Perfecting Motion: Tribology and the Quest for Sustainability

Episode 4 – The Role of Nanotribology in the Quest for Sustainability

Contributors: Dr. Neil Canter, STLE Advisor, Technical Programs and Services, Dr. Steven Thrush, Tribologist, U.S. Army DEVCOM Ground Vehicle Systems Center, and Dr. Marina Ruths, Professor of Chemistry, University of Massachusetts Lowell

Neil Canter:
Examining interactions among atoms and molecules at the nanoscale will help us gain a better understanding of how-to perfect motion on our way towards sustainability. To help us, please welcome Dr. Steven Thrush, a tribologist from the US Army DEVCOM Ground Vehicle Systems Center. Dr. Thrush has been working in the nanotribology field and has co-authored papers, including one that received an award from STLE earlier in 2021 regarding an evaluation of zirconia nanofluid.

Steve, congratulations on your award, which you share with your colleagues from the U.S. Army and Oakland University. Welcome, and thank you for joining us.

Steven Thrush:
Yeah, thank you for having me, Neil.

Neil Canter:
So, let's start here on nanotribology, which I think is a very pertinent subject because when we're trying to look to perfect motion, we want to learn more about what's going on at the atomic and molecular level.

Briefly describe what you've learned about nanotribology, and nanofluids. And can you provide one or more examples about how a nanofluid can contribute to a process that impacts society?

Steven Thrush:
Sure, so nanotribology is a widely researched field and nanofluids are only a small part of that. So, in terms of the greater research field, I could best summarize it through an experience I had attending the STLE Annual Meeting in the nanotribology sessions.

As an experimentalist, I am amazed by some of the recent advancements in probing the tribological interaction of a single contact using either an atomic force microscope or scanning tunneling microscope. They have the capability to capture at a fundamental or mechanistic level the forces at play, the friction, the wear tribal film growth, and many other aspects. At these sessions, there are also great molecular dynamics simulations, which I cannot claim to be any kind of expert, but it is a great experience watching the discussions between the nanotribology experimentalists, like myself, and the nanotribology modeling and simulation experts, and we relate our findings with each other and see how they might be joined for a more unified theory in answering some longstanding questions in the field. And one great example of this is understanding how ultralow friction may be obtained through the use of 2D materials such as molybdenum disulfide, graphene, or diamond-like carbon coatings. But more specifically to the nanofluid research area, I spent a lot of time investigating how to better disperse and stabilized nanoparticles in oil.

The literature had already proven that these nanoparticles could improve the friction and wear performance of the fluid through a variety of mechanisms, depending on the size, the morphology, and the chemistry of the particle. But if they are not stable for months or even years, they're not commercially viable. I could obtain nanoparticle stability on the order of months through the use of surfactants and dispersants, but now there are researchers that have addressed the issue obtaining stability for years, even in a fully formulated oil and this is key because of the potential interactions between the other additives in the package. Perhaps most critical being the dispersant, so this advancement really reinvigorated my interest in the area.

But as far as the impact to society, understanding friction wear at a nanoscale level will allow us to design more efficient mechanical systems. It may change how we surface finish or add coatings to hardware, even how the fluids are formulated themselves. We will have less frictional loss in the form of like waste heat and more usable energy. So, it really is an exciting time to be a researcher in this area.

Neil Canter:
Thank you for your answers, that's good. One thing I think to follow up on is how does, as we are trying to perfect motion and get closer to low or maybe ultralow friction and wear, how does friction and wear appear to you as a nanotribologist versus many of the rest of us who see it on the macro level, whether we're driving a car or skiing down a mountain or that sort of thing, what are the differences when you probe down to the molecular level?

Steven Thrush:
Well, it really kind of correlates to what you're emphasizing. So, at a macro scale, oftentimes in these studies you're ignoring or neglecting the nano or atomic kind of interactions. But you can imagine that when you have like a highly idealized situation or scenario, with like an atomic force microscope, the atomic force microscope probe can be a single atom and the surface that you're testing can be atomically smooth.

So, really what you're highlighting in these tests is the atomic interaction, not the more macroscale-like topography and interactions that you might have, so we really focus in on a single asperity but it's also critical to relate that to more micro- and macroscale levels, as well, to really enhance the full picture of what's going on.

Neil Canter:
Because certainly I can relate from a macro level—not being a nanotribiologist—if you think about an extreme pressure, at an example, where it's going to react on a surface to form a film basically, at a high temperature, but I presume somebody like yourself can look at that or any of nanofluids and see what it will do on an atomic scale in terms of when it's an atom of the nanomaterial than a nanofluid is going to do to an atom of the surface material.

Steven Thrush:
Correct, that interaction is critical. A way to relate it is the nanofluid that I deal with contains nanoparticles around 5 nanomaterials in diameter, and that's an average measurement. And really the

interaction with the surface on that nanoscale if you have something too smooth, the nanoparticle may actually like roll on the surface. If you have something with a little bit of nanotopography, you might be able to capture or entrap the particle within that topography, and that's kind of what ultimately leads in the generation of antiwear films through nanoparticles.

So, right that interaction at a nano level is very key in understanding the mechanisms of the nanoparticles' performance.

Neil Canter:
Are you almost suggesting that having sort of some topography or some roughness in the surface at a nano level may be a better thing—let's say than having a very smooth surface?

Steven Thrush:
Yeah, there's actually a very interesting research article from the University of Pennsylvania if you're familiar with Rob Carpick's group. They actually found that when they took their atomic force microscope, they actually had atomically…I think fairly atomically smooth silicon wafer that they actually had to roughen the surface before a tribofilm was generated.

So correct, you need some roughness, but it's correlated to the size of the particle itself. There's this interaction there to entrap the nanoparticle in the topography.

Neil Canter:
Fair enough and let me comment. Living and I live outside of Philadelphia, Steve, and work at the [STLE] Philadelphia Section. Rob Carpick is a major supporter of the Philadelphia Section, so I know Rob quite well. So, thank you for bringing his name up in this. He's a very active member in STLE and I know in this field as well.

So, let's move on. I think you mentioned to a certain extent about with nanofluids about the issues with dispersions and as surfactant chemist, Steve, I can relate to that, particularly when you're dealing with a hydrophobic oil, let's say which is a hydrocarbon-based oil and a nanoparticle that may have some polarity to it.

Trying to get that to remain stable and not drop out or not agglomerate can be an extraordinary challenge, so it's very heartening to hear that some researchers have come up with ways to keep those type of nanoparticle dispersions stable for even years, which is what we're looking for here. So, talk about some other challenges faced in learning more about how to use nanotribology to reduce friction and wear.

Steven Thrush:
Sure, yeah, this is a great question because of how multidisciplinary tribology is. There are still many unknowns pertaining to a lot of the physical and chemical mechanisms behind tribological performance of additives. So, we really need the collective expertise of material scientists, chemists, physicists, and engineers to reach a consensus on many of these phenomena.

The good news is the instruments that we have continued to advance for more sensitive control and measurement of nanotribological context, this will enable us to more accurately characterize what is happening at an atomistic level. Molecular dynamics simulations are also increasing in fidelity, so the tools are in place to conduct really powerful research in the field. Joining nanotribological studies from the micro- and macroscales, as well as the modeling and simulation across these scales, should be a concerted effort though to advance the science and how they relate with each other. But pertaining nanofluid research, there's still much more to be done investigating all of the proposed mechanisms behind nanoparticle performance.

Nanoparticles have been documented to polish surfaces, roll along the topography, filling the valleys, effectively mending the surface and form protective films. There's also an additional mechanism specific for layered nanoparticles, either in the form of nanoplatelets or fullerenes where there's low friction shear along the layers of these structures, but one mechanism that I have a deeper experience with is the ability for these cercone these metal oxide nanoparticles to form these antiwear films through a process called tribo-sintering.

So, tribo-sintering means that tribology drives a sintering process through the entrainment and accumulation of nanoparticles, followed by diffusion processes driven by the pressure and temperature in the contact to join these particles together in a cohesive film. Researching the science of sintering, I found that there is a pressure-driven sintering process called dynamic compaction. This process requires an impact pressure, so imagine gigapascal scale pressures occurring over microsecond time scales. I calculated the pressure and time scale, and nanoparticle would be subjected to in a single asperity contact and it correlated well to this type of sintering process. We had found that increased temperature and pressure would assist the tribo-sintering process and that also assists dynamic compaction.

So, it was pretty exciting to find a greater connection between tribo-sintering and a conventional sintering process. However, we still do not have a true *in situ* experimental verification of this mechanism, but we have investigated the morphology of the films' post-test and found the diffusion between these particles to form these films. And there have also been some visualizations of nanoparticle antiwear film growth through modeling and simulation efforts.

So, relating back to what I previously said about relating nanotribological studies to the micro- and macroscale, what I mean by this many times these studies are highly idealized at the nanoscale, so if everything is tightly controlled, your operating conditions, your surfaces are atomically smooth and your atomic force microscope probe is a single atom, that is kind of the emphasis of the test. In the macroscale, really people don't focus on how it relates to the nanoscale in general, but if your fluid contains nanoparticles the interaction between the asperity context and the nanoparticle is essential—it's necessary for this sinter tribofilm growth, so you cannot neglect it. You cannot ignore it. It is part of the full picture, so you have to understand the process across all the scales from atomic all the way through macro and really join them in a unified theory. So there needs to be a collective research effort from the greater tribology community, in discussions with each other, if there is to be any chance for a true understanding of the additive and the mechanisms behind its tribological behavior.

Neil Canter:
That said it brings me up to a couple points that may help us to answer the third question regarding the movement towards sustainability. I think you're saying, in the sense, nanotribology is one piece of it, but you need to have a full piece of it, but not nano—but also macro tribology in order to help better understand how to move things toward sustainability, perfecting motion, reducing friction and wear,

Steven Thrush:
Correct

Neil Canter:
Okay, so let me back up with one point you made in terms of what you were talking about and if you would be so kind to just give a brief definition of sintering for those who don't know what it is, please.

Steven Thrush:
Yeah, so a lot of people when they think about sintering, they think of a thermally driven process, so you'll have a powder that will be subjected to high temperatures. So, if you think of Zirconia, specifically, it takes oh about 1400 degrees Celsius to thermally sinter a ceramic cercone part, so you have a furnace that can achieve these very high temperatures so that this powder that you have—that this dry powder that you might precompact before sintering, all of these individual particles will diffuse together to make a cohesive part.

So, what's kind of interesting on how a thermally driven sintering process relates to a tribo-sintering process is we run the test at 100 degrees Celsius in our tribometer. We're not running at 1400 degrees Celsius. You'd have a lot of issues with the auto-ignition of the oil itself if you're doing that, so. But really what's fascinating about it is, we actually have a more pressure driven sintering process, and I actually found that there are a few different ways to achieve this through dynamic compaction. You'll either have a punch and die with a powder that you'll drop a dead weight and that impact force of dropping a dead weight on the punch will have that energy needed to form a cohesive centered part.

So, in our tribological study, if you entrain a nanoparticle between surfaces, you will have that event that there will be a stress concentration point on that particle and there will be neighboring particles with it that have accumulated in the contact to generate these films. So, you have to kind of think less along the lines of what we're used to seeing from a thermal sintering process and more along the lines of a pressure driven sintering process.

Neil Canter:
So, are you saying, and again for those out there, that you can sort of simulate the harsh temperature conditions in the sintering process by applying pressure and running at a temperature that's equivalent to the boiling point of water?

Steven Thrush:
Right, it's really the majority of the energy input from this process is by the pressure applied, this impact pressure.

Neil Canter:
Fair enough. Good, thank you.

So, why don't we finish up by and I think you've talked to about it a little bit, but let's talk about where nanotribology is going. You've alluded to it a little bit more, but if you want to expand on where you see the future of it and what it's going to look like?

Steven Thrush:
Sure, so I think it's important to look at the past of nanotechnology to kind of forecast its future. And you can always find nanotribological studies pertaining to essentially all areas of tribology, because there is always a need to understand any area at a more fundamental level. Understand the fundamentals of it. The mechanisms for performance will actually equate to the higher potential for optimized mechanical systems, if you will, so it becomes clear that nanotribological studies will accompany emerging technologies as well. And the power of these nanotribological studies will only increase as the experimental tools improve, and modeling and simulations increase in fidelity, and that's why I strongly encourage collaboration across the research community of whether it be from academia, national laboratories, industry, government agencies, because every research facility will have their strengths and weaknesses based on their capabilities just as every researcher will bring a different perspective to the conversation, depending on their background and experience.

But I see a bright future for nanotribological studies. For something that's particularly intriguing to me is the electric vehicle technology. If we apply the same methodology to understand the fundamentals that the mechanisms, there is one area that I think is quite interesting to me is the manipulation of ionic liquid additives. These molecules you can actually apply an electric field and attract and align molecules on critical surfaces, offering locally enhanced friction wear performance. So, it would be interesting to see how, if somebody took a nanotribological approach to this science, to really understand the fundamentals of the mechanisms, how to attract, how to repel, based on an electric potential. Really, you could get at the core of how to formulate a fluid to offer this locally enhanced friction wear performance.

Neil Canter:
So, two points and thank you for those comments. One on ionic liquids, ionic liquids are materials that are actually salts, much like sodium chloride, which is a salt, but instead of being a solid at room temperature, many of these or liquids with melting points in these ranges. And I agree, I've followed the ionic liquids as well and see them as being very useful, and the other comment I'll make is you had talked about, at the beginning, about the linking between the theorists with the molecular dynamics and experimentalists such as yourself with AFM (atomic force microscopy). I assume, Steve, you envision the modeling will get better and AFMs, while they're very good and they do an excellent job, there's new technology I assume that's coming out there that may be even better or will improve upon the capabilities of AFMs.

Steven Thrush:
Right, being able to get a really higher-resolution data, more sensitive data at these levels, it can always be improved, and it is quite amazing how they manufacture AFM probes to get a single atom as the tip of the probe and it is also quite amazing how we can generate two-dimensional structures that are atomically smooth, right. So, really, when we can more idealize the situation, the scenario, the more valuable the data that is the output from the experiment, so it's exciting as an experimentalist, and I see really some great work on the modeling and simulation side as well.

Neil Canter:
Well, very good, Steve. Thank you very much for your time. I think that works well and our timing is good. So, thank you!

Neil Canter:
To gain a better understanding of friction and wear in the nanoscale, nanotribiologists are looking at natural systems such as human skin as a model we use in the development of technologies that can, as an example, modify the texture of human skin. This work may prove to be important in developing skin care products that can lead to youthful looking skin, which is demand some consumers have as they get older.

An individual working on this particular aspect of nanotribology is Dr. Marina Ruths, a professor in the Department of Chemistry at the University of Massachusetts Lowell.

Marina, welcome, and thank you for joining us.

Marina Ruths:
Thank you.

Neil Canter:
And let me begin by asking you briefly to describe what you've learned about nanotribology, and can you provide one or more examples about how nanotribology can contribute to a process that impacts society?

Marina Ruths:
Yeah, so nanotribology provides us a lot of fundamental information about the relationships between structure and property of materials from the atomic scale up to the nanometer scale. And with this, armed with this new knowledge, we can move to applications where we can design new materials and make better use of existing ones for effective lubrication in many different areas.

So, nanotribology research focuses on molecular films and surfaces with roughness from atomic scale up to hundreds of nanometers, so we're typically dealing what we call boundary lubrication, and that's where high points on rough surfaces come in contact, and that can sometimes be at fairly high pressures. So, we study the deformation of the surfaces locally, which we typically talk about in terms of contact mechanics. We study friction forces, and we study wear—so damage processes and mechanisms as well, and things that we learn from that are the effects of confinement on materials properties and we can also learn about something that you had a previous podcast on chemical reactions on the surface, how they are affected by the mechanical stresses in the sliding contact.

In soft materials, for example, related to skin and some many materials in the body, friction is very sensitive to organization and, to say, collective or cooperative relaxations of self-assembled structures, much more so than, for example, adhesion measurements are, so we can learn about differences between different types of materials from these friction measurements. In terms of impact on society, while tribology, in general, is associated with strives to reduce energy consumption and the wear and damage of materials, specifically for biomedical applications and future therapeutics and also in the cosmetics applications, we have many different types of moving contacts between surfaces in the body, and we also have very commonly the additional aspect of them being aqueous systems, which introduces additional complications.

Neil Canter:
What type of complications are introduced being aqueous systems?

Marina Ruths:
First of all, you typically have multicomponent systems with different solubilities and very often in biological type systems, the lubricating properties are really strongly dependent on the presence of hydrated molecules. So, if you disturb the hydration of, for example, charged molecules or hydrophilic molecules, you can lose the lubricating properties. And then the flipside of that is that where if you can keep the water where it needs to be, you can sometimes achieve low friction and wear-resistant surfaces.

Neil Canter:
And one point of clarification for those who are not technical, it's hydrophilic molecules or molecules that are water loving, as opposed to hydrophobic molecules, which are oil loving, per say.

Okay, what in your perspective—you've been in the field for a while, how is the nanotribology field evolved over time?

Marina Ruths:
So, I myself had been involved in nanotribology research since the mid-90s approximately, but nanotribology experiments, as we know them now, became possible from the early 1980s, with the development of new instrumentation. So, scanning probe microscopy specifically, so AFM. Also, another type of instrumentation, the surface forces apparatus, became widely used for friction type experiments and at the same time came the realization of how an existing type of instrumentation the quartz crystal microbalance could be used for tribological studies. So, the term nanotribology came around a little bit later in the early 90s when research was already underway. And in the early days of this type of research, very many different phenomena were observed, commonly very different from bulk friction in terms of the magnitude of the friction forces, their load dependence, their dependence on sliding speed, and so on.

In many cases, these observations could not be described or be predicted from bulk mechanical properties of the materials or from previous macroscopic, so large scale tribological studies and, of course, it was initially very hard to connect between results obtained with different techniques on the nanoscale. So different instrumentation led to having experiments done at different lateral length scales, different loads or normal forces and pressures, speeds on surfaces with different topography, a different structure on the surface and at different lubricant film thicknesses. So, there was a variety of results, and it was difficult initially to reconcile a lot of the results that were being obtained. But since then if we're now talking from the early 1980s and on, increasingly sophisticated theoretical models have been developed, and many connections between results from different nanotribiology techniques have been made, thanks to the development of computer simulations in the field, which really helps because typically in tribology one studies a buried interface and it's difficult to sometimes tell from a before and after analysis type situation what really happens at the surface. Connecting nanoscale to larger scale friction results is still a challenge and also during this time of development, nanotribology has become understood to be more interdisciplinary and multidisciplinary than originally believed when only a fraction of the possible systems had been studied and fraction of the possible applications had been discovered, and some of these areas have developed into subfields of their own, so, say, nanomechanics, biotribology on the nanoscale and so on, and that development is still going on.

Neil Canter:
Very good, so it sounds like it’s still, you know, even though it started in the 1980s, almost 40 years ago now, it’s still a field that’s unfolding, new applications are being looked at, new information is being provided, which I think is one of the themes of our podcasts in trying to strive towards perfecting motion and sustainability, looking at these type of small scale type interactions are critical. So what challenges are faced in learning more about how to use nanotribology to reduce friction and wear?

Marina Ruths:
Yeah, so a lot of progress has been made in all this time, but commonly real systems are more complex than what we typically study in fundamental research in our research laboratories. So real systems are multicomponent systems, they are heterogeneous at different length scales, they may change their topography and the chemical functionality at the surface with time and after repeated sliding and often when we do a lab experiment, we start from really-well organized and defined systems, but real systems with time and age have different components developing in them that we may call contamination but it’s maybe just a natural situation that develops. It’s very hard to study a buried interface, so when your sliding surfaces are in contact and then you’re trapping material between them, how do you access that region with spectroscopy or with modeling and so on and that can lead to difficulty in understanding where different regions of deformation or other phenomena take over in a real heterogeneous system compared to what we study in the lab.

It’s hard to take the results you get and make general conclusions that apply to other systems, so we are now at a point in this type of research where it’s often possible to understand a chosen or given model system at the nanoscale, but it’s hard to create general design rules for topographies, elastic properties, and so on. These models are beginning to emerge now in the last 10 to five years, so something like this. Scaling up to macroscopic phenomena from nanoscale remains a challenge, so realistic surface topographies and random roughness is a problem. For bio-related, and as we say, biomimetic systems, it’s very popular to try to get inspiration and understanding from nature right now. We’re still struggling to understand what components in these systems are most important for their friction. Nature has many as we say, smart systems, so systems that adjust to external stimuli and so on, but the response is still quite complex and hard for us to study and there is a desire to develop systems that are more as we say, self-healing. So, with replenishing of the lubricant or repairing their own surface wear and damage in some way and maybe one can also say that there could be a need for something that I would kind of tentatively call like a self-cleaning system that it would not accumulate wear debris and molecules that are undesirable at the surface, but that they would keep the preferred lubricant in the sliding content.

Neil Canter:
Interesting that you’ve pointed out about natural stuff, Mother Nature. I assume you’ve built up an appreciation for what Mother Nature is doing at these systems, the complexity and yet the beauty of what Mother Nature has done in many of these systems. Can you share a little bit more about what you’ve seen from natural type system, whether human skin, or anything else you’ve looked at that’s naturally derived?

Marina Ruths:
So, I think that the most discussed current topic in biological systems, and that this has been a hot topic for a while, is how water lubricates surfaces, which I alluded to a little bit before. So very many molecules on surfaces in our body, for example, on the cartilage, are charged, which makes them very

likely to be surrounded by water molecules. It is believed that it's the high mobility of the water molecules that lead to low friction, for example, but also the structure these molecules themselves in the way that they are physisorbed, so just physically attached, not chemically bound to surfaces and how they extend from the surface, give them a pretty good load bearing capability as long as the water molecules stay around them and so on, so those are fascinating properties. Then also we should though keep in mind that typically systems that we find in nature are designed to work for a specific purpose under a specific limited set of conditions, and they are optimized for that set of conditions, so when we take inspiration from them, there might be a lot of work for us to do to use that same design principle in a different system.

Neil Canter:
And when you talk about water, that to me is striking because many of us who work on the macroscale, as I've done for much of my background, consider water to be an inferior lubricant, which may be kind in terms of doing that, because many of us work with, of course, oil and hydrophobic type hydrocarbons to provide lubrication and wear, even not just mineral oils, but also natural synthetic lubricant types, so here you are talking about water and the keys to hydrating particular components on surfaces as being the key to lubrication, which to me is a striking contrast to how a lot of the industry feels about water in general but certainly I agree that is an important aspect.

Marina Ruths:
Yeah, so in many traditional lubrication principles, water replaces the molecules that you would like at the surface and, yes, then you run into enormous problems, plus that water also reacts with the surface and allow a lot of different phenomena that are undesirable in on many metal surfaces especially, of course.

Neil Canter:
Yeah, of course, you're talking about corrosion, rust corrosion, which, of course, is something we fight everyday as tribologists. Yet I can understand you talking about, you know hydrating various hydrophilic-charged molecules, water-loving molecules, can be the key to reducing friction wear at those particular types of surfaces.

So, let's continue on. And I think we've done a lot of things with natural, which, of course, is a lot of where this industry is going from a sustainability standpoint. So, talk a bit about how developments in nanotribology are contributing to the movement towards sustainability, which is really the theme of this podcast.

Marina Ruths:
Right, yes, so traditionally, of course, tribology has been on this path from the beginning, so to help solve different problems with energy consumption of course, originally, so generally the standard things that remains so critical for us: to reduce the use of fossil fuels, to reduce the production of carbon dioxide and heat pollution, and so on. And of course, the reduced wear of materials in a machine or man-made type of system you have, of course, often the opportunity to replace a worn part but still you want to avoid the cost of that. In a biological system, it might become a rather complicated operation, no pun intended, to replace a worn part and also when you are lubricating systems in general, you want to reduce any of their effects in terms of their polluting the environment around us. So, friction reduction is often desirable for many systems, not all, of course there are like brakes and clutches you don't necessarily want low friction, you want it high, but for many systems reducing friction is something

we're striving to and that can be achieved, for example, by developing new lubricants from renewable resources, for example, from agricultural byproducts, and there is a huge push towards this. And then of course, the related research on how they are possibly biodegradable and what can be done about their stability towards oxidation and various types of issues like that. But also in terms of friction reduction and wear reduction, the contact geometries in our sliding contexts are very important, so people work on surface texturing, some of them inspired by biological systems and this is something that started probably over 15 years ago, but it has really taken off in the past 10 years, so texturing of surfaces at the nanometer scale and micrometer scale, often in combination, can be used to create low friction systems and also reduce the wear of the surfaces. And there is a strive towards eliminating lubricants, or at least using minimum amounts by working on closed systems or, as we say, somewhat self-lubricating systems is difficult to achieve but to create something where everything is encapsulated and does not need to be replaced, does not need to come out. Wear reduction, of course, we want to increase the lifetime of components in our man-made systems, but we would also like to increase the lifetime of the components in our body that we were born with. So, for various types of metal surfaces, there is a strong push towards developing robust coatings to diamond-like coatings—diamond-like carbon coatings come into thought here. Creating tribofilms, which was the topic of a previous podcast, so looking at chemical reactions as surfaces between the lubricant molecules and the solid surface, developing reinforced materials that are less susceptible to, for example, giving off small particles when they wear down and so those are maybe the main routes that we would go and there is, of course, a need to then, if we develop new coatings, we may need new lubricants and so on—these need to go hand-in-hand.

Neil Canter:
So, when you're talking about nanocoatings, in terms of the body, you're almost talking about prosthetics, whether it be for hip replacement, knee replacements, things that become very common medical procedures these days?

Marina Ruths:
Right, and a lot of progress has been done in this field, so there are, of course, whole conference sessions focusing on this, so a lot has been done in terms of developing the polymers, the materials in the hip replacement devices, for example, to reduce the amount of wear debris and so on. So, this has made big strides forward in the past 10 years.

Neil Canter:
Thank you. So, let's finish up by asking you where do you see the future? We've talked about the past, talked about the progression of nanotribology moving on. What is the future of nanotribology going to look like in your view?

Marina Ruths:
Yeah, so while there is still a lot of room for people to join in on this research, I think important aspects that we need to get to, in terms of research in the lab, is methods development for studying buried interfaces through spectroscopic techniques or some other means, and computer simulations can be a big help in that regard and with increasing computing power might be possible to do a lot more work there, and hopefully obtain a closer match between the lab experiments that we can do and computer simulations that can be done, so there is a strive for development on both sides to look at a closer match of the size of systems that can be studied. So, computer simulations would need to get to larger

systems, whereas experiments need to be able to look at even decreased sizes to match what the computer can do and the range of speeds that can be looked at, and this would help us make this connection to make predictions and maybe one day help us make the connection to larger length scales from nanoscopic properties. In terms of applications, a lot is already recognized as being important, but the actual development, there is still very much room to work on this: on surface texturing for new innovative textures, new boundary lubricants and coatings that work well together and then, as I mentioned, lubrication in aqueous systems, so that's a huge challenge in developing environmentally friendly aqueous-based lubricants to work with existing surfaces where we have the problem with corrosion as you mentioned, evaporation, chemical reactions picking up contamination of the lubricant reactions to high temperatures and so on, and to develop new coatings and new lubricants for aqueous-based systems is one of the next big challenges, and work is ongoing but it's very difficult.

Neil Canter:
Yeah. And I would imagine and that I think is very consistent with our podcast because when you talk about moving toward sustainability, perfecting motion, you're talking about trying to move as many lubricants, lubricant systems to water-based type systems—water being natural, water potentially being recyclable, you want to do that, and I would also imagine that one of the things hopefully you and the other researchers in this field will do is hopefully uncover a few more of Mother Nature's secrets. It may be difficult for Mother Nature to reveal them, but hopefully that'll help us as we move more towards better understanding of lubrication of aqueous systems.

Marina Ruths:
Yes, there is a lot more exciting work ahead.

Neil Canter:
Good. Well, thank you very much, Marina. I appreciate it. Nice to meet you and enjoyed very much speaking with you. Thanks.

Marina Ruths:
Thank you so much.

--END—

CONTRIBUTORS

Dr. Neil Canter is an STLE Fellow and an STLE Certified Metalworking Fluids Specialist (CMFS)™, with more than 35 years of experience working in the lubricants industry. He received his doctorate in chemistry from the University of Michigan in 1983 and his bachelor's of science in chemistry from Brown University in 1978. Canter runs his own consulting company, Chemical Solutions, specializing in commercial development, marketing, product development and regulatory support for the lubricants industry. Canter is a member of STLE, the American Chemical Society (ACS), and the Society of Automotive Engineers (SAE). He is a contributing editor responsible for writing the monthly Tech Beat column in STLE's TLT magazine. He is also a member of STLE's Metalworking Fluid Education & Training Committee, STLE Education Committee, and the program chair for the STLE Philadelphia Section.

Canter recently assumed the position of STLE Advisor – Technical Programs and Services. Besides providing technical and commercial support, he is also the host of STLE's new podcast series: "Perfecting Motion: Tribology and the Quest for Sustainability."

Steven Thrush received his bachelor's, master's and Ph.D. degrees in mechanical engineering from Oakland University in Rochester, Michigan, respectively. Currently, he is a tribologist at the U.S. Army DEVCOM Ground Vehicle Systems Center (Fuels and Lubricants Branch). He has presented technical presentations at both STLE and SAE conferences and received industry honors such as the SAE International Outstanding Oral Presentation Award in 2019 and, most recently, was the recipient of the 2021 STLE Edmond E. Bisson Award for outstanding best paper in the field of tribology as the lead author of the paper: "Stability, Thermal Conductivity, Viscosity, and Tribological Characterization of Zirconia Nanofluids as a Function of Nanoparticle Concentration," along with his U.S. Army DEVCOM colleagues, Allen Comfort and Dr. James Dusenbury.

Marina Ruths has a Ph.D. in chemistry from the University of California, Santa Barbara. She did postdoctoral work at the University of Illinois and at the Max-Planck-Institute for Polymer Research in Mainz and is now a Professor of Chemistry at the University of Massachusetts Lowell. Her research focuses on direct measurements of interfacial forces and friction of polymers and polyelectrolytes, self-assembled structures, and surfaces with different roughness, including model systems for biological surfaces.