Microrobotics

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Micro-Mechanics System Design (Micro-Fabrication of Micro Robots) - Module 05

Hello, I am Arpit. I am a PhD scholar and a Prime Minister Research Fellow under Professor I.A. Palani in the Mechatronics and Instrumentation Lab, and I have with me Mr. Krishnapal Tomar; he is a PhD scholar and is working on the concept of micro 3D printing. Today we would be discussing the principles of micro 3D printing, how it happens, and how it can be utilized in different applications, specifically focusing on micro robotics applications, which is where the course is beautifully designed for. Before starting the underlying principle of micro 3D printing, as you might have understood in your classes, there are two basic principles: one being the additive process and the other being the subtractive process. In the additive process, we normally do layer-by-layer deposition of the material, whereas in the subtractive process, the conventional lithography process or etching process, as we normally say, is kind of in utilization. The additive process that is conventionally present, wherein we do layer-by-layer addition of the material, is normally observed to yield a minimum feature size that will always be in the mm range. This might be due to the complexity of the process, or it might be because of the feedstock that is being used.

So, normally in the additive manufacturing process, the feedstock that we use is either in the form of wire or it can be in the form of some powders, whereas what we are discussing today is the principle of laser micro 3D printing, in which the feedstock for the first time is being used in the form of a thin film. So thin film as a feedstock with a thickness in the range of a few microns, once it gets transferred, is in the microns range. Let us suppose we have a thickness of, say, 4 or 5 microns; then, based on the experimental analysis we currently have observed, the transfer of the material, once it happens from the top surface to the bottom surface which we will be discussing in detail, like what is the top surface and what is the bottom surface has a transfer efficiency in the range of 70 to 80 percent, which means that if the thickness is somewhere around 5 microns, the material transfer would be in the range of 3.4 to 3.7 microns.

So, that is what is conventionally believed, or that is what we have observed based on the experimental output. What is it used for? It is used for basically printing different kinds of sensors and different kinds of materials. As far as our experimental understanding is concerned, there is a large amount of material that we have explored, such as pure materials like aluminum, compounds, and alloys, such as shape memory alloys like nickel-titanium. Furthermore, we have moved towards exploring ceramics such as zinc oxide, and now we are exploring its feasibility for printing silicon carbide, so that is where the ranges of materials are explored from a low-density material to a high-density material. So various ranges of materials have been tried and printed, and they have been successfully printed, so I would like to just show you a simple use case. If you could see over here, basically this is the strain gauge of nickel titanium that is being printed in a specific shape, and then we have connected it with copper wires. We have tried and tested its gauge factor and compared it with commercially available strain gauges, i.e., how it is comparable and how much gauge factor we are getting. Then, if we talk about the fine feature size, the controllability of the system is also very important in our case because we are using laser printing.

When the laser hits the surface, the material ejects out, and since it moves in an XYZ state, it is in an automatic translation state. Once the material transfers, the feature size we can achieve is in some microns, specifically 5 to 10 microns. Whereas if we talk about the thickness, a single layer of thickness, as I discussed, depends on the thickness of the donor material. Once it transfers onto the surface, we need to consider how much efficiency we have discussed. So, we will be discussing the processes that follow in detail, followed by the conventional principle.

The underlying principle is that we have step one; the step we are taking is a donor material. The donor material we take depends on the laser that we are using. In our case, what we are using is a 10.6 micrometer carbon dioxide laser. The 10.6 micrometer laser should be transparent to the donor material. The donor material we are using is a silicon wafer because, as the laser falls on the surface, as you might have understood in this course, normally, once the light falls on the surface, it might get reflected, it might get transmitted, or it might get absorbed on the surface. These are the three conventional principles that follow. As the laser energy falls on the surface, what do we want? We want the maximum energy to be transmitted from the surface. It should neither be absorbed nor reflected.

Now, as we move to the second layer, it is a sacrificial layer. So, what do we do with the sacrificial layer over here? In order to create this sacrificial layer, we apply a coating of a polymer. In our case, we use a PDMS polymer. Why PDMS? Because this PDMS absorbs 10.6-micrometer wavelength light. As it becomes transparent from this surface, it goes into the second layer. The second layer we have coated is a PDMS polymer, and this wavelength of light gets absorbed in this PDMS polymer. So as it absorbs this wavelength of light,

what will it do? It will create some gas pressure here. Below this is the third layer, which is the donor material that we want to transfer. So, that third layer, once we are coating it onto the surface, as the laser falls on the surface from the first layer, gets transferred to the second layer, creating a gas pressure in the second layer.

Now this gas pressure has to be released because it creates some kind of instability in the second layer. The gas pressure should be released, which might have to either go to the front side of it or go to the back side. Now the backside of it that we are seeing is a solid silicon substrate, and it won't allow the gas pressure to go on the backside. The gas pressure will automatically come on the front side, which is a coated thin film. This thin film won't hold that gas pressure because it is very high and will eject the material from the surface. The material, once it ejects from the surface, comes onto the base substrate. Here, the base material is an acceptor substrate. So, as you have seen in this case, it is a flexible PET substrate where the material transfers and comes onto this flexible PET substrate. Now, this does not mean that the technology is only focused on the flexible substrate. We can even do these types of printing on the solid substrate.

If we observe in this case, it is a solid silicon substrate. Now, on the solid silicon substrate, you will see that this is a beautiful hexagonal shape being printed, which means the technology does not depend upon the acceptor substrate. The technology does not depend on what acceptor substrate we are using; it can be a solid substrate as well as a flexible substrate. Now let's understand step by step. So we move to the first step. For the first step, we need a silicon wafer. Now we will coat a PDMS layer on it. It also requires optimization because it does not mean that any thickness of PDMS will work for our case. As the laser falls from the backside of it and is transferred onto the second layer, which is the sacrificial layer, the laser energy and optimization are done in a way that the gas pressure is optimum enough to eject the material, because that laser energy should not interact with the third layer of the material. So we must maintain that optimized thickness.

If the thickness is less and as the laser hits the surface, it will just tear off the sacrificial layer and interact with the material. This means that the material properties will change, which we do not want. We only want the material to eject from the surface, and it should never happen that any amount of material comes out or that the laser interacts with the material. If, in any case, the thickness of the PDMS layer is very high or more, then what will happen? The laser energy, once it hits the surface, won't generate the sufficient amount of pressure that is required because of the resistance of the material. So, it won't allow the gas pressure that would form; it won't allow the material to eject, and what we have also observed while doing experimentation is that at times PDMS also comes out from the surface, and a white layer is formed along the transfer material.

So why does that happen? It happens because of the excess PDMS thickness. We have to optimize the thickness. So, the simple principle is we take this silicon vapor, put it on a vacuum-based spin coater, and on top of it, we put one or two drops of PDMS. The PDMS ratio that we use is 10 to 1; that is the ratio of PDMS A to PDMS B. Normally, the PDMS polymer that is being used has a main solution and a binder.

So, the solution to the binder ratio is 10 to 1 that we conventionally follow, but of course, it can also vary; people use 8 to 1, 6 to 1, or 14 to 1 also depending upon the application that they have been working on. We use 10 to 1 to perform spin coating. So, the spin coating, of course, is optimized again. We normally do it in the range of 5000 rpm to 8000 rpm for 100 seconds. So, 100 seconds comprises the acceleration time of 10 seconds, the deceleration time of 10 seconds, and a holding time of 80 seconds, and then we do the spin coating; the material is then spin-coated and is present on the surface. The next step, once this material is spin-coated with a sacrificial layer, is to give heat to it in the range of 80 to 100 degrees, which is done by keeping it on a hot plate. It can also be done in the oven. So normally, if you don't have a heater, you can keep it in the open atmosphere, but the time taken would be longer because it would only take heat from the atmosphere, and the atmospheric heat would be around 30-40 degrees depending on the place where you are living. Appropriately, then, it will take time to dry or it will take time to cure. We perform an accelerated heating, and based on that heating, the curing occurs.

Once the curing happens on the surface, it is ready for the third process. So, what is the third process? It is coating the donor material that we want to print. How do we apply that coating to the material? The coating of the material follows the principle of sputtering. You might have understood in the past lectures about other deposition techniques, such as the E-beam technique and flash evaporation. Now, we are going to the next process, which is sputtering. Sputtering is done to create the third layer, the sacrificial, or the donor material that we want to transfer. As we have also discussed initially, different ranges of materials have been explored in this technique. If I show you what we require in this case, you might have understood in the e-beam deposition or in the flash deposition that we require some wires or some pellets in order to do the deposition of the material. In this case, we require a target, as seen in the image. So, what I have is a silicon carbide target.

Different material targets are commercially available on the market that can be used. So, in this case, what you see is the TiO2 target. TiO2 is a titanium oxide target with a copper backing. So, a copper backing plate is given because normally, with the oxides, they do not have that conductivity; so, it becomes a challenge. So, the copper plate allows for the sufficient conductivity that we require. So, this is the target that we need in this case. So, if I try to give a basic understanding or a basic principle of sputtering, everyone might have tried plucking a mango from a tree. The conventional process is that we take a stone and then throw it at the mango that is there and has some mass. Since it has some amount of mass, it does not have that velocity. What you do is take a stone and throw it at that mango.

You have a stone in your hand, and now that stone has mass. Once you throw it at the mango, it has some velocity. This mass times velocity is momentum. Okay, now as it hits the mango that is on the tree, it will take that momentum. Now it has that momentum; it will take the velocity and come down, following the principle of momentum transfer. The momentum transfers from the stone to the mango that comes down onto the base surface. Here, the similar principle also follows. What happens in this case? So, in this case, it is basically DC or RF; it is like direct current or radio frequency. So, there is a positive bias and a negative bias that you might have read about in your class as well. What we normally do is give that amount of energy to it.

It is complete; a vacuum chamber, and this complete vacuum chamber works in a vacuum environment. So, in order to create a vacuum, what do we have? We have a rotary pump, which creates the basic vacuum up to 10 to the power of minus 3 millibar, and then, in order to take it higher, up to 10 to the power of minus 5 or even higher. Normally, in our E-beam or flash deposition, we use a diffusion pump; whereas in this case, we use a turbo pump. The turbo pump can take it to even lower than 10 to the power of minus 6 millibars or so. What do we do now as we create this vacuum? We place our sample, and then what you are seeing over here, is a substrate heater. We can do substrate heating, and whatever we see over here is a rotator; it will rotate the sample continuously. The sample that is placed over here will continuously rotate in order to achieve a uniform deposition on the surface. This will have a rotating unit. Now, this is the target; this is what we call a gun; this is the gun, okay, and on the gun, we put our target over here.

The material that we have to deposit is okay. We put the material, then the target that we have seen. Basically, the target that I showed is being put over here. Now, once you give that energy, what will happen? The electrons, or the material and the atoms that are present on the surface, are excited and want to come out of the surface, but they cannot come out of the surface. What do we have to do in order for the material to come out from the surface? Let us understand this with an example of a mango tree, as discussed. We must throw a stone at the mango tree for the momentum to transfer.

So, in this case, what do we do? We purge argon controlled through MFC, i.e., mass flow control. IT allows the material the argon in the controlled manner whatever control we want. We can control the argon floe i.e., how much centimeter cube of argon needs to be fed. The chamber will have some amount of argon. This argon will act as those stones. Why have we used argon? Because argon is a noble gas and is non-reactive in nature. Further, it has some mass. It would not allow any reaction to happen if you are feeding other gases; suppose you are feeding oxygen, then it might form oxide; if you are feeding nitrogen, it might form nitrites. We do not want that. What we will do we will feed argon gas now the argon once it comes into this chamber. This argon will act as a stone and this argon will come and it will strike the surface As the argon strikes the surface, it will eject the material from there and the material will go out. The material will go out, and it will

start getting collected on the substrate material that we have created: the silicon wafer, this coated silicon wafer.

We will place this, and whatever material you are using, such as silicon carbide, will come out and slowly get deposited. It will be like atom-by-atom deposition. So, the atom-by-atom deposition will happen on the surface, and then we will appropriately get thickness. Now, this also depends on the material that you are using, which means that it is not a standard procedure that for this amount of time, if you are doing it, then you will get this amount of thickness, because it again depends on the material. For instance, if you are taking aluminum or metals such as nickel and titanium, it takes 15-20 minutes to achieve a thickness of 3 to 4 microns.

But if we are going for silicon carbide, silicon carbide is a very tough material, so it at times requires 10 to 12 hours to achieve a thickness of 3 to 4 microns; therefore, we do it in steps to reach that amount of thickness. It again depends upon which material you are going to work with, and then you appropriately do the deposition layer by layer or atom by atom. And then slowly you will get the thickness. Okay, so if you see it in the video, the video that we have attached, that is how you are seeing that a plume is coming or plasma is coming. So, you are seeing this pink color plasma that you are observing. So, this is the plasma zone in which that material is ejected from the donor, from the target, and then it is coming out and slowly getting deposited on the top surface, which is continuously rotating. So the material comes out and slowly it's getting deposited over here, so it's like atom by atom deposition. Because it is atom-by-atom deposition, it means it offers certain advantages. What advantages does it offer? The first advantage is that the controllability is in your hands.

It is very controllable. If we compare it with the flash deposition technique, where the material just flashes off and gets deposited, the controllability is not present. In contrast, in this case, we will get a good amount of controllability that you require for your situation. Then the second advantage is that since the material gets deposited atom by atom, the uniformity will be very good. And since the sample is also rotated at the same time, giving the substrate heating on the surface, the rotation and the substrate heating induce uniformity. And since material is going through atom by atom, it will be very uniformly distributed all around the material, which means you can expect that uniformity to be maintained, which is not the case in, say, flash deposition. But again, in order to achieve that thickness, the time taken would be higher. So, it depends on the material that you are going to work with. Apart from the standard process of forming a vacuum and the time taken to form the vacuum, the third step, which is material deposition, will take more time compared to the other deposition technologies that are being used. But this is a very famous and conventionally used technology. So, sputtering is widely utilized. DC sputtering is normally used for metals, and RF sputtering is normally used for oxides like titanium oxide, silicon carbide, or zinc oxide. How do we do the material-by-material coating or layer-by-

layer coating? Once we have completed this coating, what do we do now? We have this substrate or this top material, which has these three layers. The first is the donor, followed by the sacrificial layer, followed by the donor material. We need an acceptor. As discussed, the acceptor that we are going to use can be anything, i.e., it can be a flexible acceptor or a solid acceptor. Because the laser only hits the surface, it goes to the second layer, creates gas pressure, and only until that point is the laser's responsibility. Once the material ejects from the surface, it transfers onto the third coated donor material layer, which transfers onto the acceptor substrate. So, the acceptor substrate can be a solid substrate, as in the case of a silicon wafer on which different beautiful shapes are printed. It can be a solid substrate, or it can be a flexible substrate, as we discussed at the beginning as well. If you see this, basically this is a solid substrate on which this shape is being formed.

This is a solid silicon substrate. You can do it on an ITO-coated glass, normal glass, or any other solid substrate also because the laser interaction is only happening between the first layer and the second layer. Now the third layer is being transferred only because of the gas pressure. Since the material is being transferred, any kind of acceptor substrate can be used in that case. But one important thing that you have to take care of is that while doing the transfer onto the substrate, the material, once it is transferred from the surface and comes onto the base substrate, has to adhere to the surface. What happens with adhesion? Local welding occurs for material ejection on the solid or flexible substrate. Once the material is transferred onto the substrate, it must weld to the surface or join the surface to achieve a good amount of flexibility while ensuring that the strength of the sensor being formed remains intact. So, to create that local welding on the surface, what do we do? We heat the substrate. Thus, to transfer, the acceptor substrate is heated. Once the acceptor substrate is heated, the material comes out in pixelated form, is transferred to the surface, and gets attached to the surface, resulting in good strength of the sensor, as I am showing you in this case. Basically, the material that was transferred is very much intact on the surface, and it would not come out because a good substrate is provided on the surface.

Using the principle, we have formed strain gauges, and if we bend this strain gauge in any way, the material will not come off the surface. Now, this technology, apart from this kind of printing, also provides a means of printing different shapes because it has motion stages of x, y, and z. What do we do? We have to just feed that G code and M code, and then whatever shape we want to print, we can just give that code appropriately so it can print a gear shape, it can print multiple flexible antennas, strain gauges, or even print interdigitated structures. A lot of structures and sensors that are being used in the electronics industry or microelectronics industry can be done.

Now there is another area that we are tapping, i.e., normally if we see microelectronics that people have been working towards, what happens is that the conventional process of forming a PCB is underutilized, but at times it happens that the material being joined gets damaged in between; there isn't any technology as such that will improve the process of binding it again, and then that sensor can be utilized again. The electronics can be utilized again, so if there is some damage to the fabricated sensor, it has to be thrown away, which means that electronic waste is generated. What can be done if we have something in a localized region? If we can do something, then that problem can be solved. This can be one of the techniques in which, suppose a printed PCB is damaged in between, wherever there is damage, you transfer the material to that specific zone and align that material in a way that it joins completely, and then try to utilize that sensor again. So this is one probable way that this technology opens a window. This is an additive-based technology or micro-additive technology in which, by transferring layers of microns in a layered fashion, we can fabricate micro sensors, and these micro sensors can be utilized for different applications, such as in micro robotics applications, as you are taking in this course. So, this is about the overall understanding of this. We would also be adding certain videos of certain shapes that you would see in the upcoming flights in this complete video, and you will get a better understanding of this technology.