils are currently developed. Working on a common solution would greatly benefit automakers worldwide, and customers and service technicians would be able to avoid the confusion of possibly dozens of fluids, each specific to a particular manufacturer or model.

Ed Becker is an STLE Fellow and past president. He is president of Friction & Wear Solutions, LLC, in Brighton, Mich., and can be reached through his website at ***www.frictionandwearsolutions.com.***

Multi-speed gearboxes allow electric vehicle engines to turn slower at higher vehicle speeds, increasing available power.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Siloxanes and Silanes (126)

Sliding your way to rehydration

Articular cartilage loses fluid when compressed, but how does it recover so quickly?

By Drs. Wilfred T. Tysoe & Nicholas D. Spencer

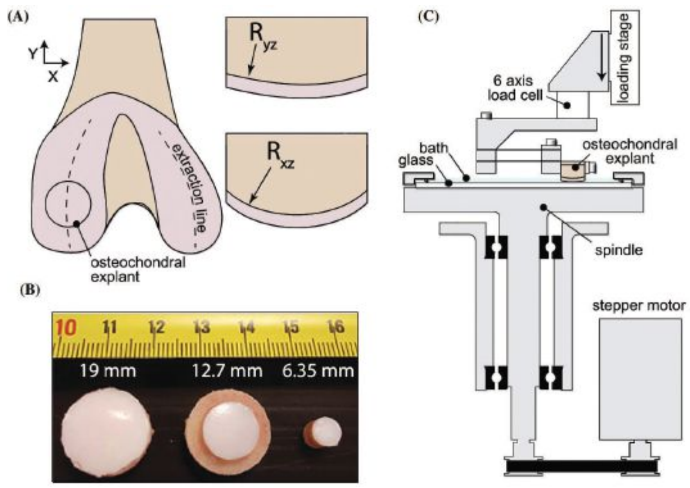

Figure 1. **Cartilage samples were extracted from the central region of bovine femoral condyles (a), machined to size (b) and tested in a bath of buffer solution, with or without added hyaluronic acid on a rotary pin-on-disk tribometer (c).** *(Figure courtesy of Ref. 1.)*

As soon as we put any load on our articular joints (e.g., knees and hips when we stand), fluid is squeezed out of the cartilage, which comprises the sliding surfaces in our joints and consists of about 80% water. This process, which can cause as much as a 50% compression, is one of the mechanisms by which cartilage sustains load and protects itself from damage. It is less clear how the cartilage recovers after loading, which it does at a rate of a few percent per hour, total recovery taking place overnight.

STLE-member David Burris and colleagues Brian Graham, Chris Price and Lucas Ramsey from the University of Delaware, in collaboration with Axel Moore from Imperial College, UK, recently reported results that offer a convincing explanation as to how this recovery may be occurring.[1] Previously they had carried out experiments on real cartilage in a reciprocating tribometer and observed that the sliding itself appeared to induce rehydration. They suggested a possible mechanism for the "tribological rehydration" that was based on the idea that hydrodynamic forces generated in the sliding contact pushed the fluid back into the cartilage.

However, an alternative explanation could be the influence of "reciprocal wedging," which involves the fluid "wedge" that is produced during sliding becoming compressed upon direction reversal in the reciprocating test rig. The induced squeeze-film effect from this wedge compression also could be a potential rehydration mechanism.

In order to settle the issue, Burris et al. changed their measuring setup to a unidirectional sliding configuration *(see Figure 1)*, thereby eliminating any possibility of reciprocal wedging. The experiment involved measuring the steady-state values of both friction coefficient and vertical deformation (once the initial elastic effects at a given load had been subtracted) as a function of sliding speed, load, fluid composition and cartilage-pin size. The deformation-versus-speed and µ-versus-speed graphs reproduced the results from the reciprocating study—a clear indication that hydrodynamic effects dominate over any wedge effect (which had been eliminated here)—and also showed that increased sliding speed above 10 mm/s led to a dramatic reduction in both deformation and friction.

As expected, higher loads led to greater compression, but higher loads also required higher speeds for fluid recovery, reflecting the competition between the hydrodynamic pressure induced by sliding and the interstitial pressure in the cartilage resulting from loading. Increasing the pin diameter appeared to facilitate the recovery of both deformation and the drop in friction coefficient, consistent with a hydrodynamic mechanism.

The addition of a large polysaccharide, hyaluronic acid (HA), to the tribometer bath, led to a reduction in friction, especially at low speeds, suggesting that it also may interact with the cartilage surface and act as a boundary lubricant. The HA also led to a reduction in the speed at which both deformation and friction began to drop. In other words, the HA, surprisingly, appeared to facilitate the rehydration process. While the increase in viscosity due to HA addition might be expected to reduce the rate of cartilage rehydration by hindering flow into the tissue, the increased hydrodynamic pressure caused by the presence of HA appeared to more than compensate for this effect.

This work moves us a little closer to understanding the mechanism by which cartilage functions so effectively and over such a long time in our joints and hopefully toward approaches to both repairing and imitating this extraordinary tissue at some point in the future.

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Nic Spencer is professor of surface science and technology at the ETH Zurich, Switzerland, and editor-in-chief of STLE-affiliated Tribology Letters journal. You can reach him at ***nspencer@ethz.ch****.*

FOR FURTHER READING

Burris, D. L., Ramsey, L., Graham, B. T., Price, C. and Moore, A. C. (2019), "How Sliding and Hydrodynamics Contribute to Articular Cartilage Fluid and Lubrication Recovery, *Tribology Letters*, **67**: 46.


STLE 365 app
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The challenge of metal-removal fluid specifications

If you're thoroughly confused, that probably means you understand.

By Don Smolenski


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In a previous TLT article, I discussed the GM LS2 plant lubricant standards and how we used them to put more rigor into how GM specified and procured plant lubricants. In this article, I examine how much more challenging it is to specify metal-removal fluids (MRFs) than "ordinary" plant lubricants such as hydraulic fluids.

Whereas GM LS2 basically had one specification for an antiwear mineral hydraulic fluid (with different viscosity grades), MRFs include the broad categories of straight and aqueous fluids, each with markedly different compositions and performance characteristics. I won't claim that what we developed at GM is the best way to define MRFs, so if you are thoroughly confused when you finish reading this article, you grasp the complexity of what we were trying to do!

Straight oil MRFs, like mineral hydraulic fluids, are used in neat form. Several key properties can be specified using available standard tests. Unfortunately some of the most important fluid properties, such as machining performance or misting tendency, are generally lacking for standard tests—much less for passing limits. To further complicate matters, the workpiece (and its relative machinability) and tool materials can vary greatly, and there are a multitude of different machining processes (milling, drilling, grinding, broaching, etc.), each with their own fluid needs. It would probably be easier to train a Labrador not to chase squirrels than to write a comprehensive specification.

A multitude of different machining processes each needs its own fluid.

So how on earth do you write specifications for MRFs? In the LS2 standard we first specified tests for certain properties (such as rust, corrosion, foaming tendency), where we believed there was a relevant existing standard test that could be applied and reasonable pass/fail limits chosen. Then we considered additional tests that we considered at least reasonably relevant (OK, maybe a little bit of a reach) to machining, but we had no clue as to what a reasonable passing limit might be.

So what the heck good are they? We included them in the specification as *report* only, the thought being that we could, in the future, review in-use performance in any given property area and see if—at least in a qualitative sense—we observed a correlation between the bench test results and performance in actual machining processes. If so, we could use this as a basis for setting a pass/fail limit (very much easier said than done!).

Specifying aqueous fluids provides an even greater challenge. We considered three different broad categories of fluids: soluble oils, semi-synthetics and synthetic oils. Soluble oils were loosely defined (by many but not everyone) as emulsions (with water), semi-synthetics as microemulsions and synthetic fluids as true solutions. Each of the three categories was further subdivided based on whether or not they had extreme pressure additives. These MRFs are diluted with water prior to use, and the characteristics of the diluent water (e.g., hard or soft, chloride concentration, etc.) have very significant effects on fluid performance. Some of the performance tests were to be run on the neat concentrate and others on the concentrate diluted to the recommended concentration with either a "standard" diluent water or the specific plant water, if agreed upon between the supplier and the plant.

Did these tests alone specify a fluid that would enable productive machining? Absolutely no, not even close! But they did exclude fluids that failed these basic tests, so at least we were starting to narrow the field. Machining trials would still be required. Even with all this, we still haven't begun to address the in-use maintenance of MRFs, which is very complicated and extremely critical to their machining performance.

Thoroughly confused yet?

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