Perfecting Motion: Tribology and the Quest for Sustainability

Episode 2 – Potential Benefits of Tribochemistry

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Neil Canter:

We will now examine the topic of tribochemistry and delve into how this approach may enable lubricants to be used in a sustainable matter to improve efficiency and productivity. Tribochemistry is the study of reactions that occur between lubricants and surfaces they are exposed to under severe operating conditions known as boundary lubrication. To help us better understand tribochemistry, we will speak with Dr. Kuldeep Mistry, representing the Timken Company, and Dr. Nicolas Argibay from the U.S. Department of Energy's Sandia National Laboratories.

I am pleased to introduce Dr. Kuldeep Mistry, product development specialist for the Timken Company, a supplier of engineered bearings and power transmission products. Dr. Mistry has been conducting research to help gain a better understanding of how tribochemistry can reduce friction and wear and machinery. Kuldeep, welcome and thank you for joining us.

To start our discussion, let me ask you about what you have learned about tribochemistry, and can you provide one or more examples of how it can impact society?

Kuldeep Mistry:

Thank you, Neil. First and foremost, here, what have I learned about tribochemistry? So, let's define what is tribochemistry then. Tribochemistry is the branch of chemistry in which the chemical reaction happens at the friction zone, and these reactions are caused because of mechanical and physiochemical changes on the surface. Because of the remaining parts, these reactions are involved as a result of different types of energies and catalysis.

Now like I have been involved with tribochemistry since 2006 timeframe and is a very fun stream. My project was early on sponsored by ExxonMobil. In 2006, I was working on other projects where we were looking into the tribochemistry of different materials. Now it was looking into the different materials, I mean like steel material as well as the coatings. Now all of this was very interesting because we were trying to figure out what are the different lubricant additives they are going to interact with these different surfaces, because conventionally the lubricants are formulated for the steel surface. They were not formulated for various coatings and coated surfaces on steel, so that was very interesting and that was very challenging, too. So, we looked into various types of coatings, which are really good for the material itself. Now they themselves can have different tribochemistry altogether because tribochemistry is not just about how lubricant interacts with the surface, it is also about the environment, how it interacts with the surface. But, of course, the major part of tribochemistry happens under the tribological conditions, where there is high loads—where there is high temperatures, where there is high speeds or low speeds and there's lot of variables, which can play a very important role here.

So, this is how I really learned about tribochemistry, and I looked into at how these different lubricants they formed different tribochemical films on the steel surface, as well as on the coded surfaces. So, that was the first part of the question what you asked, but can you give some examples of how it makes impact to the society?

I definitely think it makes a lot of impact to the society. Why am I saying that is just think about it? Think about that within the engine, there are within the car, we are losing lots of energy from the fuel just because of the energy losses. But one of the significant losses what we are having is because of the engine, as well as in the transmission.

And here there's a lot of tribochemistry going on. There's lot of tribological components. They are kind of rubbing against each other and what it was being found out that we are losing like millions and millions of Euros because of all this, not proper tribochemistry. So, if you manage a good tribochemistry here, if you have the right lubricant for the right materials, you will be making significant savings because of the efficiencies will increase, the component will last much longer. So, I think it is definitely important, and it's not just for the engines. It's not just for the cars. This tribochemistry it is in various different applications. If you can think around, think about the aerospace. Think about the landing wheels in the aerospace, in the aeroplanes, think about the big heavy industries for various components there. There are so many components like gears or bearings, and they all are being lubricated and they all have lots of tribochemical interactions going on, because they all are lubricated so, hence, it is very, very important to consider some of these aspects.

Neil Canter:
So, the average consumer who is driving cars, we all do, who turns on the car and hopefully if they listen to this, they'll realize that turning on the car, the engine goes—that in order to improve their engine—there's some tribochemistry going on as they drive down the street.

Kuldeep Mistry:
Exactly, exactly, Neil! That is correct, and it is not just that. You know like this is very important for one more other reason that if you think about it, how many cars are there in United States? In United States, we have 320 million cars and that is in United States, which is almost like we have close to 2,000 cars per thousand people. Now United Kingdom, New Zealand, Australia, they all have very similar level of cars, like 800 cars per thousand people. But countries like India, like China, they have currently much less number of cars for people, and that number is growing. Like India right now, they have just 30 million cars. Currently they just have 30 million cars, and they might have 30 cars per thousand people. But it is expected that number is going to grow from 30 million cars to 280 million cars, and that is going to happen in 2040.

So, that time clock is ticking and, hence, it is very important these cars are going to increase and there will be electrification, there will be different types of technology but still friction and wear is going to be there, and we have to mitigate that, and we have to use right tribochemistries there. So, this is very important.

Neil Canter:
Good, so let's move on. And since you've talked about the future and where things are headed in particularly automotive, but certainly in other machinery, what challenges are faced in learning more about how to use tribochemistry to reduce friction and wear?

Kuldeep Mistry:
So, the challenge is what we are facing, how to use a tribochemistry to reduce friction and wear is that the complexity. This is a complex subject, Neil. Neil, why I'm saying this is a complex subject is because, think about it, there is lots and lots of literature. If you look into the literature, there's lot of literature on ZDDPs and the steel material. Like that's okay because it is very important. Until now, most of the materials they were like steel only. And the coatings and all of that did not come into mainstream until 2000. So now more and more advanced coatings are coming up. Different alloys are coming up, so there is lots of things changing there. So now if you just took forever to just figure out how this ZDDP additive works, then it would be so challenging because there are so many other additives are coming up. The ZDDP is getting not as much used, and they are trying to find the replacement of ZDDP because they're trying to go for ashless additives. So, there are different types of particles. There are different types of chemistries, how they would be interacting with steel, how they would be interacting with different other types of alloys? Because conventionally, 50 to 100 was through hardened steel. That was a very commonly used alloy. But now the alloys are changing. They are using different types of alloys. They are using case carburized and different carbon level, so alloys are changing. So how would this lubricant, these different additives they would be interacting with these materials, so that is also a question. I already mentioned that the lubricant formulations are changing continuously, and coatings are there. They're playing role and also the environment.

Now you can do best as you can, but currently people are doing bench testing and that is all under a very controlled environment. But what about the environment, which has high humidity, water or high oxidation or contamination, so it can get really complicated. So, the challenge is going to be how to connect this bench testing to the real work, so that would be a big challenge here. So now think about that whole challenge. First of all, even if somebody solves that challenge, now this still this whole testing, it can get very expensive, very involved. Now people, who try to figure out the ways by which they can computationally do all of this testing, and they can get the answers, a lubricant formulator would like to know that oh, okay, I have this particular additive and developed this new chemistry. Now how is it going to be? Is it going to be good or it is not going to bigger? It's going to be lower friction. It is going to be what kind of tribochemistry is going to form? There is a challenge. One more thing I would like to add here is it is not easy to investigate the tribochemistry. Just rubbing is not the only thing. What you do here? It is not just like rubbing a bar on the disk or rubbing the two rings or rubbing a ring on roller. There are various types of tribological testing that's not all goes into tribochemistry. Within tribochemistry, there are so many other things which happens. There's lot of post-processing, so when once the rubbing happens, the real work starts afterwards to understand from it.

So, there are so many different techniques which goes into it and that is really very interesting and very expensive, too. So, it is very challenging. You know that what level of depth you really want to go into and how you really want to understand here, and plus different people are using different techniques. So how to make sense out of all of this thing? So that is some challenges here.

Neil Canter:
Okay, couple of things in terms of clarifications. ZDDP is a well-known additive used to reduce wear in automobile engines. It has been under scrutiny from a regulation standpoint because of issues with it. Deactivating the catalytic converter, which means hurting the ability of the car to reduce emissions to meet regulations, so you are quite right in saying that people are looking at alternatives and ZDDP seems to have a certain way of interacting in a tribochemistry manner. Unlike any other additive, at least that I've seen, and I'm sure you've seen in terms of your background, which is why looking for an alternative has taken so long from that standpoint. And then to your point about the complexity of tribochemistry. Yeah, it certainly makes sense when you have chemistries, but you have different surfaces, you have even different geometries regarding the surfaces. Let's say even in an engine. Let's say so that can lead to a certain degree of complexity, making it difficult to correlate from a ball-on-disk, ball-on-ring type test.

Kuldeep Mistry:
Correct, that is very much correct, yep.

Neil Canter:
All right, so let let's move on to talking about sustainability. As you know that has been a theme for this podcast in terms of tribology, and lubrication improving efficiency, improving productivity, reducing waste, leading to things that are more sustainable. So, the obvious question to ask here is part of this and other podcasts we've been working with is how are developments in tribochemistry contributing to the movement towards sustainability?

Kuldeep Mistry:
So that's a very good question here, Neil, and it is helping a lot with sustainability because of the fact that using this the knowledge gained by tribochemistry, we are trying to understand what is the right combination of the lubricant and of the metallurgy and which can give you the lowest friction or lower friction and lower wear. But also at the same time, we are trying to see that we are trying to get like a higher power density. So, people are going for the lighter weight, they are going to have higher power density here and they're looking into different alloying options. Looking for the right lubricant for those different alloy options. So, this is all going to help this out in longer term because it would be making the systems more efficient. It is going to make it more durable. They will last much longer, so this will be all really good.

The gains of efficiencies are quite a bit like, for example, in the automotive section there is not just the efficiency portion, they even worry about. They're also looking into the carbon dioxide emissions, so that is also very important that carbon dioxide emissions. So, there is also being considered into all of this whole equation, and it has been found out that we are making tremendous progress because of better understanding of the tribology of the tribochemistry. We are getting better understanding and we are getting the really low friction options. We are getting lower wear-related failures now and this is all really helping us out big time so, hence, this is very critical.

This is very important, and I think I really would like to take this opportunity to acknowledge STLE here, because STLE has done tremendous job in facilitating this whole forum of collaboration, so like people they can communicate their ideas. They can collaborate and, in general, it is really helping to just empower and grow this whole understanding. So that is pretty good here.

Neil Canter:
Good so as you mentioned, this is a complex problem with a lot of complexity with individual situations, but you feel that as things move along, techniques get better, more researchers involved, there's more interaction amongst researchers, so this is going to lead towards more gains in understanding tribochemistry, leading to better efficiency, better sustainability.

Kuldeep Mistry:
Yep, that's correct.

Neil Canter:
So where does the future look like in terms of how do you see, 5-10 years down the road, tribochemistry look like? You said it's a very complicated subject. There's a lot of interactions going on, a lot of different metals, a lot of different surfaces, different geometries. Will things get simplified a little bit, Kuldeep, as we move into the future?

Kuldeep Mistry:
Will things get simplified? So yeah, I think so. There is some even some other trend happening right now about how to manage this big data. So, with usage of the big data, collecting lots of data and they're processing a lot of this data, understanding all of this thing, that would really help. But what data I'm talking about, let's understand. What data are we looking into? How will the future of tribochemistry be different?

So very early on, there were some of the very routine techniques people used to use. They were using techniques like SEM (scanning electron microscopy), or they were using EDS (energy dispersive spectroscopy). They were very commonly used. They were using optical microscope and FTIR. These were the common techniques, but with the advances are newer and newer techniques coming up. In last 20 years, there have been some really good progress being made and there are some really good techniques people are using quite a bit like X-ray photoelectron spectroscopy. That is one of the very well used technique and a lot of researchers have been using this technique because we are not just trying to look into just the elemental composition, we're also trying to look into the compounds of those elemental composition. If it is sulfur, what kind of sulfur is it? Is it sulfate? Is it sulfide? What is it? Is it disulfide? What is it? Same with like phosphorus, phosphates, polyphosphates. What kind of polyphosphates are there, so there's lot of understanding gained by using this kind of techniques like XPS. There's also people are using Azure OES (optical emission spectroscopy). So OES is very commonly used for depth profiling. So, what is happening at various depth levels? So now we are getting really good understanding that I'd given that like let's say at the top layer, what is the prevalent chemistry there? What is like from 50 up to top 50 nanometers thick, and what is happening eventually? So, there is some really good understandings gained here, but thereafter there are techniques like focused ion beam. So, in the focused ion beam, one thing that is happening is they are now cross sectioning the tribochemical films and now you can literally look into those layers, tribochemical layers, and you can see what is the thickness of the tribofilm? And that is very interesting, because now you can see that. And you can also investigate it further.

There are other techniques being used lately quite a bit like AFM (atomic force microscopy) is being used and there is XFD's glancing angle. Tof-SIMS is one of the very commonly used techniques, too, for a lot of this tribochemical investigation. So, these are all like chemical analysis, surface sensitive analysis, but also now which is very important thing, Neil, is that looking into the mechanical property as well. So, something like nano-hardness, here in nano-hardness you can get the nano-hardness or echo hardness you can look into what is the tribofilm hardness? What is the tribofilm Young's modulus? These are some very important information, which can be very helpful in understanding the tribochemical reactions here. There are so many other techniques like Zanes, XES, TEM (transmission electron microscopy) and one of the very new technique is APT (atomic probe tomography). So, this is like a 3D visualization about all of these different atoms. It is an atom proton topography. So, you are looking into atomic structure. How those sulfur is binding with carbon, and it is binding with phosphorus and you can get like a very good understanding about all the hypothesis all researchers had made on ZDDP. It has made all of this different structure. Now you can actually see that whole 3D structure, and you can try to verify is that theory correct, or it is not correct? So that is really interesting. So that is really cool about the future of tribochemistry. With all of these different techniques, we are just going to get a lot of insight, but I think using all of this information some universities have to take a lead here and have to understand what all of these different researchers are. Researchers have said in their research and they will try to make sense and they can make sense by using some of this big data software or big data analysis and they can try to collaborate with various different universities and we can try to understand and make some really good hypothesis that would be really good because at the end of the day you don't want to do all the same testing over and over again. You want to gain what others have understood and you want to build upon that. So that is what I think you know—that is what future would look like there.

Neil Canter:
So, it seems to me to be very exciting because a lot of the theories that we've had about how lubricants can or even additives can provide reductions in friction and wear, which have been talked about for many, many years, maybe even a century or so. Now, we can actually look at it on a molecular level. Let's see and look at it from the tribochemistry lens, interacting with another surface to see what additional types of species form, maybe that nobody has ever seen or known about in terms of what's going on, which may lead to other ideas about (a.) the surfaces that can be used as substrates and (b.) the chemistries that can be used and maybe hopefully provide ways to simplify what's being used, if you will. So that reduces the cost, improves maybe the sustainability of the actual lubricants going into these surfaces, so that we know what they're going to do to interact to form these low friction and low wear types of tribochemistry areas.

Kuldeep Mistry:
Exactly, that is correct, yeah!

Neil Canter:
Good, good! Thank you very much for joining us for a very enlightening discussion.

Neil Canter:
I am pleased to continue our discussions on tribochemistry by introducing Dr. Nicolas Argibay, staff scientist in the Materials Science Center at the US Department of Energy's Sandia National Laboratories.

Dr. Argibay has been conducting research primarily in metal tribology. As part of this work, Dr. Argibay has examined the potential for how tribochemistry can be used to reduce friction and wear.

Nic, welcome and thank you for joining us. To start our discussion, what have you learned about tribochemistry, and can you provide one or more examples of how a tribochemistry process works and how it can impact society?

Nic Argibay:
Hi, Neil. It's a pleasure to be here. Thanks for having me on today. Yeah, so my colleague and mentor, Mike Dugger, liked to quote a former Sandia Labs Vice President, Al Romig, who had a saying that, "remarkable innovation happens at the interface between research disciplines," which I think is an apt description for the value proposition of tribochemistry research. Tribochemistry, and more broadly, mechanochemistry, relies on stress to activate bond breaking, chemical reactions, and phase transformations, which would otherwise be achieved by the addition of, for example, heat, electrical energy, and chemical agents, as a means of reducing and overcoming the activation energy for reactions on the way to some desired output or product. This is probably a good time to mention or to point out that many precursors for the industrial production of chemicals are toxic, and the traditional or conventional processes energy intensive, which, as you can imagine, both are problematic from the standpoint of addressing climate change and achieving a more sustainable future.

An exciting example of a tribochemical process from our group at Sandia was with the recent, somewhat recent past few years discovery of an *in-situ* room-temperature formation route for what are highly-wear resistant and lubricious diamond-like carbon or DLC films. This could, in some cases, obviate the need for synthesis chambers and expensive processes altogether, and even enable the possibility of exciting new prospects like designing of self-healing or "anti-fragile" systems. For example, these methods could be used to reduce and, in some places, special cases possibly even remove or obviate the need for oil lubrication in mechanical devices like gear boxes and bearings. So, imagine the possibility of *in-situ* diamond-like carbon formation in bearings as an alternative to traditional oil delivered lubrication, at least and I should an important caveat point out this is only, of course, something you can do in applications for cooling rate is not the limiting factor. So, you know that you have to use good judgment with that.

To clarify, we showed that it is possible to generate full-coverage films of diamond-like carbon in a shearing contact on the surface of an extremely hard and ultra-wear resistant platinum-based coating, which was deposited on cheap bulk material like steel. I'd like to stress as an important point that comes up often in these discussions of what we did, that these were very thin filled. So, you hear platinum, and you think expensive. And yes, you know platinum is expensive, but when you're putting a coating on the order of 100 nanometers in thickness, this incurs negligible additional material costs compared to say the sort of traditional, shall we say, the deposition of diamond-like carbon coatings and so on. So, the tribochemically grown thin films had all the characteristics and properties of engineered diamond-like carbon coatings, including superlubricity, and were generated by the decomposition of ambient hydrocarbons like alcohol vapors at room temperature, which was another helpful feature.

Neil Canter:
So, what you were indicating here is this was done with much simpler raw materials that could be made sustainable if you will, and in a sense, the alcohols could be, I assume, simple ones like methanol or

ethanol types, and the hydrocarbons could be simple hydrocarbon type alkanes like propane, butane, hexane, heptane, just name a few.

Nic Argibay:
That's right, then you know you wonder about the things we haven't explored yet. Opportunities say for taking advantage of combustion gases. You know, say, the gases vapor that's remains in a jet turbine engine, for instance, could be reacted to produce a diamond-like carbon coating. So yeah, it's pretty broadly we've shown you can use the broad range of hydrocarbons and achieve the same outcome.

Neil Canter:
Thank you. Excellent and with that which shows, shall we say, the breadth and the opportunities in this field, but that still leaves you with what challenge you're facing to learn more about how to use tribochemistry to reduce friction and wear. So why don't you address that point?

Nic Argibay:
Right, that's a good point. It's still early on the road to establishing a clear view of the value proposition of tribochemistry research. The complexity of reaction processes and demands for higher fidelity and *in-situ* characterization to better understand and optimize these tribochemical processes present substantial but highly compelling academically challenges. Additionally, many applications where there could be opportunities for improving properties like wear life carry a high risk and cost-of-entry in the implementation of new technologies that would radically shift the traditional approach and established method of doing things. But there is mounting evidence that the benefits will outweigh the costs. With that said, finding low barrier-to-entry or early adoption opportunities will be a critical step towards what are sure to be far reaching improvements in efficiency, safety, and sustainability.

One example of an application where there is relatively low risk and cost of entry and yet significant impact potential is the development of new additives for oil lubrication for devices like gear boxes and piston engines, and increasingly of interest these days, the development of combined lubricants and coolants, or "lubricoolants", which are optimized for would be optimized for electric vehicle powertrains. A central idea in these low costs or beachhead markets, is that changing additive formulations, for example, would not likely require significant changes to designs or basic materials already in use as with, say, engine blocks, piston rank skiers, and other widely used components. However, there is also growing evidence that using traditionally cost prohibitive catalytically active materials, metals like platinum sparingly. And by this, I mean in the form of thin films.

Again, that could result in overall significantly more cost-effective material solutions for the lubrication of machinery by way of tribochemical formation of hard, lubricious hydrocarbon coatings like diamond-like carbon, like we discussed earlier. This again is an example where the idea seems it probably is still too radical for industry adoption, but continued development may lead to the discovery of cheaper, alternative materials and routes that can overcome what is, in some part, an emotionally, rather, than financially-motivated response (it's not surprising that a designer would suppose that noble metals are too expensive to introduce a new gearbox or bearing, and yet to partly address this concern, I'd like to point out that coding a square meter surface area with 100 nanometer thick film of pure platinum would cost you an unremarkable $74 in materials costs).

Neil Canter:
Okay, and just a point of clarification here. A noble metal is defined as a metal of platinum, palladium, or rhodium in that type of category, almost also a precious metal because they are used as well in catalytic converters in your cars to help weed out emissions from that standpoint. And it almost seems here, Nic, that the higher cost of platinum may play in here. But if the reward, the payback is that much more in terms of the film that's formed, reducing friction and wear and those are the things that have to be weighed. It's going to be, shall we say, as it always is, looking at the benefits versus the negatives and weighing it.

Nic Argibay:
That's right, and there's real costs to taking the risks of redesigning something that works well and has been fine-tuned and optimized. So, this again speaks to this idea that some beach header entry points for tribochemical processes may be lower costs or lower risk than others, and we certainly want to pursue those first. But I think as we gradually show that we can do these things and do them well and the benefits becomes clear, we'll see that radical changes can be very beneficial from a cost standpoint, sustainability standpoint, and so on.

Neil Canter:
Alright and bringing on with the point about sustainability, which is the point of the podcast and what we're trying to achieve, let's move on and ask how are developments in tribochemistry contributing to the movement towards sustainability?

Nic Argibay:
Well, there is a great article published in the July 18, 2016, edition of the New York Times titled, "Grinding Chemicals Together in an Effort to be Greener," which is both entertaining and informative on this point especially. To give you a brief summary, the article leads into the description of a competition between University of Cincinnati Professor James Mack and his middle-schooler son, Tony. Under the supervision of one of Professor Mack's graduate students, the father and son pair raced to prepare a batch of stilbene, which is a precursor chemical for the fabrication of coloring dyes. So, Professor Mack set up, as the article explains, a traditional wet chemistry station, including heated flasks and stirrers, while his son, Tony, used similar ingredients but relied on a ball mill to activate the desired reaction. Well, you can imagine who won the race, not only achieving a substantially faster outcome, but also significantly higher yields. And all this at a safer room temperature. As the article writer and Professor Mack put it, they point out the purpose of the exercise was to prove a point: "milling, or grinding chemicals together without a solvent, could outperform established methods and yet be safe and simple enough for an inexperienced eighth grader to do so." Maybe I have an occupational bias here, but even though this was touted as a mechanochemical process, I'd like to point out that it is entirely also a tribochemical one.

Further along in the article, there is a relevant quote also from David Constable, who's Science Director at the American Chemical Society's Green Chemistry Institute. He noted that, "Chemists typically aren't as concerned about solvents as they should be." The article goes on to point out that, "many commonly used solvents, like chloroform, acetone and hexane, are harmful and volatile, posing risks to people who inhale them as well as the environment. Solvents also make up the vast majority of chemical waste and consume most of the energy used in a chemical reaction." So, you can see the sort of the theme here. I think it's safe to say that a green chemistry movement is underway that will be intimately tide to tribology methods and research goals. I really encourage listeners to read this New York Times article, which for me was a gateway to peer-reviewed publications that highlight and explore the importance of tribology and these methods we've been discussing and the numerous emerging opportunities for tribochemistry-focused research and development as a means of achieving a more sustainable future.

Neil Canter:
As an organic chemist, and I grew up, went to undergrad and graduate school, and literally dealt with and almost bath in a lot of the solvents you mentioned earlier on. The chloroforms, the acetones, even the aromatics, like benzene, your point is extremely well taken in terms of trying to reduce their usage because they're used widely in processing lubricants and even their precursor chemicals and steps, like tribochemistry, should be done to get simpler materials can reduce the type of solvency, which means reduce what we have to do in terms of either getting rid of them from a waste standpoint or recycling them, which can be a pain and the cost type issue. So, certainly this fits in, in my view, agreed very well as from a green chemistry standpoint.

So, let's move on and ask what do you envision the future of tribochemistry looking like?

Nic Argibay:
Well, there's maybe two points here. Two key points I'd like to make. So, tribochemistry research will likely move in the direction of increasing more complex, higher fidelity experiments of selected reaction processes having high-impact potential in the near-future such as, for example, targeting obviation or removing the need for conventional lubricating agents and methods, which are deemed particularly problematic or detrimental to clean energy generation and use. A tantalizing and emerging prospect is the possibility of complementing high-tech scientific experiments by taking advantage of large-scale, decentralized or "crowdsourced laboratory" arrays of low-cost experiments, which could, for example, help feed machine learning and artificial intelligence codes, which is, of course, an area of emerging, or some would say re-emerging interest. This interest is motivated, in some part, by the increasing availability and sophistication of high-power computing as you can imagine. For example, to this point of crowdsourcing the science, thinking about what is described as the Fourth Industrial Revolution or "Industry 4.0," which is currently underway. A key focus is the incorporation of sensors and wireless connectivity or smart technology into practically all facets of manufacturing and product design. And I think the scientific community has only just begun exploring ways to tap into this massive pipeline of information as a way to guide development of better materials, models for failure prediction and device optimization.

So, to elaborate a little more on the first point, at a more fundamental level, I think we need to pursue higher fidelity experiments, and this is going to require development of more sophisticated capabilities. This is an area where the community is actively pushing boundaries to try to better understand at a molecular scale the multitude of mechanisms at play and they're often complicated interdependencies. One example that I'm familiar with is an effort underway to build and install a micro-tribometer, so a friction and wear tester on the Brookhaven synchrotron, one of the beamlines. This is being spearheaded by Dr. John Curry, colleague of mine here at Sandia, in partnership with multiple national lab and academic partners like his old advisor actually, Professor Brandon Krick's group, formerly at Lehigh, now at the Florida State. So, this new capability, which should come online in 2022 or so, will enable unprecedented spatial and temporal resolution investigations of these tribochemical processes in controlled environments. And by that, I mean without having to, say, run an experiment in one lab and then run samples over to the other lab, risking exposure and all the changes that might happen because of just the time difference, the time it takes you to move the sample or exposure environments along the way that would just change the composition on the surface and kind of make it difficult to figure out what really happened. So, the goal here is, how much can we move the characterization equipment right into the testing equipment into the test method, incorporate the two.

So, as a parting thought, I would like to mention that the research I did while preparing for this podcast revealed what I'd say is a personal blind spot—and an opportunity—for how tribologists and our community can engage with a broader community of scientists and industry partners on the development of tribochemical processes to address climate change and secure a more sustainable future. And that is, we need to look beyond wear and friction reduction, which is dear to our hearts and not going anywhere, will no doubt remain high impact, a high impact focus area or high impact focus areas for the foreseeable future. But start to look towards impact potential and chemical processing [industrial chemical processing]. Specifically, there's what appears to be extraordinary unrealized potential in the development of tribology-enabled alternative routes for traditional-to-traditional chemical synthesis routes.

As an example, I mentioned an article in a 2021 review, a very recent review by Drs. Karen Ardilla Fiero and Jose Hernandez titled, "Sustainability Assessment of Mechanochemistry by Using the Twelve Principles of Green Chemistry." In this article, the authors provide several examples of how ball milling, grinding, and twin screw extrusion, which are essentially forms of context lighting and impact or shear, combined with sublimation and filtration for purification, can be used as more energy efficient, safer and lower waste generating (or greener) alternatives for the synthesis of a host chemicals and materials, such as metal-organic frameworks (or MOFs), which is a promising material system for efficient storage of hydrogen, and numerous organic and inorganic compounds, like those needed for manufacturing of permanent magnets, for example.

So, thanks, Neil, for the opportunity to discuss these topics with you and the listeners!

Neil Canter:

And thank you, Nic, and one last point regarding what you mentioned about using physical processing to maybe move things chemically. I'm seeing that more and more in areas such as developing biobased products and biosourcing, because dealing with lignin and cellulose, which is a very difficult substance to break down, and there's a lot of it around because people are looking at wood and tree type products, people are going to operations like milling and grinding, which I know well from metalworking, but looking at it here from a forestry operation to try to break down these bonds, stress them a little bit more as a means to do it in a cost effective and energy effective type way and also an environmentally sustainable way to reduce the types and the amount of compounds being used, particularly solvents.

So, I think that'll be intriguing as we move along. So, thank you very much, Nic.

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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."

Dr. Kuldeep Kishore Mistry received his bachelor's degree in industrial engineering from Sardar Patel University, India, in 2003 and a master's of science degree and a doctorate, both in mechanical engineering, from the University of Leeds in the UK. His doctoral research, sponsored by ExxonMobil Research and Engineering (EMRE), focused on the study of tribological performance and tribochemical interactions of gear lubricants on ferrous and diamond-like carbon (DLC) coated surfaces.

Mistry worked as a post-doctoral scientist in the energy systems division at Argonne National Laboratory (ANL) near Chicago. His postdoctoral work on versatile hard carbon microspheres made from plastic waste received an R&D 100 Award in 2015.

Mistry joined The Timken Company in 2013 as a principal product development engineer and led fundamental projects with Timken R&D. Today he is a product development specialist for Timken with a focus on developing and troubleshooting lubrication solutions for the wind energy sector, as well as automotive, heavy industrial, rail and heavy truck applications. He has three patent inventions and more than 35 external publications and presents his research findings at numerous industry conferences. Mistry joined the STLE board of directors in 2019 and is actively engaged in the tribology, grease, and lubrication research communities within STLE, NLGI and ISO. He has chaired the STLE Canton Section and engages in STEM activities for middle school students in northeastern Ohio.

Dr. Nicolas Argibay is a staff scientist in the Materials Sciences Center at the U.S. Department of Energy's Sandia National Laboratories in Albuquerque, N.M. He earned a doctorate degree in mechanical engineering from the University of Florida in 2011 and joined the research staff at Sandia in 2013, following a two-year postdoctoral appointment.

Argibay has published 40 technical papers in peer-reviewed journals (h-index: 17), five patents, and was selected in 2019 as a recipient of the Great Minds in STEM Most Promising Scientist Award. His research, stretching from basic science to applied R&D, has focused on nanostructured materials, and continues to be motivated by a wide range of practical interdisciplinary challenges in the areas of sustainable energy capture, electronics, aerospace systems and metals additive manufacturing.