CERAMIC TECH CHAT

Episode 31

Title – "Deformable ceramics and next-gen functionalities: Xufei Fang (E31)"

INTRO

McDonald: "I'm Lisa McDonald, and this is Ceramic Tech Chat.

During ACerS Annual Meeting at MS&T last month, students gathered to cheer on contestants in the annual ceramic mug drop contest. This contest challenges competitors to design ceramic mugs that can withstand drops from great heights.

This contest is challenging due to the brittle nature of ceramics, which causes them to fracture upon impact. What if, however, ceramics were not as brittle as we believe? What if, instead of fracturing, we could design ceramics that deform upon impact?"

Fang: "We have this, I would call it misconception that ceramics are brittle. That really depends on what temperatures are we talking about, and what materials are we talking about, and also even the texture being either single crystal, polycrystal, and including the environment and the length scales. So, for instance, we have several materials, single crystals, of course, that can even be plastically deformed at room temperature up to 10 percent without fracturing. For instance, in strontium titanate. And this actually is also very surprising. When they were first found in the community, if we go back to check these papers, the title usually states that 'surprising' or 'extraordinary' or 'unexpected,' something like that."

McDonald: "That's Xufei Fang, junior group leader in the nonmetallic inorganic materials research group led by professor Jürgen Rödel at the Technical University of Darmstadt in Germany. He explores the generation of dislocations in ceramic materials, which allows ceramics to demonstrate the surprising ability to plastically deform, as well as other unique properties.

How does plastic deformation in ceramics differ from the conventionally explored deformation in metals? Also, we'll talk about initiatives Xufei and the Rödel group are doing to spread the word about this exciting research field to the larger ceramics community."

(music)

SECTION 1

McDonald: "Usually people don't think of ceramics as having dislocations. That's usually a topic that's more explored in the metal realm. Until you took this position, ceramic dislocations was also a new topic for you. So, what has your journey been like through materials science that you ended up researching these dislocations?"

Fang: "I did my Ph.D., and also my bachelor's, in the same university, Tsinghua University in Beijing, China. I started my Ph.D. actually first in ceramics, but structural ceramics. Back then I was working on ceramic composites and ultrahigh-temperature ceramics, mainly for aerospace engineering.

And then after my Ph.D., I immediately moved to Germany for my first post doc in Max Planck Institute for Iron Research in Düsseldorf, Germany. I actually changed my topic to nano/micromechanics but with a focus on dislocations in metals. And the topic actually is hydrogen embrittlement.

In 2018, I was already thinking about moving to the next stage for my research career, and then all of a sudden I saw this advertisement that was this position in Darmstadt. Professor [Jürgen] Rödel is advertising this new [group leader] position called dislocations in oxides. And I thought, 'Okay, I worked on ceramics, I worked on dislocations, this might be a perfect opportunity for me to combine these two and then to march into a new field.' And that is how I just told myself, 'Okay, why not go ahead and apply for it?' And luckily, I got the position in the end. And things have flourished since then."

McDonald: "How did you end up doing a Ph.D. in structural ceramics? Ceramics is kind of a unique field. A lot of people don't always know about that right away, that they can pursue research in that area."

Fang: "Yeah, actually my major in Ph.D. was engineering mechanics or solid mechanics. So, besides the ceramic part, I also worked on structural alloys, for example, nickel-based superalloys. So, mechanics was my core strength, so I really was not choosing the material specifically. It just happened to be on these two material systems."

McDonald: "A happy accident that then showed up again later."

Fang: "Yes."

McDonald: "So as you've been working on ceramic dislocations, has your experience traveling through these different countries given you connections or partnerships to help spread the knowledge of ceramic dislocations?"

Fang: "For sure. And here I would like to mention that one of my close collaborators, professor Atsutomo Nakamura, and currently he is in Osaka University. He used to be in Nagoya University in Japan, and before that he was actually in the University of Tokyo. He really helped me a lot over the last three years, in particular considering the corona situation. It was a little bit funny that after I joined this group for about one year and then the pandemic starts, and everything went online and also we have limited access to the labs. But things still worked out quite nicely, and this is particularly because of this strong network that I was able to establish based on Darmstadt and then with Japan and also with my previous research institute, including Tsinghua and Max Planck Institute for Iron Research. And the colleagues were very supportive. And since I'm working on dislocations, the abundant knowledge in metals…So, I was always talking to my former colleagues and collaborators from the metal community to combine these techniques here. And in house we also have another professor, Karsten Durst. I really would like to mention the name because he's a nano/micromechanics expert working on metals. And I was able to also use his machines and setups to work on this topic, to transfer the knowledge and skillset from metals to ceramics. It really worked out."

McDonald: "It definitely takes a village when you're exploring new topics like this. And as we found with the knowledge of the metals, it really can help expand into these new areas that you never thought about before."

Fang: "Exactly."

(music)

SECTION 2

McDonald: "So what exactly does dislocation mean for people who aren't in the materials science community?"

Fang: "Right. So, dislocations we usually term as the line defects, or one-dimensional defects, in materials science. It's mainly studied in metals because dislocations are one of the main carriers for plastic deformation. That is why usually we can plastically deform a metal foil or let's say a Coca-Cola can. But if we drop a ceramic plate on the floor, we most likely will break them because there is a lack of dislocation activity there."

McDonald: "So, how do dislocations in metals and ceramics differ from each other? The mechanisms that we're seeing between those two types of material classes?"

Fang: "In order to make materials, crystalline solids, to plastically deform, we definitely need a lot of dislocations in it. I would say there are three key factors that we need to look at for dislocations behavior. And that would be dislocation nucleation, dislocation multiplication, and dislocation mobility.

So very often in ceramics, because of the conventional high-temperature sintering, we do not have many dislocations to start with compared to metals. So, this is the first difference. That means if we wanted to plastically deform ceramic materials, we have to overcome the nucleation barrier, which very often is very high because of the strong ionic and covalent bonding.

The second difference there is the mobility. So basically, we would like to move the dislocations easily if we wanted to have a good ductile ceramic material, as in the case of metals. But the case again is because of the strong bonding, very often we have very limited mobility in ceramic materials.

Another interesting feature I would say is because of the ionic and covalent bonding, the dislocations in ceramic materials, they can carry charge in the dislocation cores. And this also makes what is huge difference between the dislocations in metals. And also, it's because of this particularly charged feature in the dislocation core, we have a space charge layer surrounding it. And because of this charge features, we actually can use it for electro-functional properties. For instance, like superconductivity or electron conductivity, etc."

McDonald: "That's super fascinating."

Fang: "Yeah."

McDonald: "What scales is this dislocation occurring on? Because I know with metals, like you said, you could crush a can with the plastic deformation. But I'm assuming we can't crush a ceramic plate with the deformation."

Fang: "That's true. Yeah, so far, I would say, we were able even to deform a ceramic single crystal even up to millimeter sized without breaking them. Even at room temperature, we're talking about this at room temperature. So, this what we call the macroscale, so millimeter sized sample. But, of course, there is always a danger to accidentally induce cracks. And then…because we know the fracture toughness of the ceramic material, it's so low. Very often it's around one mega pascal square root meter [$MPa \cdot m^{1/2}$], or even up to ten. So, once we have cracks, they easily propagate and break the whole sample. And that is what we try to avoid. That is why we can actually…Let me put it this way. If we go to smaller scales, let's say micrometers, or even tens of hundreds of nanometers. The chances of inducing these cracks would be much lower. And that is also why so far I mainly work on the nano/micro scale. In the long run, I aim to bring this knowledge and to expand also the plastic zone size up to millimeter sized [samples]."

McDonald: "But fortunately, even with these nanoscale/microscale sizes, we're able to get like the electronic effects and stuff that is useful for application, right?"

Fang: "Yes, exactly. For example, like NEM [nanoelectromechanical] system or MEM [microelectromechanical] system. And this is the perfect scaling that fits. The reason I'm talking about this larger scale is because once we can deform the larger scale, we can still like slice some pieces out of it for these electronic devices. That's a very nice point. Thank you."

McDonald: "Yes. I know sometimes we always discuss about making it bigger, making it larger. But a lot of the topics recently in electronics is how do we make things smaller, how do we make them lighter."

Fang: "Exactly."

McDonald: “So, we’re actually already working on the scales that are perfect for next-gen electronics.”

Fang: “Yes.”

McDonald: “So, when we talk about these different dislocations, a lot of the research that I read on ceramic dislocations are taking place in ceramic oxides. Is there any research on dislocations in the nonoxide ceramics?”

Fang: “Yeah, sure. For instance, I can give you one example, that was a very exciting one, recently published by the Japanese group. It’s zinc sulfide. It’s single crystal, and the paper was actually in *Science* in 2018. They take a single piece of zinc sulfide, and they found that if they turn the light off, they deform the crystal in complete darkness, the material can be plastically deformed even up to 46 percent plastic strain without fracturing. But, if you turn [on] the light, regardless it is UV light or the daylight, they immediately fracture after roughly 2 percent plastic strain. And this is what we call the photoplasticity. And this is also a very fascinating phenomenon that occurs in ceramic materials. And that definitely has to do with the charge dislocation core behavior.”

McDonald: “So those charges are then very important to this behavior that we’re seeing then.”

Fang: “Exactly.”

McDonald: “During all of your times studying ceramic dislocations, do you have any favorite stories from the lab of either just funny things that happened or serendipitous discoveries?”

Fang: “That’s a very interesting question. I do have some very interesting experiences in the lab. For example, I think back in December 2019, that was roughly like 8 months after I joined the group and started working on this topic. Back then I kept asking myself how exactly can I avoid crack formation while only introducing plasticity, let’s say, dislocations, into ceramic materials? And one day in the lab, I was just checking all these indents I was trying to perform. And all of a sudden, I spotted one indent that shows these very nice slip traces without cracking. The other indents, they very often have either a very, very tiny crack, let’s say, hundreds of nanometer or micrometer, but this one we have roughly twenty to thirty micrometer plastic zone without a crack. And I was very, very excited. And this is just by accident. Originally, we really try to find this, but we never succeeded.

Following that lead, I went back to check all the experimental conditions, the detailed lab notes, and I realized that there was probably a critical size effect there. Then I followed that lead, and later we actually have one nice publication in *JACerS*, *Journal of the American Ceramic Society*, to particularly address this size effect. Whether it is corresponding only to dislocation plasticity or there might be a chance that cracks could set in. And that paper actually has already, I think, more than 15 citations just after one year. I’m very happy to see that this work is so well received by the community so far.

And again, I would like to say, that is somehow by accident, but we were prepared because we were particularly looking for that."

McDonald: "Sometimes it shows up when you're not expecting it."

Fang: "Yes, yes. Another interesting story maybe also. So, since I mentioned I was mainly working on single crystal oxides because we want to eliminate the grain boundary issue. Because that is also one of the main differences I forgot to mention between ceramics and metals, particularly at room temperature. Ceramic materials do not have sufficient independent slip systems. That's why it's very difficult to transfer the knowledge we obtained from single crystals to polycrystal, because of the grain boundary issue and also the restrictions of the dislocation transmitted from one grain to the other. In metals that happens very easily. So, regarding this polycrystal deformation, we were just trying to do some testing. Also, I was doing this with my master's student in the lab and also using our indentation technique, but this time with a much, much larger indenter, with millimeter sized indenter. It turned out to be working very nicely even on polycrystal oxide. At room temperature, we generated no cracks but have abundant slip traces on the surface. And that is a lead that my master's student, Mr. Okafor, who actually followed and finished a very nice piece of master's thesis. And we look forward to publishing that results in *JACerS*."

McDonald: "Out of all the ceramics that you've had a chance to explore with, do you have a favorite ceramic system yet?"

Fang: "My favorite currently is the perovskite oxide, strontium titanate. The ductility of strontium titanate, even at room temperature, that was already found 21 years ago, actually. And the paper first appeared in 2001, also in *JACerS*.

For me, I like working with this material is because we have basically a complete set of tools, experimental tools, from deformation to characterization and also later, particularly for the functional properties evaluation. This really helps us to do these tests, particularly to get the proof-of-concept in a very efficient manner. So, that is why I like working with this material a lot.

But of course, we are now able to already be able to extend the experimental techniques beyond strontium titanate to many other oxides, and also includes sulfides, as I mentioned there at the beginning, and also fluorides. Currently, I have roughly more than 10 materials that we can deform at room temperature very nicely. I think this would be something I really would like to share with the community as soon as possible because currently we are also working on a database for building in dislocations at room temperature. So, I certainly hope that with this knowledge and also new findings we can somehow change people's views toward the misconception of ceramics are brittle. We have to be careful now with the statement, right?"

(music)

BREAK

McDonald: "The American Ceramic Society's Engineering Ceramics Division focuses on stimulating interest in the development and utilization of technologies based on ceramic materials. This Division organizes the annual International Conference and Expo on Advanced Ceramics and Composites in Daytona Beach, Florida. Learn more about this Division at www.ceramics.org/ecd."

SECTION 3

McDonald: "You recently started a lecture, right? On ceramic dislocations?"

Fang: "Yes, exactly. Together with my colleagues."

McDonald: "What is the structure of that lecture and how did it come to be?"

Fang: "It was first established last summer. It already evolved quite nicely this summer. So, this is the master's course. It includes fourteen to fifteen teaching units, weeks of teaching. Currently, we cover the basics of dislocations and then we march into the materials systems and also characterization of dislocations and then dislocation-based mechanics, including room temperature and high temperature. And, at the end, we have dislocation-based functional properties. I would call it a very systematic and already advanced module for teaching. And particularly I would like to mention also my colleagues, like Dr. Lucas Porz, a former Ph.D. student in this group, and also Dr. Till Frömling. And we together developed this course with the support by Professor Rödel and also the department, because this is more like an experimental experience. I myself am an experimentalist, and the course itself also has the experimental feature, I would call it. Because we were originally thinking about, 'Right, this field is going to rise.' I still strongly believe that, and we need younger people, particularly starting from the master's study program, to get them into the labs and work with us. That was one of the original intentions why we want to establish this course. To attract more people, younger people, to work on this topic together with us. It really worked out very well."

McDonald: "So you've had good feedback from the students then."

Fang: "Yes. I can even be very proud to say I have three students recruited from the lectures, and they are doing fantastic jobs now."

McDonald: "Well, then, it worked out very well, then, if you got three students to join you."

Fang: "Yes. And all of them will be doing Ph.D. at a later stage."

McDonald: "That's wonderful."

Fang: "Yes."

McDonald: “And I know also in October, you were able to do outreach at our Annual Meeting at MS&T. You were able to help organize a symposium all about dislocations in ceramics. And so, how did that come about organizing and gathering people to present at that?”

Fang: “Actually, before MS&T this year, at EMA 2021, we already organized one symposium, dislocations in ceramics, together with my colleagues, as I mentioned. But because of the pandemic, back then it was completely online. But anyhow, it worked out quite nicely considering that this is still at the very early stage of this topic. And we were able to get, I think for the EMA 2021, we have roughly eight talks in the session and on this topic. Since the feedback was very positive, we were thinking about ‘Okay, we should move forward and set up another symposium at a different conference.’ And then we aimed at MS&T.

I still have to admit that because of the traveling restrictions, and also some personal reasons for the speakers, this symposium we have onsite only four lectures. But I was told that, again I myself was not able to travel because of the visa issue. But anyhow, one of my students was representing me there, and the feedback from him was quite positive, I would say. The audiences there, they were able to ask many questions, very involved questions, and to have very extensive discussions even. So, this does not discourage me to further team up with my colleagues for setting up more symposia on this topic. For example, next year, in 2023, in Dresden, in Germany for the German Physics Society, we are already trying to set up another session [on] dislocations in ceramics. And this time, we definitely hope that we will be able to get more speakers and contributions.”

McDonald: “It’s wonderful that you’re having the opportunities to host these symposiums at different conferences so different audiences are exposed to this topic and might hopefully join in and maybe collaborate with you in the future.”

Fang: “Exactly, yeah. It was also a great opportunity. For example, at EMA 2021, I was able to get to know two potential collaborators, and now we [are] already collaborating. And this time at MS&T, based on the feedback from my student, I already see that there is another potential candidate that we would like to team up with from the simulation field, that we can definitely work together.”

McDonald: “That’s really exciting.”

Fang: “Yes, yes, definitely.”

McDonald: “As we’ve talked about, two of those meetings, the MS&T and EMA, they’re actually ACerS coordinated meetings with The American Ceramic Society. So, how did you come to become a member of The American Ceramic Society? And what have you found most beneficial being a member with us?”

Fang: “Yes, with my membership at ACerS, actually it started from EMA. I still remember the date. It’s January 3, 2021. Yeah, I tend to memorize this type of dates because for these important days, I already have them in my mind. It was a very, very interesting experience for me, and also very helpful experience for me. Because once I become a member of it [ACerS], I started receiving many useful informations from ACerS, for instance, like the *Bulletin* articles and also the *Ceramic Tech Today* and etc. Of course, including many other glass and ceramics industry informations. That really helped me to expand the, I would call it, my view toward ceramics because before that I was mainly like in the metal community and also very focused on this dislocation topic itself. But then I was able to learn there are vast opportunities out there, and also through this platform, I was able to get in touch with many other ACerS members. Because particularly for these *Bulletin* issues, like each month we get, and when I go through them, I pay attention to specifically what people are working on, which topic. If I find something interesting, I very often just again step ahead and be active and just contact the people there. And they turn out to be that very [nice], very often I get very responsive replies, and that even further enhances my confidence, right? It's like a very good cycle there.

And besides that, I would also like to say that I also benefit from this type of exposure. For instance, even later get my own work highlighted by ACerS. That is also the reason why I have already involved my students, including master's and Ph.D. students, that's six students in total. Also get them registered for become a member of ACerS. And the feedback from them is basically the same. It's very positive. And, of course, I would like still to continue this. And I'm going to have this lecture on mechanical properties of ceramics in this winter semester, and that's exactly what I'm going to promote to the students in class as well: Start the membership with ACerS. Definitely."

(music)

CONCLUSION

McDonald: "Dislocations in ceramics is not necessarily a new topic. However, advances in state-of-the-art characterization technologies and new perspectives in dislocation-based functionalities opens the door to move this field forward much, much faster.

I'm Lisa McDonald, 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 Xufei Fang and his research. Ceramic Tech Chat is produced by Lisa McDonald and copyrighted by The American Ceramic Society.

Until next time, I'm Lisa McDonald, and thank you for joining us."