Perfecting Motion: Tribology and the Quest for Sustainability

Episode 3 – How 3D Printing Moves Us Towards Sustainability

Contributors: Dr. Neil Canter, STLE Advisor, Technical Programs and Services, Dr. Anthony Rollett, US Steel Professor of Metallurgical Engineering & Materials Science and Faculty Co-Director, Next Manufacturing Center on Additive Manufacturing, Carnegie Mellon University, and Dr. Wojtek Misiolek, Chair of the Department of Materials Science and Engineering and Director of The Loewy Institute, Lehigh University

Neil Canter:

Additive manufacturing, also known as 3D printing, is starting to have a significant impact on our lives as a sustainable means to produce different types of products, particularly those made from complex designs. Initially looked at as a way to produce prototypes, additive manufacturing is now being evaluated in such areas as the medical health care sector to tailor make prosthetic devices, implants, tissues, etc. The whole principle of additive manufacturing is to build structures layer-by-layer while minimizing waste. This technology contrasts with currently accepted production methods such as metalworking that are done subtractively, where a user will remove material from a substrate and throw it away. In our move to sustainability, nothing should be thrown out—adding to the appeal of additive manufacturing as an alternative.

To talk further on this subject, we will be speaking with Dr. Wojtek Misiolek of Lehigh University and Dr. Anthony Rollett, representing Carnegie Mellon University, to get further insight, particularly on how additive manufacturing is being used to reduce parts from metal alloys.

Please welcome Anthony Rollett from the Department of Material Science and Engineering at Carnegie Mellon University to our podcast. Dr. Rollett has been conducting research on additive manufacturing, and I was pleased to interview him earlier this year for an article in the STLE magazine, *Tribology and Lubrication Technology* on his work in using the additive manufacturing technique, Laser Powder Bed Fusion on metals. Tony, welcome and thank you for joining us.

Anthony Rollett:

My pleasure

Neil Canter:

And let me start here by asking you to briefly describe what you have learned about additive manufacturing, and can you provide one or more examples about how an additive manufacturing process works and how it can impact society?

Anthony Rollett:

Well, excellent questions. I would say that I have mainly learned that additive manufacturing encompasses a very wide variety of scales and technologies from submicron to meters. The dominant technologies, however, as far as I know, filament extrusion for polymers and laser powder bed fusion for metals. So, for their respective material classes, each of those offers the most robust combination of materials choice and reliability of fabrication. So, as an example of how additive manufacturing works, laser powder bed fusion is basically 1,000-fold repetition of spread a layer of metal powder, about the thickness of a human hair, and then use the laser to melt the powder into solid wherever it's required by the 3D design. So, this is something as I said that has to be repeated many, many times over, so you buildup the part inside the powder bed. In terms of impact, I would say that additive manufacturing already touches on many aspects of everyday life. An application that might not be so familiar is that additive it is used to make customized hearing aid earpieces, so these parts fit better and in printed metal they are nearly indestructible. Not quite so everyday but very important to clean energy sourcing is that we're using 3D printing to make advanced heat exchanges that can operate at very high surface temperatures, for example for concentrating solar energy. And when I say very high temperatures, I mean red heat. In other words, quite a lot hotter than you would put in your kitchen oven.

Neil Canter:
So, you're making, I think a good point in terms, particularly in terms of the theme of sustainability and with the movement towards solar energy—sustainable movement and having heat exchangers, which, of course, is very challenging aspect and some of our readers also know about and listeners know about the fact that heat transfer fluids were involved in that process as well from that standpoint, the hearing aids obviously also impact us as well from a medical standpoint, and we know that additive manufacturing has been very beneficial in terms of complex type geometries, which I would imagine is the case for a hearing aid.

So, let's talk further about what challenges are faced in learning more about how to use additive manufacturing, particularly in the metal alloy area, because we know that with plastics and polymer resins, things have been moving along I think a bit faster, but with metals it's been a bit slower and it's been a slow process, particularly with some of the nonferrous metals like aluminum and the ones you've been working on titanium, so talk a little bit further about the challenges faced and how they can be overcome.

Anthony Rollett:
Yes, thanks, I'll be glad to pick up that question. Right now, the biggest challenge is figuring out how to expand the range of alloys that we can print with. Metals additive is fairly similar to welding. When you weld, you generate stress from the thermal contraction of the metal and that thermal contraction gives you residual stress which can generate cracking. And many of the alloys that we would really like to use much too sensitive to cracking. So, to give a couple of examples there's an aluminum alloy called 7075 that's been used for decades in building airplanes, but if you try to weld this stuff, or for that matter print with it, then it cracks. And so, having said that there are some mitigations for this, so the most obvious thing to metallurgists is that you concede solidification.

So, what does this do for you? Well, any metal alloy has inside it many, many different crystals—we call them grains—and so the smaller that grain size, the smaller the crystallite size, the less chance you have of cracking happening, and so you can put things into the metal alloy before you melt it and resolidify it, they give you a smaller grain size and that actually helps quite a lot and so that kind of modification has actually been demonstrated by HR labs for some aluminum alloys. And along with that, of course, goes the art involved in controlling the printing conditions. So, that's one challenge. Another pretty central challenge is controlling the defect structure. This is mainly a question of the poor content. So, by poor I mean little hollow spaces inside, so at Carnegie Mellon we've developed a process window approach. So, we take advantage of what we know about the physics of the laser melting process to define limits on the power that you use, the velocity, the scanning speed that you use, the overlap that you use between the melt tracks to define an operating region in which you can reliably operate the printer, and so that physics-based knowledge of process relies on a combination of pretty straightforward experiments that you can do in your own printer, combined with what I would call Bleeding Edge experimental measurement with sort of the ultimate in X-rays that you can get at synchrotrons run by the Department of Energy.

Neil Canter:
OK, one thing I think I'd like to add to from a question is it also appears that the powdered metal itself it may be an issue here in terms of consistency from that standpoint. Is there anything can be done to have the powdered metal that you originally used in the process become more consistent, which I assume it would help the process?

Anthony Rollet:
You're absolutely right! Then, metal powder being used in the printers is a crucial input to this and a lot is being done to both make the powder production more consistent, specifically for laser powder bed fusion, because the powder size that we use is quite a bit smaller than has been traditionally used in, for example, thermal spray. So, that has caused the powder manufacturers to adapt their processes. Another very important aspect is the chemical composition of the powders. It's very important to control that, and that means that you have to pay very careful attention to the cleanliness of the machines in which you melt the metal, aerosolize the powder and generate it so that you avoid having impurities get in. Yet another aspect is that the powder particles themselves typically contain some of these pores that I mentioned earlier, and so there are also things that you can do to control that porosity to minimize it, which is what we need and so the manufacturers are also learning how to do that.

Yet another aspect is the degree to which each powder particle looks like a nice smooth tennis ball. In other words, particles can be generated that are very lumpy, or they can be almost perfectly spherical. They don't have to be exactly spherical, but it definitely helps with using the powder in the machines and so that's yet another thing that we can do, and that the manufacturers are slowly but surely improving, along with generating a wider range of compositions that we want to use.

Neil Canter:
Yeah, I bring that up because in my experience with subtractive machining, or should we say conventional metalworking, one of the challenges that I've seen in my years and working in this area is the consistency of the actual metal being used, which nowhere near has the type of sophisticated quality control that you see with powders, and particularly with things like cast aluminums where the silicone impregnation is not consistent, so you can tap or drill a few holes and everything looks fine and you go to another piece of the metal and you break one tool after another, which is inconsistent in my view from that standpoint.

So, you talked about cleanliness here and that brings me to moving this thing to a commercial manufacturing sector. The manufacturing sector, itself, cleanliness has been a major challenge. Is this going to put us in a situation for the future where the cleanliness of shall we say factories that are going to do 3D printing is going to have to be closer to the electronics industry than it is to what we have, let's say, for an automotive plant?

Anthony Rollett:
So, that's a really interesting thread to follow. I would say that the cleanliness of the factories I don't think it will have to get to quite the cleanroom status that it is in the electronics industry, which is just as well because powders are very hard to, shall we say confine to one place, and I think the most hopeful developments that I see going on is that the early machines you basically open them up, fill the hopper with powder, close up the machine again, press the button and let it print. In other words, there was really not much attention paid to the mechanical details of powder handling. That is changing very substantially, and for the good in the sense that the manufacturers are using much more containerized approaches. So, it's now possible to buy canisters of powder and you simply plug a canister into the machine. They've also paid attention to the depowering. In other words, when you're done with a print run if you like, how do you get the powder that wasn't melted away from the parts that you want? All of that is being automated and streamlined so that surplus powder can be pulled out to the chamber and sieved and recycled in a sensible and crucially atmosphere-controlled way.

So, it's a gradual process as it always is, but I do believe that the manufacturers are becoming a lot more sophisticated and that also, by the way, in this sense of sustainability, is going to make it much safer for the workers to be around these machines, meaning it's not a good thing to breathe in fine metal powders. Well, not a good thing to breathe in fine powders of anything, and the increasingly sophisticated powder handling will help with that.

Neil Canter:
You raise an excellent point about safety with powders. As a chemist, I looked through a lot of the safety information, which are called safety data sheets commercially, and you would think about a piece of metal not exactly being hazardous. You put a piece of metal on the table that's not exactly going to be threatening, but the same case if the metals in the powder form, you're absolutely right if you get inhaled and obviously get into your system, whether it be respiratory digestive and if you look at the safety data sheets for those, they are exceptionally hazardous for some metals like cadmium, nickel, cobalt. Extremely hazardous, even carcinogenic in some cases, so you raise an excellent point from that which is one thing I was going to bring up too, because in a conventional subtractive manufacturing facility, mist and also powder and metal all over the place and all sorts of things like that have been a major health and safety issue. And if the industry is already recognizing this and moving to this type of cartridge approach, that's going to make it a lot more worker friendly and safer for workers in the future, which is something that has been a big problem in manufacturing. A lot worse 30 years ago when I started, Tony, now it's a lot better because 30 years ago you couldn't see across the plant now because of the mist in the metalworking subtractive machining plant. Now you can, because a lot of the ventilation, as well as a lot of what is done to trap the misting in the machines through various kind of trapping type techniques in terms of doing that and the ventilation is a lot better, but still it has been a problem, so that helps and I think that helps me move to the next question regarding sustainability. You have a sustainability approach here, as well as with the whole out of manufacturing thing where you're building something instead of taking out metal and metal chips which have always been a pain, shall we say in a conventional manufacturing facility.

So, talk a little bit further about additive manufacturing and sustainability and also talk as well about the post processing and where you see that. How much post processing do you think will continue to be or need to be used after the part is 3D printed?

Anthony Rollett:
Right, I'll have a go at the sustainability question, and I will approach it from the perspective of a couple of projects that are ongoing in our laboratory, which we are using additive manufacturing to print heat exchangers for high temperature service, which I already mentioned. I freely admit that a little bit of an edge case in the sense that the intent is to open up future possibilities in solar energy, gas turbines, modular nuclear power, and so on, but it has been quite a journey for us because it has strongly illustrated the importance of co-design. And so, what I mean by that is additive manufacturing is very, very flexible, and so when you take your first design of a component, in this case, heat exchanger and you try to print it, you run across problems. But the wonderful thing about additive is as soon as you've printed it and gotten out of the printer and inspected it, you would fairly quickly understand what's gone wrong or what's not exactly what you want, and so Serial Number Two can be a significantly adapted design, and what we're finding is that the way you design your components depends on the printing process and everything is very interactive, so to make that a bit more concrete, the design of heat exchangers tends to focus on the actual heat exchanger unit itself, and it doesn't worry so much about the headering and the manifolds, but it turns out that the headers are a really rather important part of it but also a source of weakness in the joints.

Well, another very nice thing about additive is that you can print the heat exchanger unit with its headers—even some of the piping, depending on how far you want to take it, and that can be completely integral, so I will leave it to my audience to judge just how much that helps with sustainability but there are two pieces of this: one is the specific technical aspect of this, and the second is how quickly you can adapt your design. So, by the time you've gotten to Serial Number 20, which is not very far into a manufacturing development process, the design that you're working with can look really very different from where you started, and that also speaks to speed-to-market. In my opinion is that additive is buying its way in, not on a cost basis, but on a speed-to-implement production basis, and so that has to help as well.

Neil Canter:
No, I totally agree, additive has to prove itself from a speed-to-market much like subtractive has, in terms of cutting parts made for economics based on the way manufacturing, just-in-time manufacturing, has been going.

So, let's finish up by talking about the future and where you see the future of additive manufacturing going and what it's going to look like.

Anthony Rollet:
Certainly, and cut me off when we run out of time. It's very hard to say where we are on the Gartner Hype Curve. Additive started life as a rapid prototyping technology and, as already mentioned, has shifted towards being mainly a quick-to-market or if you'd prefer continually adaptive production technology. My estimate is that in terms of metals (AM), nearly all companies that produce metal parts are using additive and they are continually evaluating new applications. So, as the users of printers gain experience, I think their appetite for new materials will increase and their ability to qualify the process will improve. I especially hope that the cost of the printers comes down. A good metal printer is north of a million dollars. That's really too high for it to get widespread acceptance. I also mentioned qualification. I think that qualifying additive for part production is attracting very serious attention from numerous standards bodies. NASA itself has published at least a couple of standards document to address this, and what I mean by this is that traditional approaches relied purely on testing and

statistical analysis and we would encourage the community to take advantage of knowledge of process, physics-based knowledge of process and streamline the qualification process.

Neil Canter:
Very good. Tony, appreciate your time. Thank you very much.

Anthony Rollett:
Sure, hope the remarks work out.

Neil Canter:
I am pleased to introduce Wojtek Misiolek from the Department of Material Science and Engineering at Lehigh University. As part of his research, Dr. Misiolek is working to better determine how additive manufacturing can more effectively be used in the manufacture of metal and plastic parts. Wojtek, welcome and thank you for joining us.

Let me start first by asking you to briefly describe what you've learned about additive manufacturing, and can you provide one or more examples about how an additive manufacturing process works and how it can impact society?

Wojtek Misiolek:
Thank you so much, Neil, for this introduction and presenting my research interest in additive manufacturing. I want to mention that I've been with this technology for quite a bit of time because my first Ph.D. student in a previous century when I was with Rensselaer Polytechnic Institute did his Ph.D. in rapid prototyping. There was the name of this technology, and today since 1997 at Lehigh mostly I'm interested in metal additive manufacturing and I believe there are great opportunities and possibilities for this technology, but quite often the simplified may be too much and some promises are being made in media, which probably are exceeding the capabilities of these technologies, so I would say we should be optimistic, but I think we should also be very realistic about limitation, technical limitation and economical limitations of these technologies. There are some real challenges, and these challenges need to be addressed.

Neil Canter:
Why don't you talk a little bit about, for those who don't know about what happens during an additive manufacturing process, what's going on, how is a part made using an additive manufacturing process?

Wojtek Misiolek:
So, there are number of families of additive manufacturing processes. I think, according to ASTM, I think we have seven families but what is happening, in general, is we are adding layer-by-layer material to form the part using different techniques, but in most cases, they are based on powder materials. So, we are going to center these materials, or we are going to melt these materials in order to build the final part, which because of additive character and building this layer after layer, can be very complex in geometry and because of using if we are using powders can give us quite interesting and promising mechanical properties of physical properties of these parts, so that's what is new in terms of doing this, because in the past or present, the most typical processes would be casting when we are just using

molten material and cast it into the form, into the mold and get the shape this way or we are deforming the material from initial shape into the final shape. Or we're using machining processes where we are subtracting layers by layers, so this is something new that has been around you know about 30 years from the first ideas introducing polymers and now they are spread out into ceramics and metals as well these technologies.

Neil Canter:
Can you get an example of a metal or plastic resin that's used and the types of parts that have been made from additive manufacturing?

Wojtek Misiolek:
So, depending on which family or processes we're looking to resolve different options. We can mix, for example, metal powders with polymer binders and extrude filaments which can build up the shapes, and then we have to remove this polymer binder and cindered the material and get the final shape this way. Or we can use the powder directly but using the laser as a source of energy and center these particles together, according to the computer file which represent design of our parts. So, we can just scan the powder and make it into the part layer-by-layer, so we are going from the bottom to the top of this part, and there are different options that I mentioned is sintering, but today the lasers are much stronger and we are very often melting the powders and controlling the solidification process of this liquid metal, and this helps us to eliminate porosity in the parts, which is critical in terms of performance, mechanical or physical performance of these parts.

Neil Canter:
OK, fair enough. You've talked about other alternative technologies that additive manufacturing maybe looking to replace whether it be casting, whether it be subtractive machining, if you will. How does additive manufacturing differ from those and how does it contribute really to the movement towards, shall we say, sustainability improving productivity, efficiency and reducing waste?

Wojtek Misiolek:
So, what is very important to mention is that we are using material which we need if it's used in the form of the powders, we are pretty much using 100 percent material, we do not produce technically any scrap metal, however, things are a little more complicated when we look a little closer because the powder, which we can recycle sometimes, changes the properties when it is exposed in a chamber to laser—doesn't have to be hit by laser but we are seeing some oxidation and some other chemical reactions, which can create different surface composition of this powder and it is different powder after that. So, again kind of a statement that we don't see any scrap material whatsoever are correct, however, sometimes we need to look to be more careful and more precise to find out that the powder, which we can recycle, is not of the same quality and not always can be used for the same purpose. So, things that require a little more discussion and research and our understanding needs to improve before we can make these statements.

Neil Canter:
Is it a matter of changing the conditions in which, for example, the laser operation maybe not using the same intensity or the same wavelengths, or is it a matter of basically changing the powdered metal alloy being used, or at least additizing it so that it can resist oxidation?

Wojtek Misiolek:
I think both of these things play an important role, plus depends what kind of atmosphere we are going to use in the chamber during sintering or doing laser sintering or laser melting, so it is quite complicated because if we optimize only for this recycled powder, then we may not get the same properties in our parts. So, things are kind of multi-dimensional and we need to see all connections between process parameters and the results.

Neil Canter:
And with the atmosphere, you bring up a good point because I assume some of the atmosphere from which is done could be inert, whether be nitrogen, whether it even be argon, a noble metal that's highly inert, and to move this thing towards a more commercial phase, it's got to be done, but I daresay an ambient temperature and pressure where you've got plenty of oxygen around that could potentially cause oxidation—how much progress has been made on additive manufacturing being done, shall we say, under ambient conditions without needing severe operations, or even, shall we say, not under using an inert gas.

Wojtek Misiolek:
Quite honestly, I don't feel qualified to answer this question because maybe there are processes which I'm not aware that are doing better than what we are working with. My work is mostly with selective laser melting and we meet a protective atmosphere and argon is very typical gas which is used, and everything translates into one more dimension which we talk about complexity of a geometry, which is a plus for this technology. We did mention mechanical properties, which sometimes is a challenge because of the presence of the porosity but there is also a problem with cost and speed of making these parts and these are economical arguments, but there are sometimes showstoppers and what we see today is mostly industries like medical and aviation are looking into this technology because they can afford it. If we go into more price sensitive for industries like automotive there is a lot of interest in automotive parts made by in polymers by this technology, but in metals the cost is still too high to see there's a massive production, high volume production.

Neil Canter:
No understood. Yeah, because certainly in the metal production and the production of cars, its high volume and high speed, which has not worked for additive manufacturing. So that leads me to what is your crystal ball tell you about the future. How do you envision the future for additive manufacturing looking like, where is it headed…is it headed to a high-volume type application, is it going to remain with aerospace and medical, what do you see?

Wojtek Misiolek:
Well, this is a tough question, but the way I see today is that we will solve the technical problems, we will probably drop the price of the metal powder because it will be more and more competition in making these specific morphology of the powders, usually we are looking for spherical particles of certain size and this is usually made by gas optimization process, and so there is going to be some progress, but I can imagine there is a more liberal technology in the sense of which application uses powder injection molding and the reason I'm mentioning it is because very similar or almost the same powders are needed in powder injection molding and in comparison to traditional powder metallurgy it is an expensive process, but it gives enough classes in terms of benefits that people are willing to spend the money and make many parts this way. I see that additive manufacturing will be used for expensive

materials because the cost of process is expensive, so the materials which are very inexpensive won't be a good candidate, and I believe we will develop a niche for the application and with the added post processing to eliminate eventual porosity and processes to improve the surface quality, we will see more applications, but all of this leads to more expensive processing. So again, I think we will be seeing these applications in relatively expensive materials.

Neil Canter:
Okay, where does hybrid additive manufacturing, sort of the mix of using additive and subtractive manufacturing that you're trying to use the best of both worlds, where does that fit into this as we move into the future?

Wojtek Misiolek:
I think it has a very good potential for especially repaired technologies. We are actually working on something like that in our lab, where we are looking into rebuilding some forming tooling for metal forming for the forging process and it is challenging, but with this technology it's possible to improve the performance of these tools by adding better, not as material, which was used originally but improving this material by controlling chemistry, but we need to control, of course, the interfaces. So, there are some technical engineering challenges, but these look to be something which we can overcome.

Neil Canter:
So hopefully with hybrid additive manufacturing, the speed could be picked up using the hybrid aspect of it, in terms of the efficiency, the economics could look better yet the additive manufacturing features of precision, particularly in terms of making complicated geometries, could come into play here to be combined. Is that something you feel hopeful about?

Wojtek Misiolek:
Yeah, because if we are talking about the repairs, for example, we are not building the entire tooling out using this technology but we are building only adding on the surfaces, which were warmed out, and this will, at this point, the speed is not such a limiting factor because we are building up the percentage only of the whole volume of the material and if we can just make sure that our properties, mechanical properties, plus surface quality are going to be acceptable, we have a potential for very quick repair method. So, the challenge will be the interface between old metal and the new metal and here the subtractive approach is helping us because we can prepare the desired surfaces.

Neil Canter:
And what about post processing, which you indicated, I think, has to be done with additive manufacturing is that going to remain an important element, and say metalworking fluids, which are commonly used in subtractive machining, are going to I assume be an important part in post processing, will that continue into the future and be an important element of additive manufacturing in the future?

Wojtek Misiolek:
I should go a little back for a moment and mention that when we are building layer-by-layer I already complained about this speed. We can speed up the process by putting thicker layers of the material, but automatically we are going to make our service quality worse, so there is a compromise between speed and quality of the surface. So, we may have different solutions for different problems with different parts, and in one case we will be going with high speed and the other one we will be going with the

much slower speed and just making sure that we get the better quality. So, I think the definition of what the quality of the part is will determine the speed with which we can operate.

Neil Canter:
Thank you, Wojtek, very much for contributing to the podcast. Appreciate your time.

Wojtek Misiolek:
Thank you so much for inviting me.

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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."

Anthony Rollett has been a member of the faculty at Carnegie Mellon University since 1995, including five years as department head. He is the co-director of the Next Manufacturing Center on additive manufacturing. Previously, he worked at the Los Alamos National Laboratory. There, he was group leader of metallurgy from 1991-1994 and deputy division director of materials science and technology for a year after that. He has been a fellow of ASM since 1996, Fellow of the Institute of Physics (UK) since 2004 and Fellow of TMS since 2011. He received the Cyril Stanley Smith Award from TMS in 2014, was elected as Member of Honor by the French Metallurgical Society in 2015 and became the US Steel Professor of Metallurgical Engineering and Materials Science in 2017. He received Cyril Stanley Smith Award from the International Conference on Recrystallization and Grain Growth in 2019, and also the International Francqui Professor for 2020-2021 from the Francqui Foundation, Belgium.

His research group is supported by industry, several federal research agencies, and the Commonwealth of Pennsylvania. He is a member of the Basic Energy Science Advisory Committee and the Defense Programs Advisory Committee under the Department. of Energy. His lecture notes on texture and anisotropy are widely known and used, and he started a new course on additive manufacturing and materials in 2016. He started a new master's program in additive manufacturing in the fall of 2018. Rollett's research focuses on microstructural evolution and microstructure-property relationships in 3D, using both experiments and simulations. Interests include 3D printing of metals, materials for energy conversion systems, strength of materials, constitutive relations, microstructure, texture, anisotropy, grain growth, recrystallization, formability, and stereology. Relevant techniques include high-performance spectral methods in micro-mechanics, dynamic x-ray radiography (DXR) and high-energy diffraction microscopy (HEDM). Important recent results include definition of process windows in 3D printing through characterization of porosity, 3D comparisons of experiment and simulation for plastic deformation in metals, the appearance of new grains during grain growth, and grain size stabilization. He has 250 peer-reviewed journal publications with an h-index of more than 50.

Dr. Wojtek Misiolek is an internationally recognized leader in the field of materials forming and processing with more than 30 years of independent research project management, teaching, and consulting. As both Chair of the Department of Materials Science and Engineering and Director of The Loewy Institute at Lehigh University, he collaborates with several research institutions around the world.

He conducts interdisciplinary research in materials processing and process engineering. His research and teaching interests have focused on deformation, powder, and machining processes along with applications for structural and bio-materials. The common theme of these studies is to understand and develop characterization techniques for microstructure evolution in different materials during forming and processing. These scientific challenges are being addressed by the use of various physical and numerical modeling procedures in conjunction with state-of-the-art materials characterization techniques. Dr. Misiolek has contributed more than 300 publications to the research literature. He served as co-director of the RPI Aluminum Processing Program, an international industrial consortium performing pre-competitive interdisciplinary research that focused mainly on the aluminum extrusion process. He holds two patents and has been recognized with several awards from technical and academic organizations. He is a Fellow of American Society for Materials International and member of American Powder Metallurgy Institute; Polonia Technica; Society of Manufacturing Engineers; and Minerals, Metals & Materials Society.