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The Current State of 4D Printing Technology [Podcast interview transcript]

Angie: Hello. You're listening to the Prospector Knowledge Center Podcast. I'm your host, Angie Pedersen. Today we're speaking with plastics expert Andy Pye about the current state of 4D printing in the plastics industry. Andy is a technologist, technical writer, journalist and editor based in London. And he has spent a time as a consultant where he has specialized in advanced composites, asbestos substitutes, and the methodology of material selection. In fact, he's known as "the materials man," and has covered many of the early innovations in engineering plastics. He has written several books and technical papers on the subject. So we are glad to have him on the podcast today. Welcome, Andy.

Andy: Hi Angie, nice to be here.

Angie: Great, we really appreciate you coming to help share your insights on this.

Andy: Not at all, and thanks very much for that wonderful introduction.

Angie: Let's just jump right in. So you've written a number of articles for the Knowledge Center on 4D printing, and those articles have given a background on the innovations and kind of what it is. But why don't you go ahead and explain what it is, and how it's different or an expansion on 3D printing.

Andy: Yep, absolutely. Well, as you say, we've written three articles on it. And I came across it, first of all, I guess in 2013. So it's not that long ago. And the articles we've written have created a huge amount of interest I think, because it's such a futuristic technology. Four-D printing, in effect, is a development from 3D printing, which people will be much more familiar with. And 3D printing is otherwise known as additive manufacturing, or, when I was a kid, it was known as rapid prototyping. But that phrase seems to have somewhat gone out of fashion now.

And basically what it is, is a means of manufacturing items out of, not necessarily just polymers, it can be metal powders as well, layer by layer, by a number of different techniques, of which probably the most familiar is a technique called stereolithography. So that's 3D printing. And 3D printing and 4D printing are inextricably interlinked. So we'll be talking about both of them together.

So what's different about 4D printing? Well, essentially you take a 3D printed object and then once it's out of the production process, you then provide a stimulus to encourage it to change its properties in some way. Maybe change shape or change one of its other properties. And the stimulus might be heat, it might be water, it might be light. It could even be pressure or current or something like that. So there's a fourth dimension, which is usually a shape change, which is time-dependent after the initial manufacture. And that's what the fourth dimension means.

So, a common kind of example from sort of olden days might be shape-memory alloys, which use temperature changes to cause changes in material shapes. And they've been around for a very long time. So that's kind of a similar idea to 4D printing. And some aspects and some applications of 4D printing do use the shape-memory effect. We might also use things with electroactive polymers, which use catalysts to activate polymers with pressurized fluids, gasses, or even light. So, and other 3D printed structures might use moisture. So there's a whole range of different possibilities, pretty much all of which are still in the research stage.

Coming back quickly to that fourth dimension, we're often quite used to the idea of time being a fourth dimension, you know, with three dimensions of X, Y, and Z being movement directions, and time being the fourth. So here we're using the fourth dimension in effect to be the time taken for a self-transformation after manufacture. Because of that, some industry commentators like to use the term "3D printing and self-assembly" as an alternative to "4D printing." So that's a pretty long explanation of what we mean.

Angie: Well, it's a great background and kind of baseline to get people all on the same page on what we're talking about. So I think you mentioned a couple of examples. But what other kinds of applications does the technology have?

Andy: Yep. Well, that's a good question. And perhaps it's better to ask what applications might the technology have.

Angie: Right. True, since it's still in research.

Andy: Yeah. A lot of it is in research. The ideas really came out of MIT as much as anywhere. But you'll find Georgia Institute of Technology is quite predominant as well. So is the Singapore University. And there are other researchers in Australia and even the University of Bristol here in England, also active in various aspects. And most of them are looking at different little parts of how this whole thing works together with sort of different specialized technologies.

So, one area that's very excited by it is the medical engineering area, because they can see, for example, how components like stents to band arteries could be manufactured by 3D printing and then be made to expand when in situ. So that's an example. Another medical application is printing new skin for skin grafts which could then be, you know, encouraged to freely change shape over time. So, medical is a big area. Third area of medicine would be using drug capsules that release medicine at the first sign of infection.

Angie: Wow.

Andy: Yeah. So the infection would cause heat. And if it could be set up so that the thermal temperature was at the right level, body temperature could be used as a trigger, and medicines like an antibiotic could pour in at the right time using a standard spray instead. So, yeah, though, medical we think is gonna be a big area.

And other areas, looking at areas where we might get a high-volume application, because I think that's what we need really is, you know, one high-volume application would really get this to take off. And then a lot of the other areas would follow suit. So that's, I think, what it needs to meet some of the ambitious expectations of what the technology might provide. So in that context, another area that could be quite good would be solar cells, because clearly we're all moving towards renewable energies and away from traditional energy generators, or at least we hope we are.

One of the areas being examined by MIT and Singapore University in combination is shape-changing techniques in solar cells. What they do there is to create a complex 3D structure. A proprietary process then programs them to return to their original forms using light, which is obviously great in a solar cell application, as soon as the temperature reach a certain predetermined value which they call a sweet spot. So, in that case, they're using a photo curable shape-memory polymer as the basis of the work. So that's an encouraging area. And that material, as you'll realize, can switch between two states, a hard state at lower temperature, and a softer state at higher temperatures. Now that ability to switch states would open up some other areas of application, we think, in biomedicine, robotics, even wearable sensors and artificial muscles as well. So down the line, people looking at a lot of possibilities. What it just needs is a kickoff.

Transportation is the third area which has a lot of potential, using programmable carbon composites and sometimes wood grain materials. And you might be able to use things like a car aerofoil which would morph according to particular circumstances that the car was in. There's a program going on at a company called Briggs, with a number of other partners looking at that, using flexible carbon composites.

And in Europe, Airbus is interested in a similar program, considering what they might be able to do with aerofoils in carbon-fiber composite structures for aircraft. And if they could use this type of technique to replace things like hinges or hydraulic actuators even, and motors, you know, you're looking at the potential to save an awful lot of weight and mechanical components, which is extremely important in aircraft. So, that's some of the ideas that are bouncing around at the moment, without any of them having reached the commercial stage at the moment.

Angie: Sure. Well, that's all just fascinating, and obviously, some pretty big brains working on this research. But what excites or interests you the most about this kind of technology and its applications?

Andy: I think that's a very good question, I suppose. What excites me, I suppose, is the, if you like, the whole field of what you might call functional materials, you know, where materials are actually designed to have a special specific property or combination of properties, rather than the traditional materials science which I grew up with, where engineers use materials which have specific bulk properties, and you can't really do too much with them. You can alloy metals or you can put fillers and fibers, and polymers. And that makes a difference. Of course, it does.

But nowadays, where we really are starting is to design the material for the application, rather than the other way around, and I think that's very exciting. And there are a lot of examples of that.

Obviously, graphene, you know, in the carbon area, maybe two-dimensional form of carbon, which has very different properties to the conventional forms of carbon, such as graphite or diamond, lot of potential.

Nanotechnology generally, building up materials layer by layer, even at the atomic level. This is a very exciting area. And it's a real step change in materials science. You know, it's 40 years since I graduated in metallurgy, unfortunately. My course was all about large lumps of steel and a little bit of aluminum really, or aluminum. But, you know, last year I actually returned to my department. And it's a totally different technology now. You know, there are materials being created in fume cupboards on the atomic scale.

Angie: It's amazing.

Andy: It's really exciting stuff. One of the materials they did show there on the day were various shape-memory metals, copper based or nickel titanium based, which I did have a play within the 1970s when they were just coming into existence. And in a way, we were looking for applications for them. I remember we designed a control for a greenhouse window, where the temperature operated a screw, and the window would open or close depending on what the temperature inside the greenhouse was. A

nd I designed a little part for a thermostat for one consultancy job that I did where they had oil-based bellows which were part of a temperature sensing system. But they were getting terrible problems trying to solder this together. So we went for a memory metal with a diffusion bonding technique instead of soldering. And that replaced the soldered part. So that was quite an early application of memory metal.

But of course, nowadays, that whole assembly wouldn't exist. It would have been replaced by some sort of electronic temperature control, and everything would be totally different. So it doesn't really have any current relevance. But it's an interesting use of those sorts of materials. So I've seen lots and lots of parts and prototypes being 3D printed. And I've seen the other end, where I've seen, you know, shape-memory metals and the like in operation.

What I haven't seen in firsthand, and I'd love to do it, maybe U.S. or Australia or Singapore, would be combining the two to make the 4D part. And that's gonna be very exciting when I do get an opportunity to see it.

Angie: So what are the different materials that are used in 4D printing projects?

Andy: That again is a good question. Traditionally, I mean, starting with 3D I suppose, the range of materials has traditionally been quite limited. And that's held the development of 3D printing back, perhaps as much as any other factor. Perhaps we'll come on a bit later to look at some of the limitations of 3D printing, because I think it's quite a big factor in how fast this technology can take off.

But of course, when we're talking about 4D printing, then it's even tougher, because we're looking for materials that can not only be 3D printed, but also have this ability to be acted upon in some way to change their shape or change a property afterwards. As things stand, the range of materials that's available is pretty limited. There are some carbon fibers. I mentioned a form of wood grain. There are various hydrogels.

Each of these materials is really being largely researched by one group of researchers, either at one university or a combination of universities. The information that I have at the moment is that it's gonna be the carbon fiber segment which is likely to be the largest contributor to the overall market. And it's thought at the moment that would have a share of about two-thirds of what market there is by 2019, which is, you know, only two years away of course.

I mentioned the hydrogel. That's being developed at the Australian University of Wollongong. That's a very different type of approach, because this is a material which changes shape in response to changes in water temperature. And it's also compatible, as obviously, it has to be, with a 3D printer. And they're looking at applications for medical soft robotics.

To talk chemistry for a while, it's a type of interpenetrating polymer network which comprises an entanglement of one polymer network cross-linked with metal cations, and a second polymer network cross-linked with covalent bonds. What it can do is it can show reversible length changes of almost 50% of its length, which is very significant. And at temperatures which are very manageable, between about 20 and 60 degrees centigrade, which is, you know, very easy to manage. So you're not doing things at ridiculously high or ridiculously low temperatures which would make it more impractical.

So what they've done is they've 3D printed a water valve, and when it's exposed to hot water, it opens once the water temperature drops. I suppose it's a little bit like that shape-memory device I was describing for the greenhouse window. And, unlike a standard 3D printed material, it doesn't require any human intervention to change. And is just repeatedly opens and closes without straining for a large number of cycles.

So, it looks like quite a promising kind of development, you know. So it basically closes upon exposure to hot water and opens in cold water. So, using things like CAD modeling, that kind of approach I think could easily be extended to other types of moving structures as well.

Angie: All right. You just mentioned 2019. Do you think that we're on target for seeing commercialized versions by then?

Andy: Again, good question. I keep looking to see when something really commercial is going to turn up. I'm seeing a lot more interest. And I'm seeing, you know, a lot more visibility. For example, I went to the Hannover Fair a couple of weeks ago. And there were two or three quite interesting applications being demonstrated there, but still at the research phase, you know. So the visibility's increasing, but not, at this stage, I don't think the commercialization.

I think a lot of analysts get very excited by these sorts of technologies and put up some really exciting predictions. But usually, what happens is that the time scales take, are longer than expected. But probably, the benefits will ultimately be as they expect. But it's just keeping people hanging in there until the first one or two key applications do actually take off.

So I think that's where we are. What should we look for? Most of these 4D printed objects at the moment are being manufactured under university conditions; they're gonna need lot of scaling up though. We need an application looking for a solution rather than a material looking for an application, I think.

Angie: Great. That makes sense. So, in your first article on 4D printing on the Knowledge Center, you mentioned that there are quite a few challenges with 4D printed projects, such as large items taking days to print, as well as the limitations in materials that you've mentioned and the size and things like that. Do you think that those same challenges apply today, or has the technology evolved?

Andy: Three-D printing is getting there. We have a much wider range of materials than we had before. We have desktop printers which are now affordable. For parts that aren't too large, I think it's becoming quite a viable process. It needs to be targeting parts which are either early prototypes or small volume production runs or products that can't be made any other way, because it is actually possible to get some three-dimensional shapes with holes and channels in that are just actually impossible to make by any method other than building them up layer by layer. You can't cast them because you can't get the parts out if you try to cast around a mandrel, similarly with molding. So there are parts that are actually impossible to make any other way, and is a very good factor in their favor.

The speed, I think, is still quite an issue. We are seeing some metal parts for aero engines at Rolls-Royce being made by 3D printing now, great, and of course, with aerospace, the volumes aren't as prohibitive as they would be for example in the general automotive sector. So of course the amount of money available to save weight or to produce parts is of a different scale. So it's reckoned that by 2025, the 3D printing market should be worth as much as, globally, about between 200...it's very wide range, this, but between $230 and $600 billion, which is a lot more than I earn, but it's a very wide range. I think whoever came up with that figure is certainly playing safe. But, of course, as we said before, only a fraction of that would be using a 4D effect, and therefore, whilst it's not unrealistic to expect a really high growth rate in 4D, that will be a high growth rate of a small volume, I think, least for the next decade or so, but exciting nonetheless.

We talked about breakthrough application. I think that it's important to say that you need a product champion and a good application to make this happen. You identify a suitable part, and sometimes a bit luck as well, you know. You need to be in the right place at the right time. You know, I'd be surprised if we see significant commercialization in two years, but it could be that one of the specialist areas where a high price can be commanded and something that can't be made or made to function in any other way, could cause the technology to take off. I mean, if I had to guess, I'd probably guess for the medical sector. But it could be any one of the others.

There is one other area which we haven't mentioned, but we did cover in one of our articles, was the fashion industry. And I'm not sure whether that's really qualifies as an engineering application. But actually clothing has been manufactured out of 4D printed materials. And there's a custom-fit dress which we showed a picture of in the article, which comprises of pattern structure of thousands of little triangular panels interconnected. And they're all 3D printed as a single piece. But by folding the garments before they're printed, you can make complex structures which are actually larger than the 3D printer would otherwise be able to handle. And so that's quite a big factor in terms of 4D printing being able to improve the capability of 3D printing.

Because, you know, shape folding, I think, is quite a big area of potential application. Another area might be where something needed to be transported and then used. So you could transport it flat after being 3D printed, and then expose it to its stimulus when it gets to the other end, unpacked and then it will change shape and be ready to function. So that's another possible application of the 4D printing process.

Angie: That sounds very handy.

Andy: I think so. Yes, I hope so. People are looking at that for things like robotics and, again medical devices, but even toys, you might be a possibility there, plastic toys which are often shipped halfway around the world, and very often made out of polymer. And that might help with the packaging and transportation process.

Angie: Right. So, you mentioned the obvious direct tie between 3D printing and 4D printing. What do you think needs to evolve within 3D printing for 4D printing to progress?

Andy: Yep. Well, that's the key, isn't it? As we said, we're seeing an increase in the number of available materials for 3D printing and definite improvements as well in the engineering capabilities. So the machines are being produced in higher volumes, which means they are deeper and in desktop sizes, which means they're manageable.

But as I said before, the process is, I think, still quite slow as a high-volume manufacturing process. So that's still a limitation. Obviously, 4D printing is dependent on 3D printing. And it does use a much more specialized and limited range of materials. But I think it will take some big steps forward as 3D printing becomes more accessible. That's really the key. They work together.

You know, I was actually at a 3D printing company last year, and they were two days into producing a part. Unfortunately, they then had a power cut. They were then zero days into producing the part, and they had to start again, which was very frustrating, and think they've improved their power supply system now. You know, that's the kind of difficulties you've got. It takes ages to produce a really big part. There has to be a very good reason to do it.

But, you know, smaller parts obviously don't take anywhere near as long. But then you're competing with different technologies like injection molding or die casting, many cases which are very fast. Most of the materials, I think, it's probably true to say are nowhere near as strong as those used in other modern manufacturing processes, so that's still having to be worked on.

There are some developments in metal powders which have been quite useful on the metal side, and an increasing range of 3D printable polymers as well. So we face the limitation of size. Most of early applications of 4D printing are using water absorption or a shape-memory effect to change their shape or change their property. But they're often quite slow to respond, and you don't get a lot of force out of them. So I think those are areas where materials engineers will be working to improve the speed of response and the amount of force that you can get out of the change, which could be very useful for things like the valve example.

You know, you might need more force than is currently possible from that hydrogel. Some of them don't have a totally reversible property. So just like for example, a battery. You have a phenomenon called hysteresis where your motion one way, or your charging in case of a battery, doesn't follow the same back path back. And over time, you get less and less of the effect. So there's a kind of a fatigue effect as well. So we need better reversibility of the property, and we also need, I suppose you'd call it, better cycle times. You know, higher cycle time so that the device can operate reversibly.

That may not matter in some applications. Wouldn't matter in a stent, because it only has to expand once, but in a valve, where it's seeing hot and cold water, it would maybe have to happen several times a day, and for several years, so different applications would require different specifications on that. Obviously, I think, the fastest stimulus for change would be heat, more so. The things that change as a result of moisture or light tend to take longer. And I would say that heat is also easier to manage, and if you need a specific temperature, it's probably easier to design that way. But not all 4D printable materials are using heat. Some are using other things for very good reason.

Angie: So, you've said that 4D printing is obviously still in the research stage. But do you have any predictions of what comes next?

Andy: What can we expect beyond...Yeah, what can we expect beyond where we are now. We are very much at the research stage. I think what the researchers are currently doing is evaluating the capability of the materials they've got. You know, what is the durability, how strong are they, how reproducible are they, because engineers are going to need that sort of practical information in order to have confidence in the materials. And I think that has gotta go hand-in-hand with all the blue sky research that we're still being inundated with about little specialist materials for very special exotic applications. You know, the exotic applications are still pouring in, by the way, and I've seen one that NASA is playing with 4D printed space armor using….

Angie: I saw that too.

Andy: Yeah. Similar metal fabrics to the ones we talked about for the fashion industry. And that can be useful for having things that can change shape, I guess, in space. And I've even...I must follow this up because I need this, a cure for bald men. You can form polymer hair, believe it or not. So I may look different next time you see me.

But yeah, practically, you know, I was very encouraged at the Hannover fair by looking at...MIT had some exhibits there which I thought was terrific. And they were showing self-folding water pipes with an expectation that they're not too far away from manufacture. And they can, rather like the valve, they can expand or contract in response to water pressure without using any sensors or actuators or microprocessors, you know, just basically around the design of the material, which is I suppose coming back to that point about designing a material for the application, rather than the other way round, which I thought was great.

And another exhibitor was showing self-assembling robots, which was terrific. So you produce your robot in a folded form, take it to an accessible place, and then it automatically unfolds and gets on with the job, which was pretty exciting. And there was a kind of a related application. It's not really 4D printing, but I'll mention it anyway, which is self-mending materials, which repair themselves. And they were using an ultrasound so that you start with a carbon fiber composite, which can

3D printed. It contains tiny little nanotubes which are filled with an unhardened polymer, and then you use the ultrasonic energy to shake them around, which breaks open the tubes, and the liquid polymers are released, which mend the material, which I thought was kind of nice. So it's almost 4D printing in a slightly different guise, I suppose. Clever idea and I always like clever ideas. Lots happening. It's good to see it at...Hannover Fair is a very big show. Two hundred thousand people go there. So it's getting good exposure. And when, you know, a lot of design engineers see an idea or a possibility, then very often the ideas follow. So it may be that purely showing it to all those engineers in Europe might stimulate some ideas, and we may suddenly find we're back on track for 2019 commercialization. Well, let's hope so, anyway.

Angie: Right. Do you think there's any potential for consumer demand? I mean, as research findings are being shared in the news and things like that, do you think that the public will be kind of clamoring for any of these things?

Andy: Well, that's an interesting question. Consumer applications I suppose are still, they're still really engineering products aren't they, in a kind of a different guise?

Angie: Well, I was thinking like the skin grafting that you were talking about.

Andy: Yeah. Well, definitely. I think, you know, for medical applications then, that's an area where high prices are sustainable. You know, we have increasing expectation, don't we, of how much money is spent on our preservation medically. So, you know, that still can command high prices. I mentioned the toys area, because that's an area where prices might be low. Volumes could be high if the parts were small enough. And then the cost saving is about total cost of ownership, about being able to transport things in smaller volumes and save money that way. So maybe consumer items like toys might be able to utilize that shape folding effect to take shape when they arrive, rather than when they leave their factory. Possible, but I haven't seen a lot of consumer applications as of yet.

And I guess it's typical of new technologies that they start in aerospace, defense and military, medical, high prices, and then that helps to fund further development into general engineering and perhaps ultimately into consumer. That's, you know...consumer industry has changed as well, hasn't it? I mean, you know, we all have a smartphone. The volumes of smartphones are massive, the lifetimes of products is getting shorter and shorter.

So there's a demand pattern for consumer products is changing. Whether that's necessarily pointing favorably towards 4D printing, I'm not sure, because we still are faced with the speed issue, so producing very high volumes by 4D printing or even 3D printing is still a challenge.

Angie: All right. Well, this has been absolutely fascinating. And I love hearing about the applications and different ways that is being studied and could be used. Are there any significant points that we didn't address or anything you'd like to add about the technology or the market?

Andy: I think I have actually covered all of it. I think that's probably a pretty good summary already of exactly where we are. And obviously I will do what I always do, which is to keep a watching brief, and hopefully, I'll see some very exciting new applications very soon.

Angie: Right, Right. Well, we would love to touch base again with you when you do see them.

Andy: Absolutely. And I will certainly look forward to that.

Angie: Absolutely. Well, thank you so much for sharing your insights with us. We really appreciate it. And know that as a person that always sets his eye on the industry innovations, that your insights are extremely valuable. So thank you.

Andy: Well, thank you. And thanks for having me.

Angie: Absolutely. You've been listening to the UL Prospector Knowledge Center Podcast. I've been your host, Angie Pedersen. We hope you've enjoyed the podcast and found it informative, and maybe even entertaining. Please let us know in the comments if you have any topics that you would like to hear in podcast format. Thanks for listening.