CERAMIC TECH CHAT

Episode 24

Title – "Engineering surfaces using thermal spray: Christopher Berndt (E24)"

INTRO

De Guire: "I'm Eileen De Guire, and this is Ceramic Tech Chat.

The Victoria Prize for Science and Innovation is an annual award that honors the lifelong commitment and achievements of Australian researchers in the life sciences and physical sciences. While the prize is typically given to an individual, the webpage for the award—and former award recipients—are quick to point out that the outstanding achievement is often the result of long-term collaborations and team contributions."

Berndt: "What I'm trying to say here, Eileen, is that although the prize is possibly about me, it should not be. That prize also recognizes these many people on whose shoulders I've stood and who've been very patient in answering many of my strange, curious, and sometimes silly questions."

De Guire: "That's Christopher Berndt, recipient of the 2021 Victoria Prize for Science and Innovation in the Physical Sciences. Chris is Distinguished Professor of Surface Science and Engineering at Swinburne University of Technology in Melbourne, Australia. He has conducted research in the field of surface engineering for close to 45 years, and specifically the application of coatings using thermal spray technologies.

So, what is thermal spraying, and what challenges do companies face when thermal spraying materials on an industrial scale? We'll also discuss the future of this field and how early career professionals can get involved."

(music)

SECTION 1

De Guire: "How did you get interested in studying surface engineering and, from there, getting interested in thermal spray technologies?"

Berndt: "I guess I have a story which starts off when I left high school. I come from a relatively poor background, so I got a job as cadet metallurgist, which means that I could study during the day at work and then go to classes in the evening. So, I worked for a large company called Broken Hill Proprietary, BHP, a very large iron-and-steel-making company. Their plant was in Whyalla, which is a very remote part of South Australia, my home state. And as I was working around the steel-making industry, I saw many things. I saw a lot of coatings. I saw a lot of rust. I saw a lot of enamel coatings. I saw a lot of galvanizing. And I started asking questions. What do these coatings do? How do you make these coatings? What are the corrosion properties? Why do they stick to the object that you're trying to make? Can you make them better? Why do you need a wear-resistant coating? So, it really just led on from there, where I had an inquisitive nature, where I'd ask questions about what I saw in my environment. And many people were patient enough to answer my many, many questions. And that led to a Ph.D. at Monash University, which is sponsored by a welding association. And the topic of my thesis was the adhesion of flame and plasma sprayed coatings. So that was the beginning of my 40-odd career in thermal spray coatings."

De Guire: "And why is surface engineering so important?"

Berndt: "So when you think about it, every artifact in the universe has a surface, just by definition. And that is the surface that interacts with the environment. So, if you're able to modify that surface to have some functional properties, which are enhanced or which have a longer life in adverse environments, then you're doing a good job for society.

So, surface engineering is in fact all around us. Anodizing, for example, of window frames, paint on cars. I don't deal with paint, but paint on vehicles, I call transportation platforms. I do deal with transportation platforms in the aerospace industry. So there are ceramic tiles for the shuttle, for example, and The American Ceramic Society had a wonderful issue on those ceramic tiles way back in the mid 80s, which was very, very illuminating for my own career at the time. So there are many sorts of coatings ranging from the metals to glasses in the ceramic environment. And also metal coatings for thin coatings, such as physical vapor deposition. So surface engineering, in summary, is pervasive is everywhere. You just have to look around and say, 'There's a coating. How can I make it better?'"

De Guire: "So you mentioned a wide range of types of coatings. Paint being one of them, and anodizing. But you've really built your career around thermal spray coatings. So, can you tell us a little bit about what thermal spray is and what the process involves?"

Berndt: "So thermal spray is a generic term. So there's a big family of processes that are incorporated under the big umbrella called thermal spray. So, people may have heard of flame spray, surface spray, high-velocity option to divination gun. Cold spray, liquid thermal spray is a new one. But there are all these processes. What they have in common is the following. You have some source; some processing zone, which operates at a temperature which could range from 700°C to much greater than 3,000°C. So you have a great big torch, it's like a highly charged, great big Bunsen burner. And into this highly charged Bunsen burner, you inject the particles. And these particles are sized from about 20 micrometers to up to about 80 or so micrometers. So these particles are injected into this high-intensity flame by accelerating up to Mach 3 in some cases, but typically about 80 to 100 meters per second, which is about 60 miles an hour. They are accelerated by heating up to high temperature. And then these particles, just like throwing mud balls against the wall, these particles impact the job to be coated, also called the substrate, and layer upon layer, you can build up to 100 layers within a time frame of about a few minutes, and you build up this coating which consists of layer upon layer upon layer. So one way that I describe this is think of a shower. When you go into the shower, you see a tile structure, so I think of a three dimensional, interlaced, tile structure. That is the generic structure for thermal spray coating."

(music)

SECTION 2

De Guire: "From an engineering and design perspective, where is the biggest challenge?"

Berndt: "So there are many challenges, Eileen. The feedstock is a challenge. The good news is that there are many feedstocks, such as alumina, many metals, zirconias, glasses. There are many feedstocks which are readily available and have been designed for, say, additive manufacturing. But we can use those feedstocks for traditional thermal spray.

There is a huge financial incentive in feedstocks because you must need feedstocks and many companies make a lot of money just on feedstocks, and they can supply other markets, such as additive manufacturing. Welding companies produce these feedstocks as well.

Then we've got the actual process. So, this is called the torch. So it could be a plasma torch, which operates on electricity. It could be a chemical torch operating on propane or oxy-acetylene, such as flame spray, a high velocity oxide fuel. That is an art within itself, and there are many companies, there's something like 125 torches that one can buy, by the way. Many of them are very similar. But there are many torches that are available because the patents are running out. So, these torches involve a lot of mechanical engineering. Fluid dynamics, in other words. So, how do you control the effluent? How do you control the combusting source? So this is a match between chemical engineering, we're talking about burning of the combustion material, or how do you get a flow of gas, of high-velocity, high-temperature gas, so that it can allow entry of small particles. So, there's a mechanical engineering challenge there, which is also exciting. And a lot of mechanical and chemical engineers do a lot of numerical modeling to help the people who carry out the actual experiments.

Then, when we actually get to the substrate, we've gotten the rapid solidification processing, because these particles are at high temperature, high velocity, they have cooling rates in the order of a million degrees per second. So, with that very high cooling rate, you get these wonderful, exciting microstructures that researchers just love. We get meta-stable phases. We can prove the professor's wrong because we see structures that should not be there. And these structures, these phase structures, very often have very interesting properties which are functional for certain environments, such as magnetic properties, such as [radiation] reflection properties, [radiation] transmission properties, because of the interfaces between these three-dimensional interlaced tiled structures.

So let me recap. You've got the feedstock, you've got the process zone, and then you've got the actual splatting, you've got the formation of the coating. So there are the three regions that we talked about, and they all have materials science, mechanical engineering, chemical engineering, or fuzzy logic, if you want to go into control networks that get feedback loops. So, there are many interesting aspects of thermal spray. I'm hoping that addresses your question."

De Guire: "It does indeed. And it actually, it suggests my next question which is, this is a process that clearly takes place far away from equilibrium. So how do you control things like the microstructure? How do you control phases and phase stability, coating uniformity, and those kinds of things that need to be repeatable or reproducible in order for a component to be usable in the long term?"

Berndt: "So in the field, the companies that are actually producing these coatings every day. They have their workshops. They have their spray tables. They have a parameter set. And they have learned by the Edisonian method, which is a long way of saying trial and error, they have learned by trial and error that this is what they need to do. That their equipment for their components using a certain sweet spot according to their specifications. So, they have learned the art of thermal spray.

The science of thermal spray is still relatively a virgin field. Sure, we've been studying it for 20, 30, 40 years, but there are still many, many unknowns because we do want to get to the point in time where we can use the outputs of the process to control the inputs. In other words, we want to be able to look at the hardness, the porosity, the phase structure, and then looking at the temperature, the velocity, and the particle size distribution of the flux in the plasma zone or flame zone. We can somehow feed back to the actual operational characteristics of the equipment. That is an expensive proposition because the kit, the equipment, the diagnostic tools that you need in order to get those control loops are relatively expensive.

Now let's talk about phase structures. That is also being very well investigated, and there are many theses which look at specific materials under specific process conditions. But what we are trying to do, what we the community of thermal sprayers, what we're trying to do is we're trying to more deeply understand exactly what is happening so that our control loops will be based on phase structures rather than just "it works." Right? You know, don't touch it, it works, leave it alone, we don't want to fiddle. But we're not going to go to the next phase of evolution, the really exciting part of evolution, where we go into the frontiers of exploration just like Star Trek. We're not going to get to that point until we closely understand the transmission electron microscopy, the nano hardness indentation maps, the porosity sized free distribution using neutron sources, such as the APS [Advanced Photon Source] in Chicago. We're not going to be able to get those full control loops until we understand that real detail about how the phases are formed. So, it is indeed quite exciting. There's plenty of work to do."

De Guire: "And how close are we to being able to start understanding some of those things?"

Berndt: "We need to, I'm sort of stuttering here, because what I really want to say is that material scientists need to speak to other people. I've already mentioned neural networks. So we need to speak to electrical engineers who can help us and mathematicians, applied mathematicians, who can help us understand how the variability in controls can provide us with a unique signature that allows the outputs, in other words, the microstructural characteristics—hardness, porosity, phase structure, build up rate, splat size, other metrics—how those can be provided with a single, mathematically robust, rigorous signature. So, I've already mentioned mechanical engineers, chemical engineers, physicists, of course. The typical thermal sprayer needs to get out of their comfort zone and be prepared to say, 'I need help to understand why we have such a distribution in data,' or 'This doesn't look right,' or 'This artifact is interesting. Does this artifact have an application that we can take advantage of if it is produced reproducibly?' So, that is one thing that we need to do as a group."

(music)

BREAK

De Guire: "While networking within your field is valuable, networking across disciplines is a golden opportunity to pursue paths you might not have imagined before. ACerS Member Community offers ACerS members an online platform to connect with other members and possibly spark new collaborations. Learn more at ceramics.org/acers-community."

SECTION 3

De Guire: "What kinds of materials are well suited to thermal spray? I imagine not all materials are well suited."

Berndt: "You've just given me a challenge. Usually we can spray many, many materials which people say you cannot spray. So people say you cannot spray polymers because they've got low melting points and they're just going to vaporize within the intense flame. But what we do, we control the temperature or we control where we put the powder into the flame. We don't put the powder into the hot part, we put it into the cold part, and if it carbonizes because it's a polymer, we use an inert atmosphere. Or we can tolerate a slight degree of polymerization or carbonization, or we try to sell it as a carbon nanofiber, which is incorporated within the structure.

So, the difficult materials are in fact ceramics. And it's reasonably open knowledge that the zirconium diborides and the hafnium diborides, extremely good high-temperature properties, but to actually deposit them as a coating is very, very tough. And it all revolves around controlling the environment. So if it's oxidizing, try to have an inert environment around the torch. If it's not melting, then maybe the particle size is too big, so you go to a smaller particle size. Or maybe the velocity is too great, and the residence time, the time that the particle is in the flame, is not sufficiently large for heat to actually make the material melt in some form. So even materials which pyrolyze or do not have a melting point can become semisolid and you can get what is called a partially unmelted splat, which can form part of a coating.

Or you try to form a composite. So the material which is highly beneficial that cannot be sprayed easily, you try to combine that with another material in the binder phase, control that with a binder phase like alumina, no problems. Zirconia, partially stabilized zirconia, no problems, easy. So you use that as a binder phase and form a composite. Or if you want to spray fibers, maybe spray onto the fibers rather than spraying with fibers. So you get a carbon fiber reinforced material by spraying a metal, if you wish, onto fibers.

So, there are many examples where the process or the material can be designed out of the traditional spray parameters or operating parameters, and this is where the trial and the experience of the big companies or any company or the academics comes into play. That's the art of thermal spray."

De Guire: "It sounds like you're really balancing thermodynamics and kinetics in an extremely dynamic environment with the goal of controlling the outcome for functional reasons."

Berndt: "The word control is often used, but speaking as a rigorous scientist, it's not probably the appropriate word for thermal spray. We can get data about the temperature, velocity, and particle size distribution of in-flight particles during the process. We've got a huge amount of data, terabytes of data. In principle, those inputs will allow us to get the control networks. But because of the variability in the data, it is tough to exactly use the word control, which is why we go to neural networks. Because neural networks do have that learning machine algorithm so that you can get to a more rigorous control process."

De Guire: "What you're describing parallels with a lot of the trends that are happening with data science and informatics that are happening in materials science right now. Do you think that's where the future of thermal spray is heading?"

Berndt: "It is a future."

De Guire: "What are some other futures?"

Berndt: "There are more processes on the horizon. This is a competitive field in the engineering commercial sense, and the question that I wake up with every day is how do we get away from the vacuum if we're using vacuum technology? How do we get away from high-cost feedstocks? Because some of these feedstocks are costing hundreds of U.S. dollars a kilogram. Sometimes thousands. Hydroxyapatite is costing about $1,500 a kilogram, and artificial hips are using hydroxyapatite. So that is quite important. So, it's cost driven, so the other approach is how can we reduce cost by using a process such as liquid thermal spray rather than using powders. Why can't we inject with sol-gel? Because after all, the high-quality ceramic powders come from the sol-gel route. So why don't we cut out that process of transforming the sol-gel into a solid powder and just put the sol-gel into the torch. And that is what has been happening, especially over the last seven years.

So, there are new processes for feedstocks and for the actual torch application. With regard to substrates, I've already mentioned spraying on the carbon fiber. That was not done or even mentioned a decade ago. Now it is. Here's a question. Why don't we spray onto a traditional additively manufactured material? Because additively manufactured materials are going to wear away. So we already refurbish and overhaul traditional components, so another horizon is let's spray onto an additively manufactured component to take advantage of inherent porosity that can be designed into, I'm going to call it traditional even though it's new, a traditional AM product.

So, there are many, many things on the horizon. There are new applications arising every week."

De Guire: "Okay, so we'll have to stay tuned to see what comes around the bend. What advice do you have for young material scientists considering a career in surface engineering and thermal spray engineering?"

Berndt: "Oh, I guess there are many things. So, I need to be careful about what I say here because what works for me or what works for my students may not work for everyone. The advice should be first of all, do not limit yourself just to thermal spray. Think about the big picture of materials science and engineering and apply those principles to ceramic technology or thermal spray. Because if they do not have that very strong grounding in phase equilibria or mechanical testing, you can still get into the area, but you're going to have to somehow pick up those skills in your free time, in your own time. So, what I'm saying is that the early career professionals need to be very open minded.

So, the next thing is that I advise the early career professional to go to professional meetings, in an area which they're interested in. So sure, if there's a ceramics meeting close by, go to it. If it's on tiles, and you're interested in electronics, still go because you still meet people and learn something, and it could be that electronic structures are not as interesting as tiles or whiteware or making beer bottles. There could still be other topics which would open up your vision and horizons. But more importantly, it will allow you to meet a person who could give you a future job.

Let me add another postscript, and that is the role of professional societies. And this is where, you know, I'm very proud to be a Fellow of The American Ceramic Society. The American Ceramic Society has helped my students and myself tremendously. The *Journal of the American Ceramic Society* is the gold standard for ceramic literature, in my opinion. That's where all my students go to, that's where I go to, to not only read but to publish. The conferences are of high integrity and caliber. That's where the networking has assisted me personally. The meetings at Cocoa Beach, Dayton, and many other places as well as the other affiliate societies or member societies, such as the Australian Ceramic Society, the European Ceramic Society. So, professional development through the societies has also contributed tremendously."

De Guire: "Well, thank you for sharing that experience with us. And we're very happy to be a part of that experience for you and our many, many members throughout the world."

(music)

CONCLUSION

De Guire: "While specializing in a specific research field is a worthy investment, keeping your mind open and networking across disciplines is key to advancing your field to places it's never gone before.

I'm Eileen De Guire, and this is Ceramic Tech Chat."

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"Visit our website at ceramics.org for this episode's show notes and to learn more about Christopher Berndt and his research. Ceramic Tech Chat is produced by Lisa McDonald and copyrighted by The American Ceramic Society.

Until next time, I'm Eileen De Guire, and thank you for joining us."