Nanotechnology Science and Applications
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Lecture - 22
Effect of Nanostructure on Damping Properties

Hello, we have been going through a series of topics through this course on Nanotechnology the Science and Applications of Nanotechnology. And in almost every class or a set of two or three classes we have looked at one particular application of some sort in which we have really considered what kind of a nanomaterial could be used; what kind of synthesis techniques are involved; what kind of characterization techniques are involved, many such things we have looked at. And in that context, we have tried to understand what the nanomaterial is accomplishing and what kind of things we have to stay alert to.

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So, in this class we will follow a similar trend, we will again look at the effect of nanostructure; on a particular kind of property which is the damping property. And often, I mean in our normal day to day activities, we do not hear much about damping, we do not hear; so, it maybe seems like a topic that is not very, immediately applicable to us. But as you will see through some of the examples that we will consider, it is actually very commonplace in many of the activities that we are involved in. And we just I mean;

in fact, it is so commonplace and so routine, that we do not realize that it is actually happening and we just take it for granted.

And therefore, we do not think about it much, but actually it there is a very, significant application of this process of damping. And therefore, there is a lot of study on how to do it and how to you know, action to accentuate it and so on. So, these things are very much in place and so we need to become aware of it and figure out how we can manipulate it.

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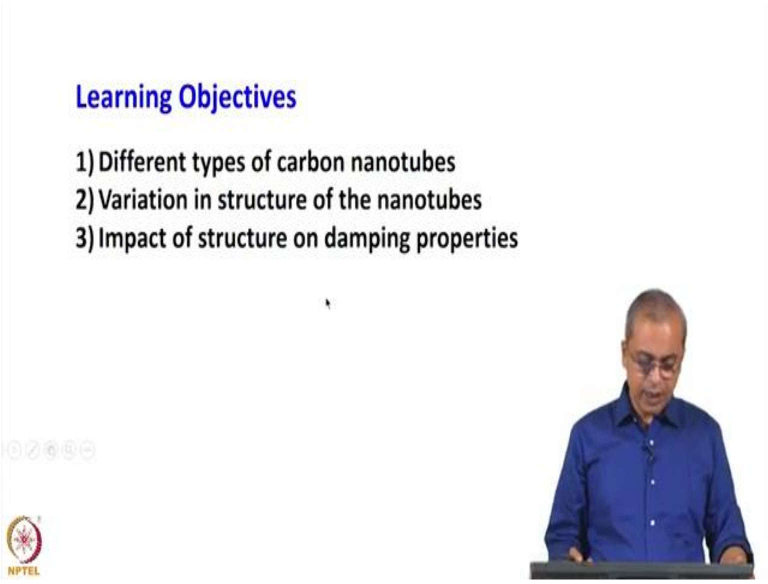

So, our learning objectives for this class are we will look briefly at different types of carbon nanotubes, we have discussions on carbon nanotubes through this course, but in the context of the damping activity we will look at different types of nanotubes. In particular we will look at the variation in structure of the nanotubes and this is where the science aspect of this work is present. We are looking at the variation of structure of the nanotube and therefore, we have some sense of what maybe it can accomplish for us it, may not be able to accomplish for us, things like that and it is also true that you can get nanotubes with a variety of different structures. And therefore, we want to understand those structures, see what is possible with respect to them and then look at the impact of structure on damping properties.

And so that is really fundamental material science, we are really looking at structure-property relations. So, here you are looking at carbon-based material. So, the element is the same. You are looking carbon nano at carbon nanotubes, so, therefore, the general structure is also the same; however, within the carbon nanotubes, there is a variation in structure which we will highlight through this class.

And in the context of that variation in structure, we want to see what variation is there in the property and also try to understand why there is a variation in the property. So, it is a very good mix of the morphological aspects of the carbon nanotube, the structural aspects of carbon nanotubes, their presence in a technological application and the implication on the technological application.

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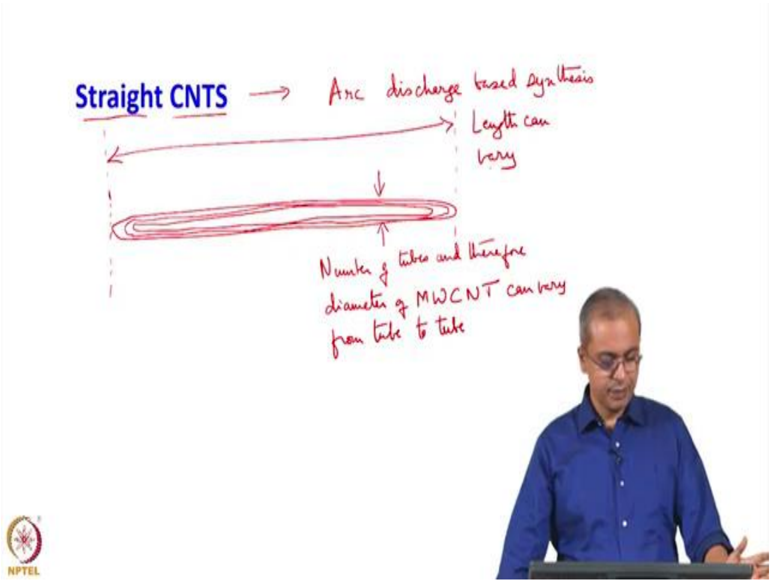

So, we will begin by looking at what are considered straight nanotubes. So, generally what happens is; when we prepare synthesized nanotubes, we have different techniques by which you can synthesize carbon nanotubes. So, usually when we do an arc discharge-based synthesis and we look at the suit that is generated and you clean up the suit and then you look at it in the microscope.

What we find is? We get what we can describe as straights CNTs; essentially what this means is, we get CNTs which if you look inside the microscope, will be like needle-like straight CNTs. It is a very straight tube you will see, a needle like straight tubes and so, inside this it will be concentric. So, you will see if it is a multi-walled carbon nanotube, we will see the inner wall will be somewhere there and so on.

So, you will have let us say, let me just draw one more wall. So, we get a sense of what were dealing with here. So, you will get needle-like straight nanotubes and several of them. So, that is the and so, it is not just a one, it is not just an occasional nanotube that looks like this, when you get done with that process, when you look at it under the electron microscope, you will find several nanotubes that look exactly like this. You will have variation in the thickness, so the number of tubes and therefore the thickness and therefore, the diameter. This is a multi-walled carbon nanotube; you can call MW multi-walled carbon nanotube, CNT multi-walled carbon nanotube, so MWCNT.

So, the diameter of the number of tubes can change and therefore, the diameter of the multi-walled carbon nanotubes can vary from tube to tube. So, that can vary from tube to tube and also the length which is basically, from that this region here to this region here. So, you look at the length. So, length can also vary. So, if you do the arc discharge-based synthesis this is the kind of product you get.

You get a suit which you have to clean and once you get done cleaning, you will find and then you cleaning would mean, you have to you may have to clean with some solvents and then do some say medium temperature range oxidation in air maybe 500 600 ^{o}degree c and up to that and many of the other forms of carbon will go away and then what you will have remaining will be carbon nanotubes.

If you look at them through the microscope, electron microscope you will see this kind of structure straight, needle like straight nanotubes with variation in the number of tubes; and therefore, a diameter being different and lengths that can vary. So, this is what we will see.

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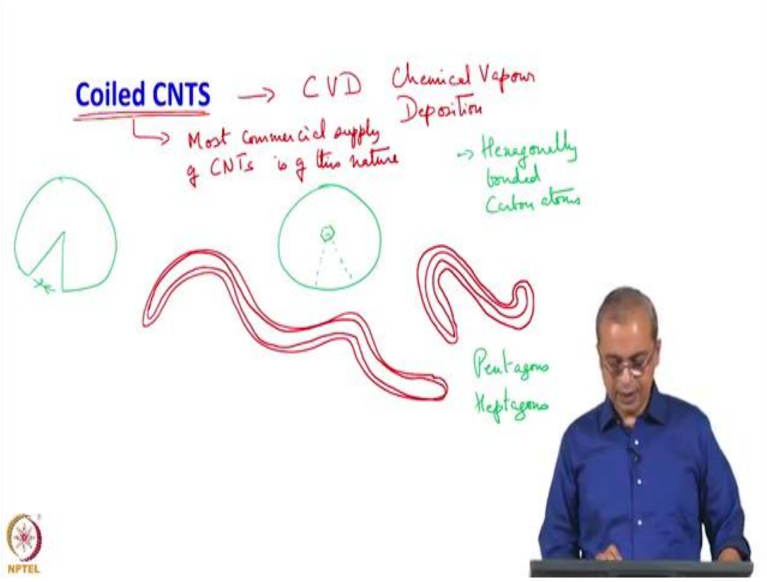

So, this is one possibility that we have; another possibility is coiled CNTs, CNTs is carbon nanotubes here; so coiled CNTs. So, this actually comes from, this is often seen from the CVD process, Chemical Vapour Deposition. So, the chemical vapor deposition synthesis process will give us coiled CNTs. I must point out that most commercial supply of CNTs is of this nature; most commercial supply of CNTs comes from the CVD process and therefore, you typically find that it is of this nature you find that it is coiled CNT. What do we mean by that? You will see something like that, tubes that look like that and so the inner wall of the tube will look like that.

So, something like that, you will see a tube that looks like that or you will see a tube that looks like that, I am just showing you double-walled tubes because I am hand drawing it and it is going to be difficult to draw several of these, but basically you will see tubes like this. This is what you will see using CVD synthesis, as I said you today if you check on the internet for suppliers of carbon nanotubes; you will find many companies internationally which synthesize and supply carbon nanomaterials and almost all of them uniformly use the CVD synthesis.

The reason they do that is, there is much better control in terms of the diameter of the tubes, the length of the tubes and so on, when you use the CVD synthesis process. The only, I would not even say is a downside, the only variation that you get because of doing the CVD synthesis is the fact that you see them quite coiled. You see them in different curved as morphologies and there is a significance to that curved morphology, it is not just a curved morphology sort of independent of everything else, it is not simply a bent tube and so on. It exists in this form even without the application of any stress this is you know, sort of relaxed position of this nanotube.

So, what is the significance of that, why is it that one tube is straight and the other tube; I mean one tube that we saw from the arc discharge process is straight whereas, this is curved. That has got to do with how many the fact that, if you have only hexagons, the walls of this tube is consisting of typically of hexagonally bonded. So, the expectation is hexagonally bonded carbon atoms.

So, as long as your sheet of graphene, if you think of it that way consists of only hexagonally bonded carbon atoms and you roll it up, you will get a straight tube. So, in that sense that is from the perspective of hexagons being the most you know, stable sort of geometry for those carbon atoms, that is like you can think of it is a defect-free carbon nanotube, that is your straight nanotube.

Whereas carbon nanotubes of this nature, with the coiled nature; typically have either pentagons or heptagons on the surface. And therefore, a pentagon or a heptagon would mean that now the surface is not straight, it is forced to distort to accommodate for the fact that instead of only having hexagons you now have a pentagon. So, it is no different than taking a flat sheet of paper, cutting off a sector of it and then folding it back to close the.

So, whereas, previously you had a sheet that looks like that which was flat, you now have a sheet that looks like that and then one sector of it is missing and now we are trying to close these two; and therefore, it curves and that that is missing because what was a hexagon in the center. So, you had a hexagon here, now suddenly this part of the hexagon is missing and therefore, that central hexagon has become a pentagon, right. So, that is what we are dealing with and that is how you get these coils CNTs. So, they are considered as CNTs having surface defects.

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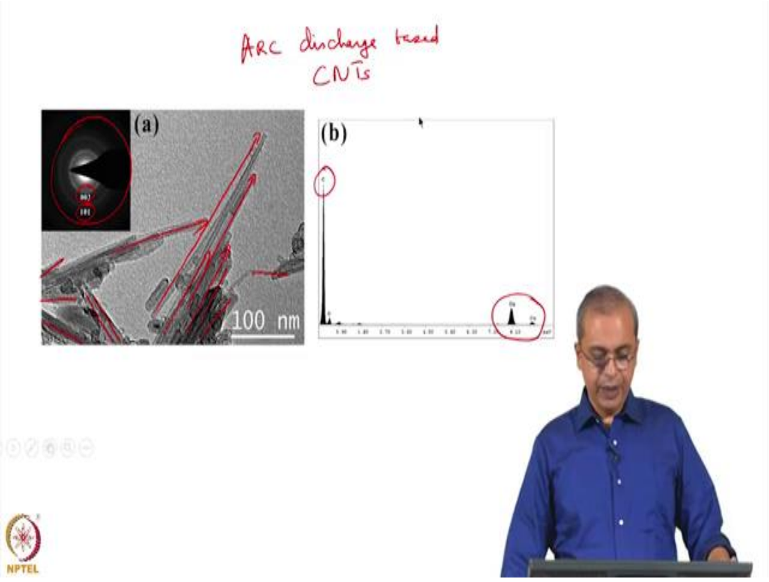

So, for example, just to show you actual TEM images; this is a TEM image of CNTs that have been synthesized. You can see that these are all straight, you can see it is quite evident from these micrographs, electron micrographs that these are all straight. You can see this tube here, I am just drawing the lines here, straight tubes you would see and almost all of them are straight tubes; so many of them straight lines. So, I am just drawing lines along the various tubes that I can see here, you can see straight tubes out here.

So, this is what you see and if you look at say the EDX analysis of it you basically only see carbon. You see carbon out here, that is what you see, tiny bit of oxygen shows up there, that could be due to some oxide layer that is present, but more likely that it is present on the copper grid from which we are taking, on top of which we put these materials for viewing inside the electron microscope.

So, this is what we see, straight tubes which are very evidently straight and this is the diffraction pattern corresponding to it; it is indexed you can see the (002) and (101) planes corresponding to this nanotube. So, this is what we see and this, as I said, is arc discharge synthesized.

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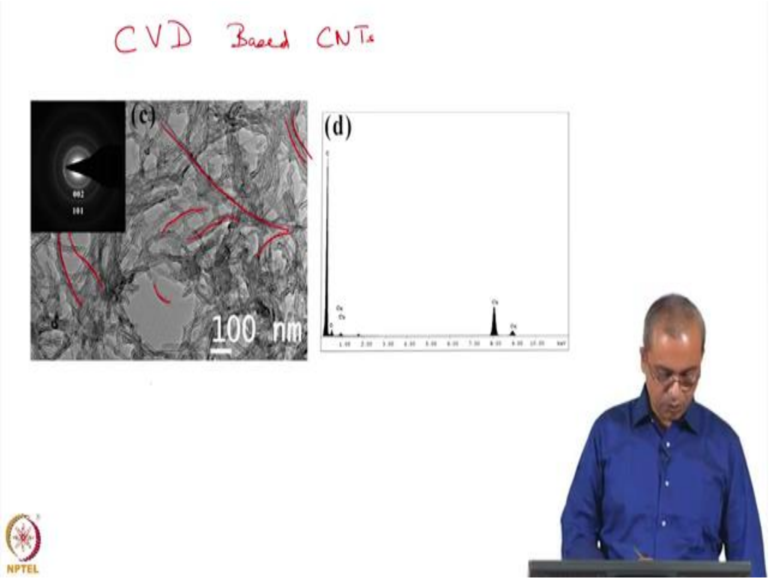

Similarly, if we do the CVD synthesis and we look at the CVD based CNT. So, this is CVD based CNTs, clearly, you can see lot of wrinkling and coiling and so on. So, plenty of movement of that nature you can see almost everything is coiled, you can see here this is curved, you can see these are all curved you can almost everywhere you can see a curve, you can see curves here, curves here, I am just highlighting a few.

So, that you get a sense of it; but it is quite evident that you almost do not see anything that is needle like straight, that is a distinct difference between the morphology that you see here and the morphology that you see here right. There is a distinct difference you just have to look at it visually and you can see it, this is distinctly different again, this is again a straight CNT, you see nothing like that there is almost no straight line here everything is a curve of some nature and maybe much more if you actually follow a tube much more carefully there is significantly curved ones inside here.

So, this is what we see. Again, of course, you still see the cleanliness twice it is still primarily carbon and just some peaks from copper, which come from the electron microscope setup; where we have a copper grid on which we place the sample and on the basis of that we do the analysis. So, that is what we see here right. So, it is clear that this is not something imagine, you can actually see it, there is no doubt about it.

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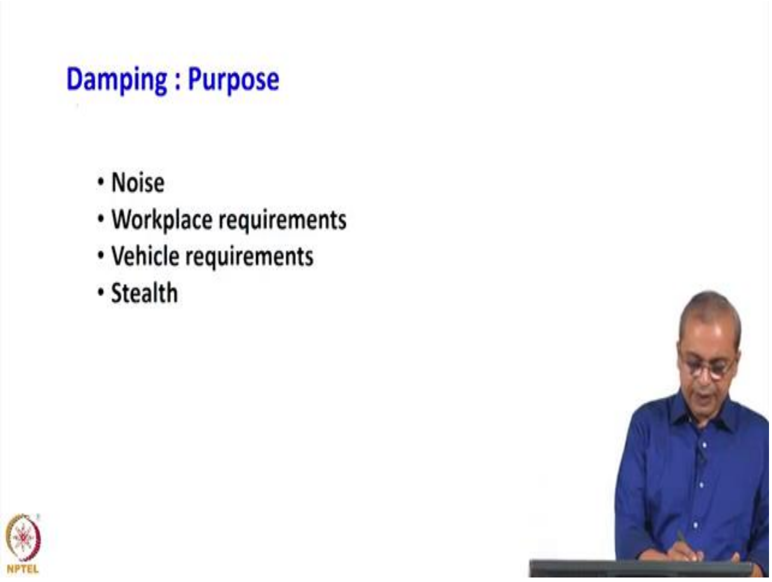

So, now, we will look a little bit more on what we can do with this, what I said that the nanostructure is enabling for us. To do that now let us, since we are looking at damping and I said that it is very commonplace, it is just that we do not pay much attention to it. In fact, it is that commonplace that we do not pay much attention to it, but it is a very essential part of many of the technologies that we use. So, what is the purpose of damping? So, there is noise, so there is a lot of noise, which we want to eliminate from any work environment.

So, we have a lot of absorption processes go on, which happen and that essentially is damping out the noise, it is removing the noise; lot of it has got to do with workplace requirements. In olden days people did not care much about or did not they were not aware, I would say they did not care they were not aware of things that were happening in the workplace, which they that they needed to be alert to. So, it was not unusual to have people working in places where there is a machine, because that is how it is in factories you work with machines near you and the machine is doing some activity.

So, there is some steady noise coming from the machine, the noise itself means there is some vibration coming from that machine. The machine may also have much more prominent vibration which may travel through the ground or be there on that workbench that on which that machine is mounted.

So, those things were always there, people just worked with those machines and put up with it so to speak. And what happened is, over the years people realize that if you spend carrier with that kind of a machine, you spend years in front of that machine, even months or years; weeks, months, years in front of such machines or in the proximity of such machines then it can do significant damage to people.

Again, varying from person to person, based on some person's general body built and some health criteria, maybe some person is affected significantly more, some person is affected somewhat less and so on. But generally there is recognition that this kind of continuous exposure to vibrations is not considered good for the body, it is not considered good and therefore, we have to do something to ensure that if a person in that workplace has to work with a machine, that is generating vibrations that those vibrations do not reach that person right. So, that you have to do.

So, how do you do that? I mean you have to ensure that the machine is sitting on a structure which damps those vibrations. So, we will talk about what; that means, it has to damp those vibrations. So, that as you come away from that machine essentially no vibration has been passed on to the environment and therefore, you may be standing next to a machine which is vibrating, but you do not feel the vibrations, so that is important.

This is also very important from the perspective of say a vehicle; in vehicles, they do this a lot, the more sophisticated the vehicle the more work they have done on this. You have shock absorbers, you have many other things in vehicles; the engine is running engine mill will have some vibrations, but sitting inside the car you do not want those vibrations, you do not want to feel those vibrations.

Imagine if you have to drive for like 3 or 4 hours in a vehicle and your whole vehicle kept on shaking for those 3 or 4 hours, there has a terrible feeling. When you get off, you would be extremely fatigued and very likely that is something that is not good for your health, it will do significant damage to you and then you have to do something to recover from it. So, any automobile company, any serious automobile company which has R and D going on, we will be doing a lot on vibration control; we will be doing a lot of work on vibration control.

And essentially the, what they are doing is, of course, you can try to may make sure that the engine does not create those vibrations, to begin with; but one other major part where you have to pay attention is, in the event that there are vibrations how do you damp those vibrations, how do you absorb those vibrations. This is also true for you know, huge structures such as buildings which have to maybe absorb some vibration due to say some level of earthquake activity or whatever; again, some vibration damping has to be done to take care of that.

You also have buildings which have to which may sway in the air, because there is a tall structure and the breeze is blowing on it. So, again there is some periodic moment that is happening to that building that you have to handle in some particular way and tone it down in some particular way. So, these are all very common things. So, our workplace is a very common thing for us, our mode of commute to the workplace and from the workplace is common to us, the buildings we live in are common to all of us.

So, these are already examples which are extremely commonplace, where there is a need and a necessity to take care of vibrations to damp the vibrations. So, the damping process, although the word damping is not something we hear on a regular basis in normal conversation or normal I mean general reading that we do, it is actually quite commonplace from the perspective of technologies that we use. So, that is something you should be aware of. It is also of something of relevance to say trying to introduce stealth, into some structure where basically you want incident radiation to get absorbed and not reflected by that structure.

So, any incident radiation that is falling on the structure should get significantly absorbed by the structure, so nothing is getting reflected and therefore, it develops the characteristics that are stealthy. So, this is the damping purpose, as I said very commonplace to a very sophisticated, we all have this going on in a technological sense.

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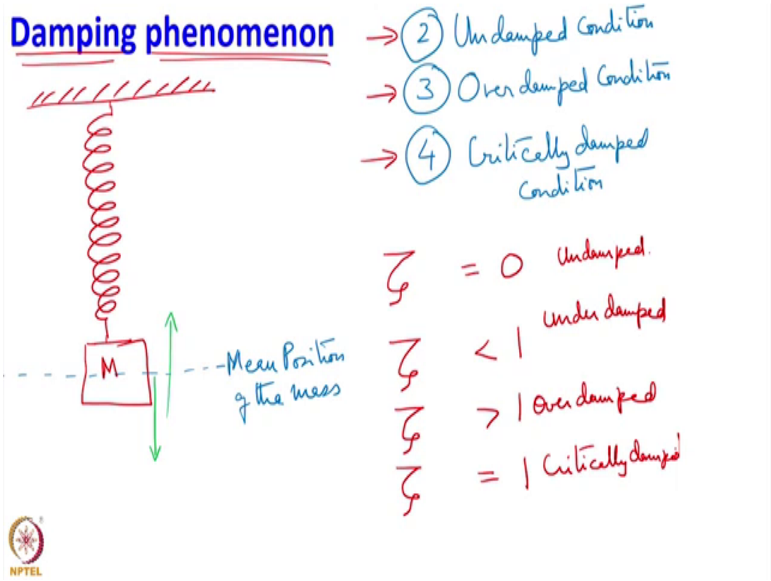

So, let us look briefly also at the damping phenomenon. So, to understand this, just to understand how they in the scientific literature, how they lay out the different possible extents of damping? So, that is something we want to get a sense of. So, the system that is easiest to relate to is a spring, to which we are attaching a load of mass M. So, to that we attach a load of mass M.

And then what do we do, we generate some vibrations in this; what does the vibration, we basically we pull this down and you release it and it will go back. So, once you pull the spring, it will have a spring constant, you pull it to some distance and then release the, so you pull the weight down to some degree. So, this is fixed. So, this is some ceiling from which it is hanging down. So, gravity is putting it down and then on top of it, you pull it down some more and then release it and then it goes back up. So, this is the typical I mean scenario of something that is vibrating, it is moving back and forth back and forth and so on, so this is the idea.

Now what generally happens is that, if you do this, I will do a simple experiment like this in your home, you just have a spring you put a load to it and you pull it down and you release it. What you will find is, it will you will see that it will keep vibrating up and down, slowly the amplitude of vibration will start coming down and then eventually it comes to a halt right.

So, what is happening is let us say, this is your mean position. So, that is your mean position. So, that is your mean position. So, that is the mean position of the mass. So, our most common experience of this kind of situation is you pull it below the mean position and release it; it will go above the mean position, below the mean position and it will keep vibrating back and forth about that mean position, overshooting.

So, it pulled it down, it tries to come back, it comes back, but it overshoots, it goes in the opposite direction. So, it causes compression of the spring. Then again it reaches a point where it comes to halt, again expands goes pass the overshoots the mean position and then comes back overshoots. So, it continues to overshoot in each direction several times and this continues for some time and then slowly the amplitude decreases eventually it all dies down and again it comes to a halt at the mean position.

So, this is our most commonplace experience with this kind of an experimental setup. The most common experience that we have is referred to as under-damped; underdamped conditions. So, the most common experience is considered an underdamped condition. As you can imagine, then now you have some variations that are likely to come up. The one extreme of it, is an undamped condition; the undamped condition is one where if I pull it down below the mean point and I release it, it goes back up, overshoots, compresses the spring, comes to a halt, comes down, overshoots and continues, except that it never comes to a halt. It just goes continues to do this overshooting and expansion, compression, expansion, compression of the spring, indefinitely never comes to a halt and then permanently is doing this. So, that is called an undamped condition.

In real life, this is unlikely for us to ever see this kind of a situation; because in real life there is friction, there are many other phenomena that are occurring in real life which eventually sort of dissipate the energy. So, you have given some energy to that mass, that energy is steadily getting dissipated by a variety of phenomena that are around. And therefore, some just this expansion compression is also consuming some amount of energy, due to the elastic activity that is going on there and then and so, gradually you lose that energy.

So, whatever energy you gave initially, steadily you are losing that energy. So, eventually, it should come to a 0. So, this is a hypothetical situation, where you go consider the possibility that you lose no energy in the process and it continues to vibrate indefinitely and that is considered as an undamped condition. You can go to the other extreme. So, this is. So, what I said is that this is your most common experience, most common experience is this; one extreme is the undamped condition. Now we will look at the other extreme, which is considered as the overdamped condition.

So, the overdamped condition is the situation which you can actually create experimentally, where the spring instead of freely floating in air, is actually forced to do this process in a highly viscous liquid. So, you take some very viscous liquid, I mean it could for example, even be well it is some kind of an oil that you put there, some thick oil that you put there, say castor oil, some such thing and then you can increase the viscosity, some polymer you put which is highly viscous a polymer and you pull the spring inside this polymer and release it.

You can create situations, where it is unable to overshoot. So, it comes when you pull it down and release it. So, this is your mean position, you pull the mass down and release it; it crawls it is way back and then comes to a halt at the same mean position, it does not overshoot. The important thing is it should not overshoot, it will come back to the mean position, it basically crawls it is way back to the mean position because the spring is pulling it back up.

But it is losing so much energy in the process of just coming back once, that by the time it comes back all the energy that you have given to that mass has been lost, by the time it comes back to the mean position. So, at the mean position, it does not have any extra energy left in it to overshoot it comes to a halt here.

So, this idea that you can create a damping situation where you essentially consume all of the energy in a single return process; that is considered as an overdamped condition. So, that is called overdamped, that is our over-damped condition. And then finally, we have a version which is sort of somewhere between the underdamped condition and the overdamped condition. So, that is called critically damped. So, as we said the underdamped means it goes back and forth, back and forth, back and forth several times and then steadily decays and comes to a halt at that mean position. Over damped is you push-pull it down, release it; it barely makes it back to the mean position right. So, these are two extremes. So, you are in one case you do several vibrations, here you barely do one ok, so, it comes to a halt.

Now the critically damped condition is sort of like the overdamped condition in which case you are just coming back once, but it is the fastest to return to that mean position. So, you take an extremely viscous liquid and then you do it; it takes 10 seconds for it to come back to this mean position; then you take a little less viscous liquid and then it takes 9 seconds to come back, like this you consider continue to do this.

And then at some point, it comes back and that it comes back and say 6 seconds and it comes to a halt there. So, it is also coming back and not overshooting, but in 6 seconds and then it comes to a halt; if you go to the next you, I mean less viscous liquid that you can use, it actually begins the first overshoot, first time it ever overshoots right.

So, the previous return which was back in 6 seconds is the shortest time in which this returned and came to halt at the mean position and with any lower viscosity you are going to start overshooting. So, the damping provided in this case was like the critical amount of damping required to get it back to the mean position in the shortest period of time. So, it has some features of the overdamped condition except that it is like the fastest over-damped condition, I mean so, fastest returned to the equilibrium position. So, that is your critically damped condition.

So, these are the four conditions; undamped means no damping, indefinitely it vibrates; under damped means it vibrates several times across the mean position and then decays to our halt; over-damped means it will return only once and may take forever to return once and then critically damped means it again return only once, but it will be the shortest time to return once.

And to follow these, there is a parameter zeta that is used to follow these. So, in the underdamped condition, so when it is undamped zeta is equal to 0; if it is underdamped zeta is less than 1; if it is overdamped zeta is greater than 1 and if it is critically damped zeta is equal to 1. So, this is the way we have this damping ratio so to speak and so, this is zeta is 0 is undamped, this is underdamped, this is overdamped and this is critically damped. So, this is the variation that you have with respect to damping and we would like to see any new material we make for damping purposes, we want to study it understand; what has happened with respect to damping and try to improve the extent to which it is getting damped.

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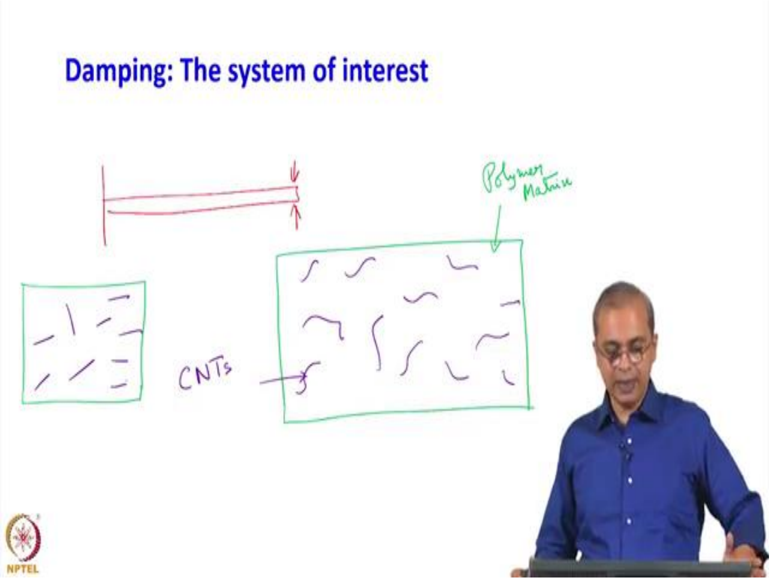

So, what is our system of interest, our system of interest is basically a composite material in which we have added carbon nanotubes? So composite materials, in this case, a polymer-based composite; so, the polymer itself will have some damping properties. So, if you just have the plain polymer and you put some vibration into it, you can see how the vibration damped, is getting damped.

And there are different experimental setups in which you can study this, but basically, one way is to you basically have it held in one position and then you apply some vibration to this and then you see how long that vibration in the continues to exist before it comes to a halt. So, this can be followed and then on that basis we can understand whether it is taking longer to come to halt or less is able to come to a halt sooner.

Our system of interest is then to take a plain polymer and test it like this and then make a composite. So, composite, in this case, has a matrix; the matrix is that polymer, polymer matrix. And in this we have carbon nanotube reinforcement. So, I will just show some foil nanotubes. So, you have all these CNTs. So, in this case, for example, I am showing you coiled CNT. So, the assumption is that these are CVD synthesized CNTs which have surface defects and so on. So, we have put these CNTs into this system and we are testing it. So, this is one system of interest, similarly you can have same kind of sample with straights CNTs. So, as you can imagine that would quite simply be a version that looks like that if that is your polymer and your CNTs would look like that.

So, something like this. So, this is your two sample systems we have and then we are trying to understand what is going on in the system, try to understand how much damping is happening and what we can accomplish with it.

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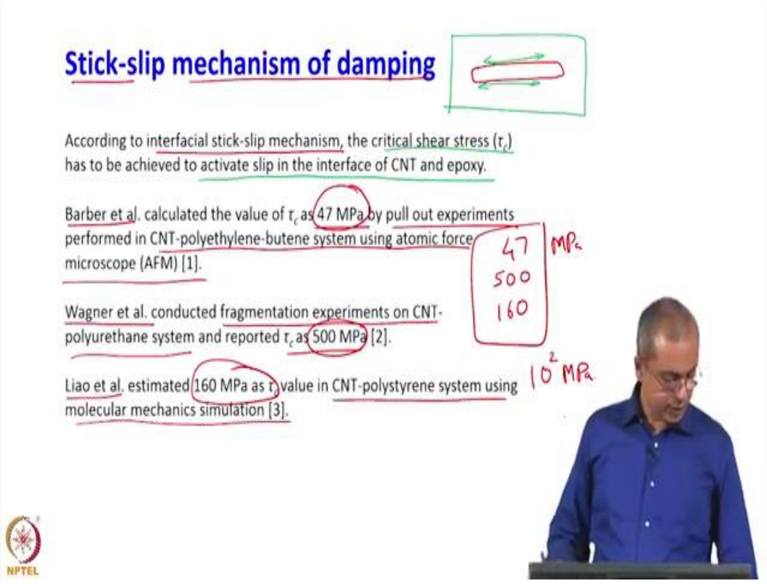

So, to understand or to consider what might happen inside this kind of a system; already there are some studies in the literature and they have tried to figure out what kind of stresses are required, for what kind of mechanism to become active in systems of this nature, where you have a CNT in a polymer. So, there is one way of damping, referred to as the Sticks-slip mechanism of damping stick-slip mechanism of damping and according to this interfacial stick-slip mechanism.

So, this means the polymer is actually sliding with respect to the nanotube. So, if I draw the nanotube here and I draw the polymer around it, then the sliding is happening here at the surface of the nanotube. So, based on the vibration the nanotube is moving within the matrix, in some sense it is moving. So, in other words, the interface between the polymer matrix and the carbon nanotube is beginning to slide that interfaces sliding.

So, for this to happen, because you have put the polymer in, you have put the CNT in the matrix of the polymer and some kind of bonding has happened at that interface. So, you have to put enough stress to now sort of overcome that bond and make this nanotube slide and therefore, there is critical shear stress. There is certain critical shear stress that has to be crossed, that threshold has to be crossed for you to activate the slip mechanism in the interface of the CNT and the epoxy. So, you have to do that, only then this interface begins to move and therefore and once that moment happens this you can sort of think of it is some kind of friction in happening in that interface. So, continuously energy is getting dissipated because of the relative moment of those two surfaces in close proximity with each other.

So, there is continuously there is energy loss at that interface, that energy gets absorbed; and what is that energy? That energy is the vibrational energy that you imparted to the overall sample. So, if you have millions of CNTs inside all of them are consuming that energy tiny bits here there and so on and then eventually they have consumed energy. And that is how they have done their damping in the system.

Now different people different groups internationally have done a lot of study, some experimental, some theoretical and so on; to try to estimate what is that amount of force that is required for us to slide a nanotube with respect to the matrix. So, that thing has been done and you can see here, for example, there is one group which has calculated this value at about 47 mega Pascal’s using some experiments.

So, in a particular system, using an atomic force microscope. So, they have done this using an AFM. So, it is a sort of an experimental study and they have got some value for it. Another group you have here another group here has done some fragmentation studies on CNT polyurethane systems and reported critical shear stress of about 500 MPa. So, you have one number of 47 MPa, another value of about 500 MPa. And then yet another group has done some experiments, using CNT polystyrene system, using some simulation; simulation kind of work has been done they are getting a value of 160 MPa.

So, you are looking at 47, 500 and 160. So, this is the order of magnitude of an in MPa. So, different groups working with variations of this system and experimental simulation different kinds of things they are looking at, they are all getting this order of magnitude of value. So, even if we do not know the exact value for our system, of a particular polymer versus CNT; it is reasonable to assume that it is in the order of several tens to a few hundred MPa, as the critically critical shear stress that is required for us to enable this relative movement of the nanotube with respect to the matrix.

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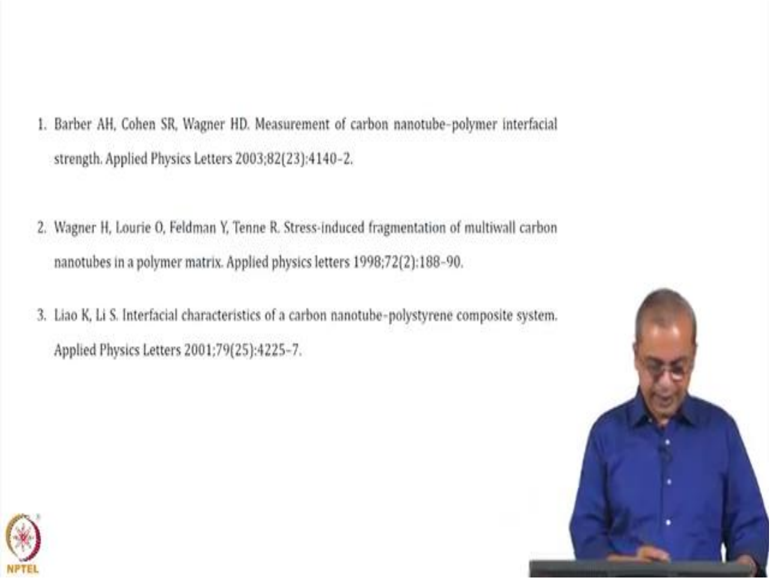

Now, again these are the references. So, you can go and look at them to get a better idea of the work. So, this is the reference here, applied physics letters; I think in this particular case these three are all from APL or all APL publications around 1998 to 2003. And so, this is a fairly prominent journal. So, you can go and look them up and you can get yourself a more direct idea of, how they have done this and come up with those values. So, that is the stick-slip mechanism of damping.

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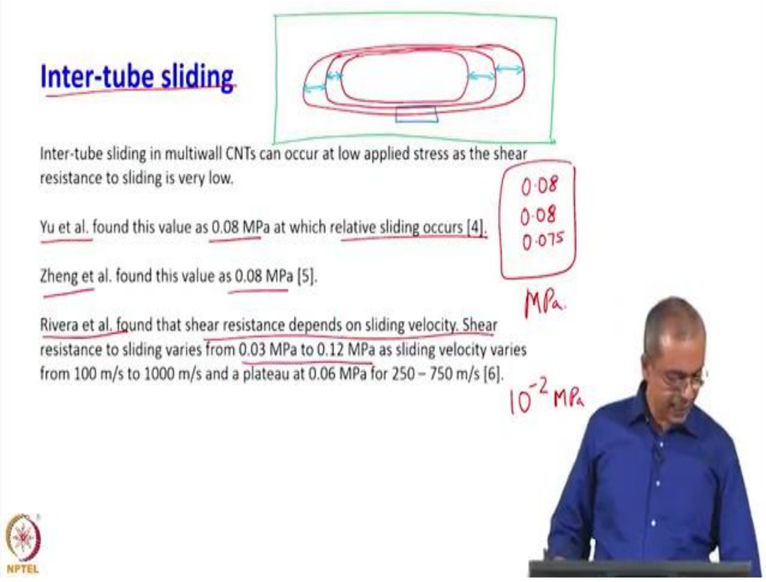

There is another way in which CNTs can do damping and that is called inter tube sliding. So, now, in this case, what we are saying is, if you have the nanotube and I now draw it in a bit more enlarged way for a specific reason; we have a nanotube here and again it is in some matrix, it is in some matrix.

So, what we are saying is, this interface here, the interface between the nanotube and the matrix this interface here that is not moving. So, there is no movement happening there; in other words, if there is bonding between the CNT and the matrix, they are staying stuck they are not moving with respect to each other, they are holding their relative positions with respect to each other.

Therefore, when a vibration goes through the system, they are vibrating in unison. So, there is complete vibration in unison and therefore, there is no relative motion between the two of them. So, there is no energy dissipation occurring at that interface. So, let us assume that is the case and there is only one other way in which the energy is getting dissipated, in this particular model that we are talking of and that is inter tube sliding.

So, what that means, is inside this you will have a variety of tubes. So, you have multi-walled carbon nanotubes. So, you have a tube that is like that; another tube that is like that and so on. So, now, you can see here, that between the ends of the tubes there is space. So, potentially these tubes can slide with respect to each other internally,

internally they can slide and the tubes can move this way and that way, there is weak Van der Waals bonding between those tubes in between thus those tubes.

So, within the tube, there is very strong covalent bonding, but between tubes there is van der Waals bonding, just the way you have it in graphite right. So, they can slide, but it is they are sliding with a sort of a restoring force that is relatively weak because that restoring force is associated with that Van der Waals bonding. And so, presumably a lot less force is required to slide those nanotubes with respect to each other.

Again, if you look at the literature, so all these things we do not have to do from scratch. If you look at the literature, there is a group that is found that this value is about 0.08 mega Pascal's at which this relative sliding occurs. There is another group which has found an also the same value 0.08 mega Pascal's for the sliding to occur.

And then there is a third group, which found that sort of depends on the velocity with which those tubes are moving; and it has given a range of 0.03 to 0.12 mega Pascal's is the kind of force that is required for this movement to happen a little bit velocity dependent. So, you are still looking at values of 0.08 and then 0.03 to 0.12 if you take an average, so that is 0.15, so 0.075, something like that in MPa.

So, you can see here. So, this is 10^{-2} MPa and if you go back this is about 10^{2} MPa. So, this is 10^{2} MPa, this is 10^{-2} MPa. So, four orders of magnitude difference in the amount of force that is required, to enable one kind of sliding one kind of movement in a system, relative to another kind of moment in this system.

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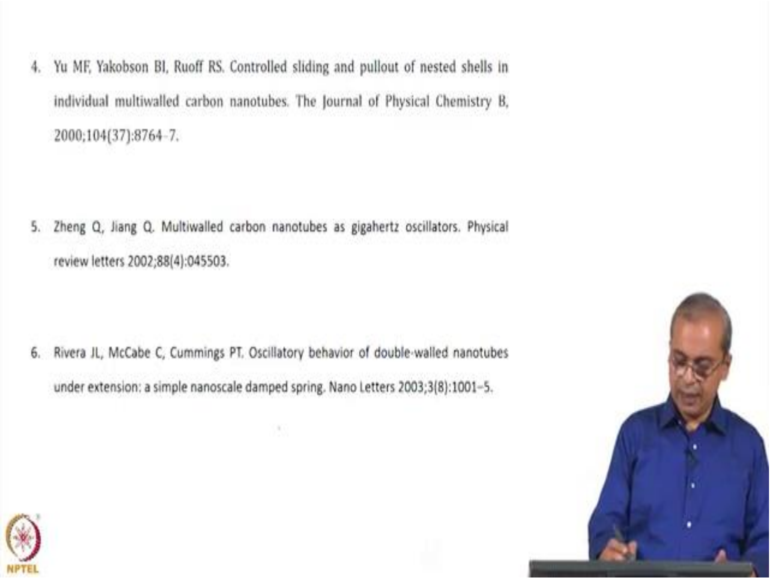

So, again these references are here, different journals here, journal of physical chemistry B, physical review letters these are all very good journals, nano letters. So, these are all very prestigious journals which you can again see, you have a 2000, 2002 and 2003 kind of work and very prominent journals where this is being published.

So, we can put some, I mean given that they are all very good journals, good review processes and also, we have different authors, in completely different groups coming up with values, that are sort of consistent with respect to each other, we can put a reasonable faith on this. So, what we understand is that there is four orders of magnitude difference; between two different phenomena that may happen at the nanoscale with respect to carbon nanomaterials present in a matrix, from the perspective of damping in that system.

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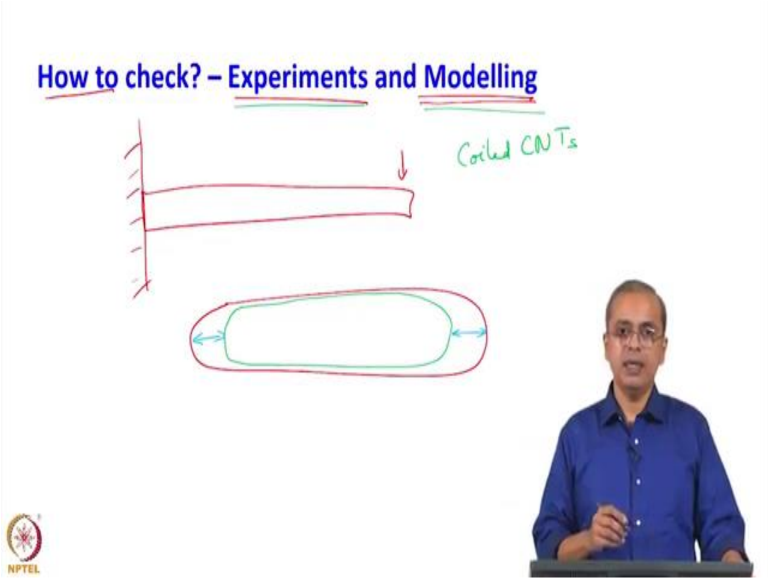

So, how do we check what is happening, well we have to do experiments and modeling; sort of what other people have done, we have to do experiments and modeling. So, we do vibration-damping experiments. So, like I said you take a system, you take a polymer composite with which has some nanotubes in it and then you vibrate it you put some force on it, it starts vibrating. So, one end is free. So, it is vibrating and then you can check how long it you can record exactly what is happening with respect to it is movement how it is decaying and so on. And from that we can back-calculate some values on what is happening in the system how much force is required to enable that vibration and so on.

And we can also do our own modeling to understand, what is happening when you apply if you have two nanotubes; you have an outer tube and you have an inner tube. And if you shake the outer tube relative to the inner tube, what will happen, how will the system move, how does it transfer energy to the inner tube and then what happens to the inner tube, how is the inner tube moving, how long does it continue to move, when does it settle down all those things you can do in terms of modeling.

So, you have this modeling data to do look at this process of relative motion and you have the experimental data which tells you that once you start vibrating the system; how long does it continue this vibration process before it settles down to stationary conditions and what can you say about quantitatively, what can you say about the vibration process that has happened.

So, it turns out that under these kinds of experimental conditions, if you have coiled CNTs; with coiled CNTs the issue is that because the CNTs are bent in different directions and it turns out that if you look carefully at those micrographs, there are a lot of kinks in the CNT, which means there are regions which are pinched, there are regions which have different dimensions and so on. In coiled CNTs, if you just look at the structure, it seems infeasible for the CNTs to slide with respect to each other.

It does not seem feasible for the CNTs to slide with respect to each other; they are sort of trapped in the relative positions with respect to each other, the layers of CNTs, the inner tubes are trapped sort of in specific positions with respect to the outer tube. Therefore, this intertube sliding mechanism is difficult to manifest in a coiled CNT; whereas, it is fairly straightforward to manifest in a straight CNT. So, just by looking at the morphology and given the various physical constraints placed on the CNT, we can say with fair°of confidence that inter tube sliding can exist only in straight CNTs, not in coiled CNTs.

However, the stick-slip mechanism potentially can exist for both the CNTs. So, this is one part of the picture; other part of the picture is you do the experimental test and you see how much force you have applied. So, it turns out even when you apply tiny amounts of force where you have not given enough force into the system to create this interface sliding; that is the stick-slip mechanism between the tube and the matrix there you are not given enough force for that sliding to happen, still significant damping happens. So, it means and it only happens in the systems where you have these straights CNTs. So, it means that in the straight CNTs, this mechanism is operational this intertube sliding is operational. So, it is able to provide damping even under circumstances that the coils CNTs are not able to provide.

And therefore, it provides a new dimension to the damping process. And therefore, in this particular kind of work we are able to see how the structure of the CNT at the nanoscale; impacts it is a damping property which is something that we can sort of microscopically measure and observe. So, this is a very nice way in which you see how structure at the nanoscale effects properties in the macro scale.

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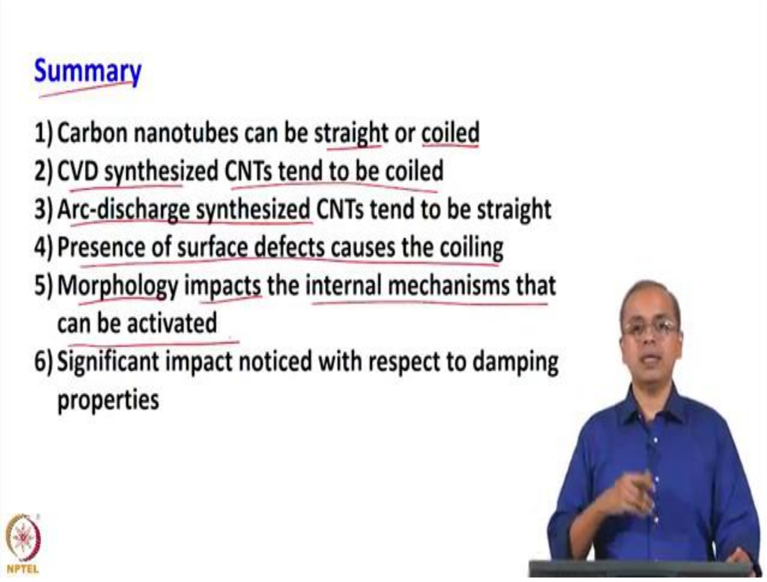

So, in summary, carbon nanotubes can be straight or coiled in morphology and they are distinctly straight or distinctly coiled, there is no doubt about it when you look at the micrographs it shows that is the case. It turns out that the CVD synthesized CNTs tend to be coiled and an implication of that is that they have a lot of surface defects in the form of pentagons and heptagons as opposed to only hexagonally bonded carbon atoms and they generally do not have a smooth surface, they have lot of wrinkles on the surface, they have pinched locations in the surface and so on.

So, the ability of moment of intertube moment in coiled CNT, CVD synthesized CNTs is less. Arc discharged synthesized CNTs tend to be straight a very well-defined geometry and therefore, the possibility of intertube sliding seems to be distinctly available in the case of arc discharged CNTs. As I mentioned the surface defects is what causes the coiling. The morphology that is of the CNTs impacts the possible mechanisms that can be activated, in both the CNTs with the coil as well as the straight CNTs you can activate the stick-slip mechanism, you provided you supply enough sufficient force.

However, the intertube sliding is a mechanism that you can activate only in the straight CNTs, simply because only they are morphology seems to permit this possibility. And this shows up as a significant impact with respect to damping properties even at low-stress levels applied to the system. So, that is our main conclusion and again as we have done through all these classes; different phenomenon we have looked at in today's class damping, we have looked at nanostructure, we have looked at how something of the nanostructure affects this phenomenon and we have seen also the science behind it, we have also seen something about the technological implications of it. So, that is our class today.

Thank you.