

Particle Characterization
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Module No. # 07

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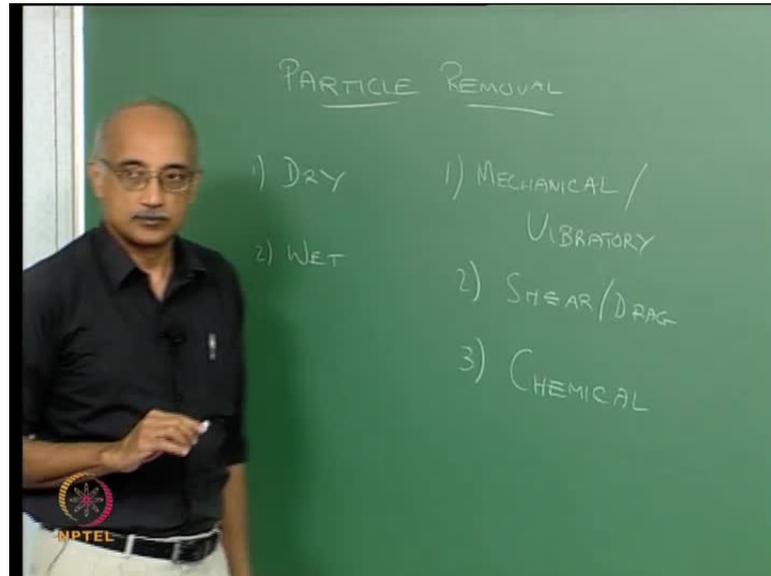
Particle Removal: Methods

Welcome to the eighteenth lecture in our particle characterization course. In the last lecture, we discussed ways of measuring the adhesion force of single particles, as well as, assemblies of particles on surfaces, and key point there is, adhesion forces typically measured indirectly, by measuring the force, that is required to remove particles from a surface.

Now, in order to be able to remove particles from a surface, again in a repeatable and reproducible way, we need to have a good characterization of particle removal methods from surfaces. And as I was mentioning in the last lecture, such particle removal methods can be classified as being dry and wet methods, depending on, whether we use a liquid medium to enhance the removal process, or not.

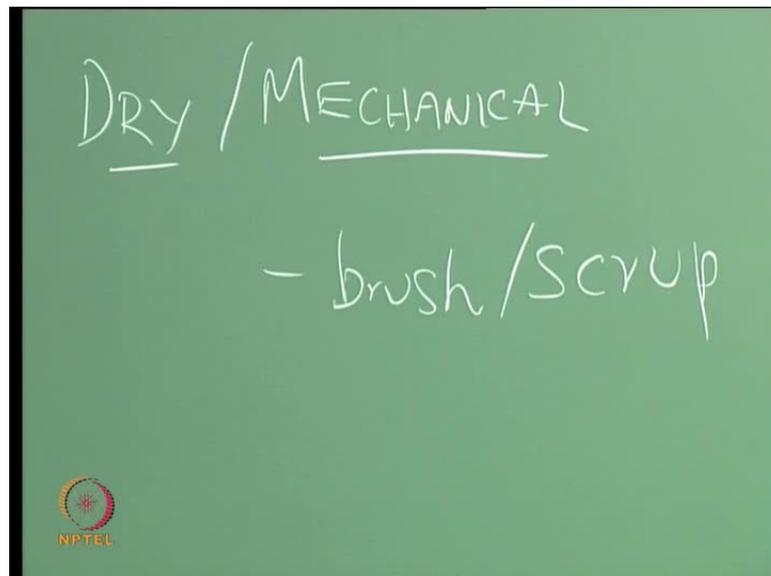
Another way of classifying particle removal processes is by looking at the mechanism involved. Particles can essentially, be removed from surfaces using three different mechanisms - one is, simple mechanical action, which includes vibratory action; the second is shear and drag based mechanisms, where you actually exert a parallel or tangential force to the particle sitting on a surface, and dislodge it from the surface; and the third **method**, method is simply chemical cleaning or chemical removal of particles, where you use a fairly strong chemistry to dissolve the particle on the surface and entrain it into the chemical media; and there are various combinations of these.

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So, we talked about dry methods of particle removal and wet methods of particle removal, this is based on the medium that is used. Based on the mechanism, the classifications are mechanical/vibratory, shear/drag, the third is chemical methods of particle removal.

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Now, if we take various combinations of these, for example, a dry process that involves mechanical methods of particle removal. A classic example of this is brushing or scrubbing, right.

So, if you can see, if you see some dirt on a surface, you can basically take a scrub or a brush, and just run it over the surface until the contamination that you see, is removed. Brushing is a process that essentially, uses an abrasive mechanism; you bring one solid surface in contact with another solid surface, and impart a motion **that**, that essentially, abrades any material, that is sitting on the surface.

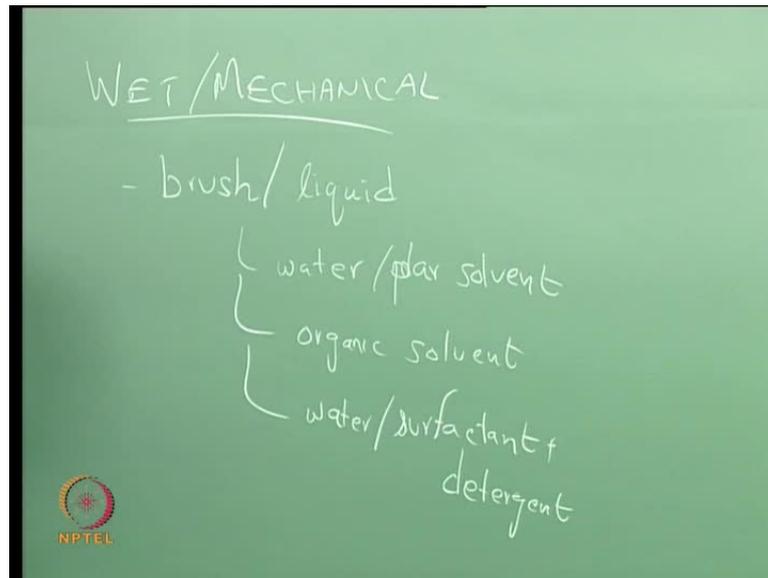
The, it is a very aggressive process, it is a line of sight process; obviously, you have to see the contaminant, in order to be able to remove it. So, if you have any hidden recesses or features in your part, this method is not going to be able to effectively dislodge particles that are located in such places. It can be automated, in fact, in many process industries, you, essentially, do double sided brush cleaning.

So, for example, if you have a rotationally symmetric part, you can mount it on a device, rotate it at a high speed while one brush goes on top and one brush goes on the bottom; and this is very effective in removing simultaneously, particles that are adhered on the top surface and particles that are adhered on the bottom surface.

The down side of brushing as a cleaning process is that it is very aggressive; it is very easy to damage delicate surfaces when the bristles of a brush come in contact with it, because when you are trying to remove contaminants from a surface, it is very difficult to control that process so precisely, that the brush only contacts the particle sitting on the surface.

It is just as likely, that it will contact the substrate itself at locations, where there are no particles, and when it does, it can cause quite severe physical damage to the substrate. So, this kind of brush cleaning or scrub cleaning in dry mode, involves a lot of potential for surface damage; so, it has to be carefully managed.

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Now, an alternative to this is the Wet/Mechanical process, which again is brushing or scrubbing, but now you do it in the presence of a liquid. So, for example, you could take a brush and run the same process as describing earlier. Let us say, you have a substrate that is rotating and you run the brush on top of it, but now, you actually introduce a liquid, like water, as an intervening medium.

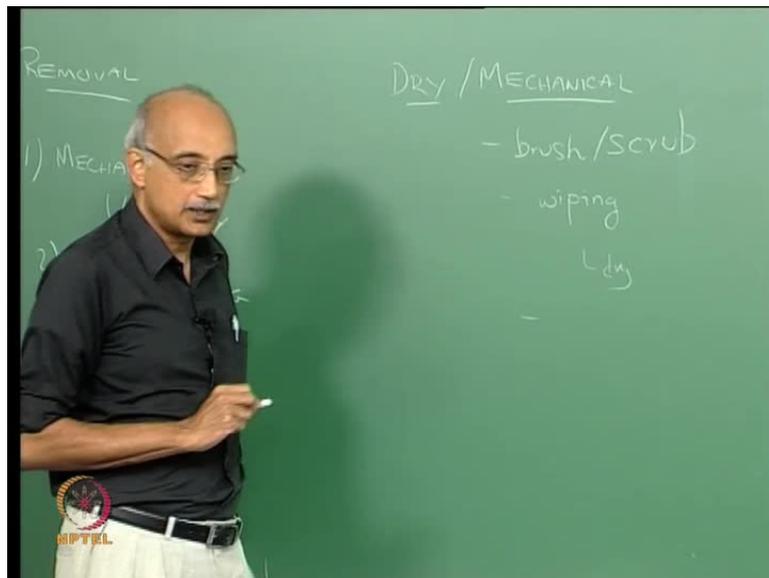
Now what happens? Actually, the brush, when there is a liquid in between, never physically contacts the surface; instead, what happens is what we call, hydroplaning. The viscosity of the intervening liquid layer is high enough, that it prevents the bristles from contacting the surface itself.

So, the solid brush tips stay essentially, a few micrometers above the substrate surface, it is being cleaned, and the liquid acts like a buffer, and prevents actual physical contact between the particle and the surface, but at the same time, it allows contact between the surface contaminants and the brush material. And so, by taking advantage of this hydroplaning action, you can remove particles, while at the same time not causing damage to the surface. And here again, it is important that the liquid be able to wet the interface between the particle and the surface; if not, if you have a highly hydrophobic surface for example, this process would not work.

So, here again, typically what is done is to use a little bit of surfactants. The surfactant enables the surface tension of the liquid to be reduced, so it wets the capillary region better, and it makes hydroplaning removal process that much more effective.

So, either in by using water alone or some polar solvent or by using an organic solvent or by using water in combination with the surfactant or detergent, you can effectively brush particles away from a surface, without causing excessive damage to the surface.

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Now, let us come back to dry mechanical processes. Another process that we can imagine is wiping. So, again you can imagine, I am sure you have done this many times, you see something, let us say, on a surface, you just take a dry cloth and wipe it and removes the material that is there.

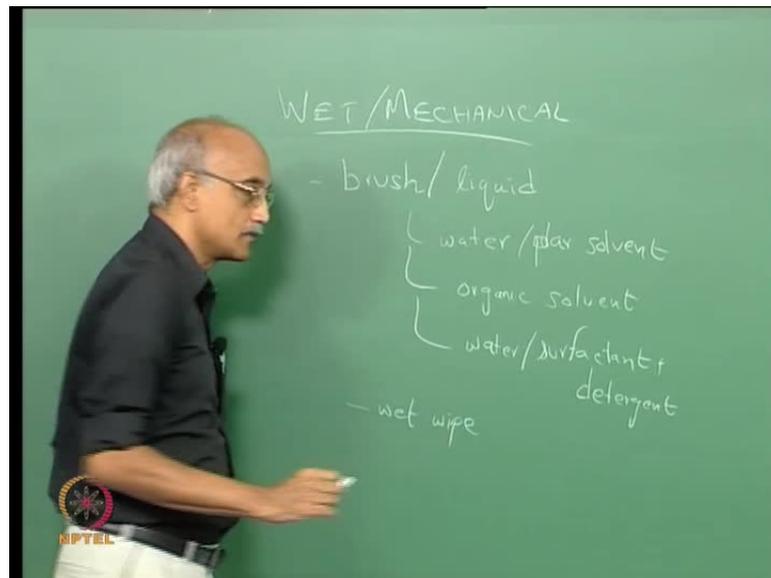
Now, dry wiping is a process that is again widely used **in**, in many manufacturing industries to remove visible dirt and in fact, it enables us to also monitor cleanliness. At the same time, if you take a very white cloth and you rub it on a surface, if there is any dirt there, it changes color, right. You can see the accumulation of dirt on this white surface; so basically, you just keep taking fresh wipes and keep repeating the process until nothing transverse to the wipe.

So, you can actually achieve end point control using this dry wipe process. In fact, there is a test in, for example, clean room manufacturing, called the white glove test.

Essentially, you wear a white glove and just touch a surface and rub your finger, if you can see something on the glove that means it is dirty.

So, you essentially, keep cleaning the surface until when you do the white glove test, nothing transverse to your white glove. So, dry wiping is a method that simultaneously removes contamination, and can also be used as at least, a visual check of how clean a surface is.

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And here again, just like in this case, in addition to doing this in a dry mode, you can also do a wet wipe. Now, in a wet wipe, all you do is take wipe cloth and soak it in some liquid - it could be water, if you are just trying to remove hydrophilic material from a surface, or it could be a solvent, if you are trying to remove hydrophobic or hydrocarbon material from a surface.

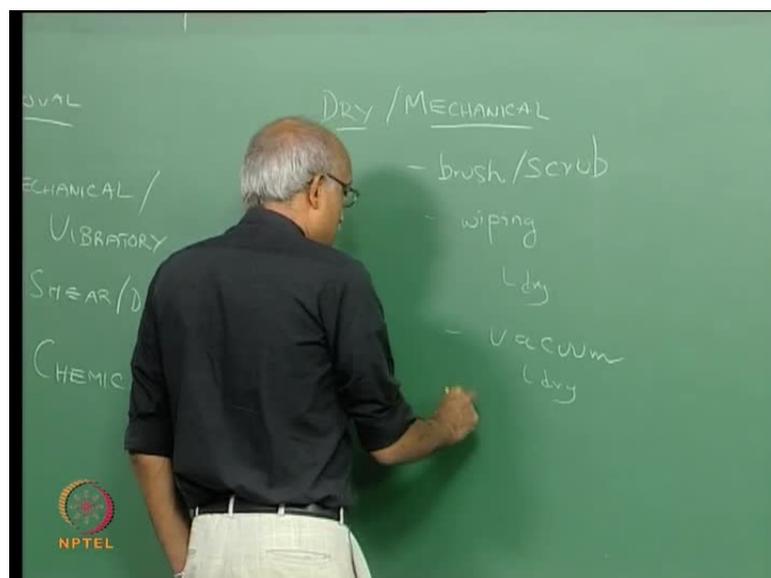
And wet wiping has the inbuilt advantage that again, it can reach particles that are hard to reach with a dry wipe. The other problem with a dry wiping process is again, there can be damage when you wipe a surface with a wipe cloth; the surface can damage the cloth and actually generate fragments of the cloth material, which can become a particle contaminant.

In the wet wipe, essentially, you avoid that to a large extent because again, when you soak the wipe, the contact between the wipe and the surface is not as stiff as when you have a dry wipe.

So, the potential for damaging the wipe is lower when you have a wet wiping process, plus the fact, that you can wet it with different chemicals in different solvents, different chemistries, means, that you can, in addition to simply removing particles from a, by a physical mechanism, you can also now, chemically remove a material from the surface.

For example, if you have oil on a table or you have this, you know, stains on the table, if I just try to remove it, with the, with the dry wipe, probably, would not work, or a dry brush, it would not work, but if I know that if something oily, then if I take a wipe and soak it with some detergent and then do the wiping, it will remove the spot. So, that is a difference between a wet wipe and a dry wipe.

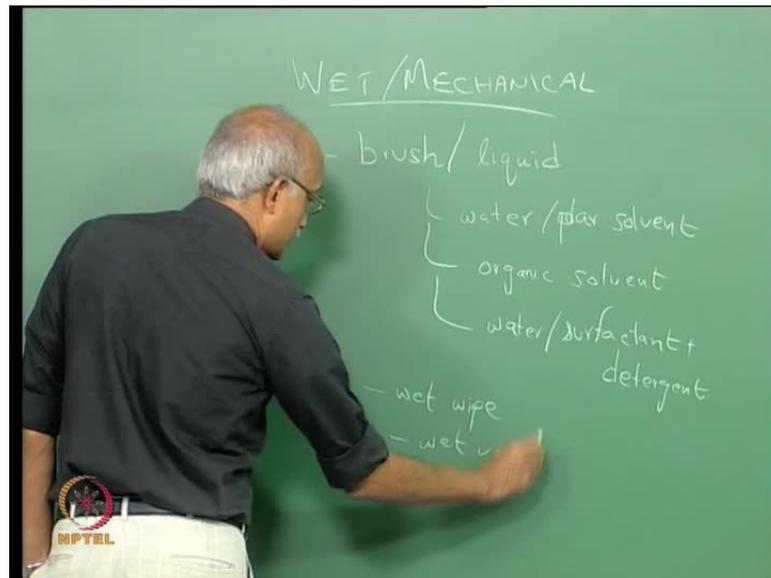
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Dry wiping works, when all you have to worry about is loose dirt that has accumulated on the surface, just because of room debris depositing on the surface, but if there is a possibility, that you can have a, an oily layer or a hydrophobic layer or something that is like a film on the surface, rather than being dry particulates, then you are better off using a, a wet scrub or a wet wipe process.

Another mechanism of dry removal using mechanical means is vacuuming. I am sure you have all seen the use of vacuum to clean houses, automobiles, and the way it works is essentially, you take a tip through which you pull vacuum, and you take the tip as close to the surface, that you want to clean, as possible, and it just, sucks up the dirt from the surface.

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Here again, I am sure, you have seen there is dry vac and there is also wet vac in a wet vacuum process. You initially soak the surface, for example if you are trying to clean carpet, a wet vacuum process works better. Because initially, you deposit a cleaning chemical on the surface, let it dry, and as it does, it converges the contaminants into loose flakes of material on the surface, and then you follow it up with the dry vacuum.

So, vacuuming has huge advantages because it is an in situ process; in other words, if I am running a manufacturing process here, and I see some contaminants, and this is my work station, then I can just take a vacuum wand and just pull off the material right here.

If I have to do a wet cleaning, I have to take it out of the clean room, with, clean it, dry it, and then bring it back in. So, vacuuming has a lot of advantages, in terms of, convenience, can be localized.

So, you can, there are what are known as gang wax, gang vacuums, where you essentially have multiple vacuum tubes, and you can use them to pull off material where

ever you see it. So, instead of applying your vacuum to over the entire surface, you can apply the vacuum in a very localized fashion.

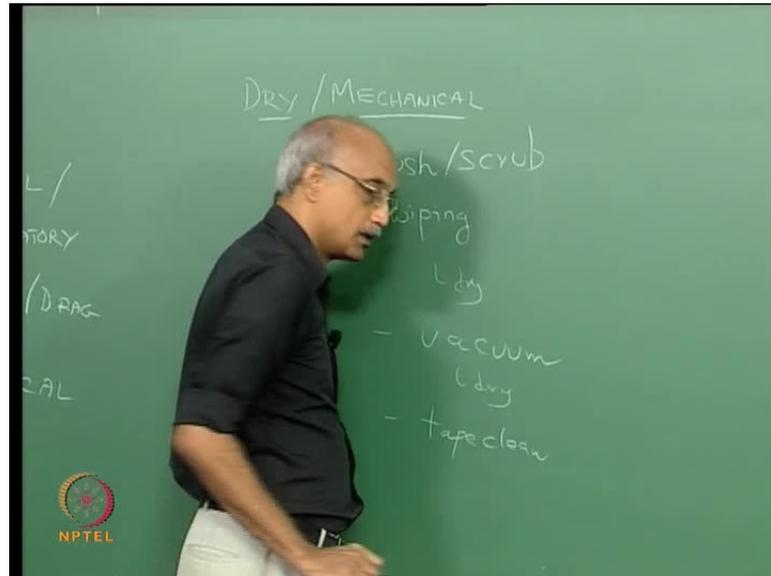
So, that makes it possible to remove particles from surfaces **in a**, in a way, where you do not have to worry about again, damaging certain materials by pulling vacuum. As an example, if you have a motor and it is filled with some lubricanter grease, you apply vacuum to it to remove dirt, it can also pull off the lube, which you do not want to do; you want to leave the grease, impact on only remove the particle dirt that you see. In that case, you are better off using this localized vacuum tips, that can just pull of material from where ever you want to do the cleaning, and leave the rest of the surface undisturbed. So, dry vacuuming is a good option.

The down side of the vacuuming is that it is only really good for removing large particles. If you look at the force of vacuum, for the kind of vacuum that you can normally achieve, it is typically not enough to overcome the adhesion force of very, very fine particles.

So, vacuuming is good to remove particles that you can see; usually, it removes visible dirt very well, but it is not very effective in removing finer dirt. The other problem is that if you do not control the distance between the tip and the surface carefully, the tip can actually hit the surface, and thereby generate particles. And so, this requires a high degree of mechanization, automation, precision control, all of which can increase the cost of the process, quite significantly.

So, vacuuming, you know, by definition is a simple process, but it is not that easy to implement it in high volume manufacturing, because unless you have perfect controls over the process, again, you can do, you may be removing visible dirt, but you may be creating or generating a thousand times as many fine particles. That is a penalty you pay, when you are using a purely vacuum based particle removal process.

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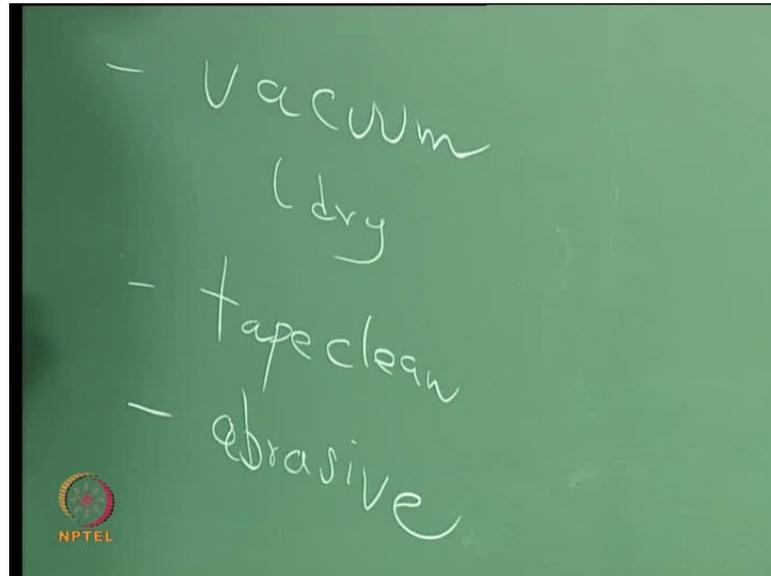


Now, there are other methods that are somewhat more **isoteric**, for example you can think about using a, tape cleaning. You can again, if you see some dirt, a simple way to remove the dirt is to take an adhesive tape, stick it on the surface, and then peel off the tape, it will peel of the dirt also.

Couple of issues with that, a, that tape itself has some adhesive material, and in the process of removing the particle, you can transfer that adhesive to the surface and thereby contaminate it with this hydrocarbon material, while you are removing particles, that are there. And the other problem with the tape cleaning is that it only works for very smooth and polished surfaces; if you have a rough surface, where particles can hide in the roughness asperities, tape cleaning would not work.

However, there are some interesting applications of tape cleaning technology. Polyvinyl acetate is an interesting material, you can essentially lay it down as a liquid on a surface, it will solidify and form a film and then you can just peel off the film. So, this p v a film cleaning is used quite extensively, again, in high technology manufacturing industries to remove particles from surfaces, where other techniques do not work.

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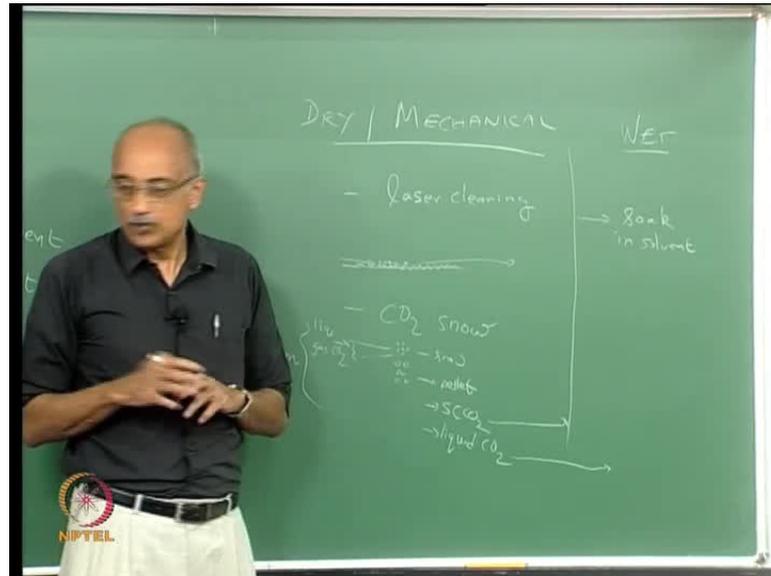
Another method of dry cleaning is simple abrasive cleaning. Now, this usually works when you are trying to remove **grouse** material from a surface. For example, if you have a machined part and there are **birds** hanging from the surface, then blasting it with an abrasive will remove these **birds**, that are hanging from the surface.

So, abrasive cleaning is a process that is extremely abrasive. You are taking material that has high mass and kinetic energy and impacting the surface with it, which will essentially, transfer that kinetic energy to whatever it impacts upon, and it will knock off material from the surface, but here again, the potential for doing damage is quite high.

If you are not controlling the kinetic energy of the impacting material and its direction, you can quite easily, cause unanticipated damage to the substrate you are cleaning.

But for a process like debarring, even paint removal, **you**, frequently, you have applications where you have to remove paint from a surface and then reapply as surface coating; abrasives are used for things like paint removal, which is virtually impossible to achieve by any other means. Quite widely used, for example, in the aircraft industry, where the wings of the plane have to be frequently repainted, and so, the only large scale process that will enable us to do that is Debarring, using abrasive blasting.

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Other dry processes for particle removal that are used, again I am going back to dry mechanical, laser cleaning. It turns out, that if you train a laser on a surface, you can actually knock off particles that are on the surface.

There is two ways in which this can happen - when the laser hits the surface, if it happens to hit exactly where the particle is, just the energy transfer alone may be sufficient to knock off the particle. But even otherwise, when you train a laser on a surface, you essentially increase its state of excitation, you setup a microscopic vibration of the surface, simply by increasing its thermal energy, and as you do that, the particle that is sitting on the surface and the surface itself, starts oscillating; a particle that was initially sitting on the surface is now also, oscillating on the surface.

So, if you do the laser entrainment, and have some gas flow at fairly high velocities over the surface, it can actually entrain these particles and transport them away. So, laser cleaning is the, again, widely used.

When you have very localized contamination that you want to remove, and the surface is such, that you cannot expose it to water or any other chemical, laser cleaning gives you a way to do this particle removal very precisely and completely.

Laser cleaning can also be drawn in a wet mode. Here, what you do is, you soak the surface in a solvent. For example, let us say, you soak it in methanol and then you train the laser on it before the methanol has evaporated, then what happens?

The laser energy actually, causes that solvent to evaporate in an explosive way. It essentially, just boils the solvent **half** the surface, and as it does, once again, the particles that are entrained now in the liquid, or the solvent, that has been, that the surface has been immersed in, are removed from the surface, not just by the vibratory action of the surface, but because of this explosive boiling of the solvent, that has been placed on the surface.

So, particle removal efficiency using laser can be enhanced by a factor of ten or higher, simply by presoaking the surface in a highly volatile solvent. (()) the really does not work very well if you use water as the medium, because water takes a lot of energy to vaporize, but if you take a solvent like methanol that has high volatility anyway, all it takes, is a little bit of laser energy to cause it to evaporate from the surface, and as it does, it takes a particle with it.

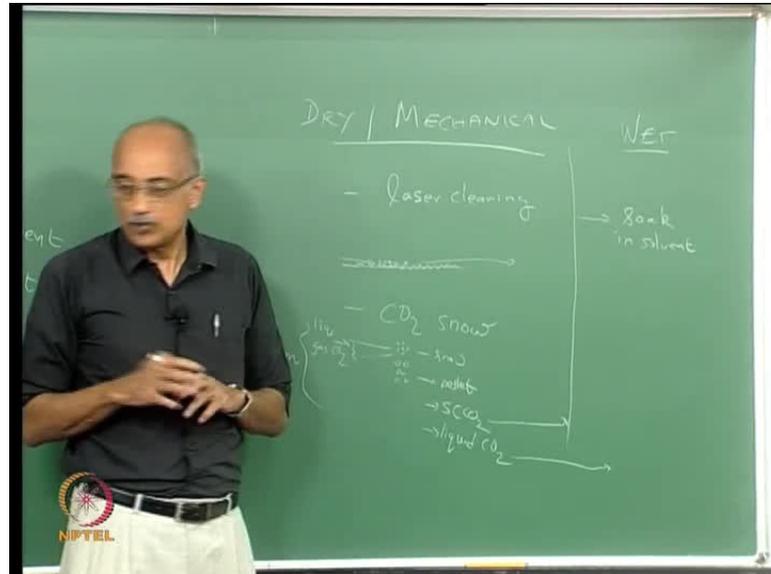
Another dry cleaning action, which does not involve liquids is a, much known as CO₂ snow cleaning. CO₂ snow refers to the conversion of either gaseous or liquid carbon dioxide to a form, where it looks like snowflakes.

So, essentially, by taking the source supply and expanding it through the nozzle and cooling it, you can convert it to **very**, very fine particles. In fact you can control the size of the particles that you create out of these nozzles. If we create **very**, very fine CO₂ particles, this is called snow; if you create larger particles, this is called pallet; and if you expand it in a such a way, that it reaches a super critical region, where it behaves, where it has properties of both, the liquid and a gas, then that is called the super critical carbon dioxide.

So, simply by controlling your expansion process, by controlling the design of the nozzle, you can feed in liquid or gaseous CO₂, and produce either snow, CO₂ snow, which is **very**, very fine flakes of carbon dioxide, or CO₂ pellets, which are larger sized solid carbon dioxide, or a fluid super critical CO₂, which has essentially the density of a liquid, but the diffusivity of a gas. So, from a particle removal view point, it combines

the best aspects of both, liquid carbon dioxide, as well as, gaseous carbon dioxide and by the way, if you liquefy it, you can certainly produce liquid CO₂.

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Now, CO₂ is **a**, an excellent solvent for many reasons; one is, that **it**, it works very well in terms of reacting with hydrocarbons, **and**, and dissolving them also. This conversion, **of**, of CO₂ to various forms, can be done pretty much close to atmospheric conditions. You do not have to go to extremely low pressures or high pressures or extremely high temperatures, in order for these conversions, to happen.

Now, when you take CO₂ that has been converted, for example, to liquid CO₂, then that becomes a wet cleaning process. Liquid carbon dioxide is an excellent solvent, so you can take any material, that has again, visible hydrocarbons on it, like oils use, expose it to liquid carbon dioxide; it will completely remove the hydrocarbon material.

Super critical CO₂ has the ability to remove materials selectively, so you can actually tune it to remove the contaminant that you are looking for again, by controlling the conditions of expansion. You can produce super critical CO₂ with very different solvency properties, and make it particularly effective for certain types of contaminants. So, if you know, what the nature of the oil is on your surface, you can produce a super critical carbon dioxide, which is specifically optimized to remove that particular oil.

So, this is a, kind of, somewhere between a wet process and a dry process. It is not liquid CO₂, so you really cannot call it a wet process, but at the same time it is not a fully dry process, so it kind of, falls in the region between wet and dry cleaning.

CO₂ pallet cleaning is somewhat like the abrasive blasting, **that I**, that we talked about earlier. So, instead of using abrasives like alumina or silica to do your blasting, debarring and so on, you take carbon dioxide pellets and do it.

Now, the advantage of carbon dioxide pallet cleaning is, it does not cause surface damage to the same extent; the hardness, the abrasiveness of carbon dioxide is much lower compared to commercial abrasive, at that you may use otherwise. And also, the biggest advantage in all these processes is that once the particle removal is done, the CO₂ basically, evaporates.

You do not have to do any post process drying or cleaning, in order to remove residual carbon dioxide from the surface, and it is also a net zero addition to the atmosphere; you know, you are not adding CO₂ to the atmosphere by this process because originally, you are taking the CO₂ from the atmosphere anyway, and you are just putting it back into the atmosphere. So, there it is a green process.

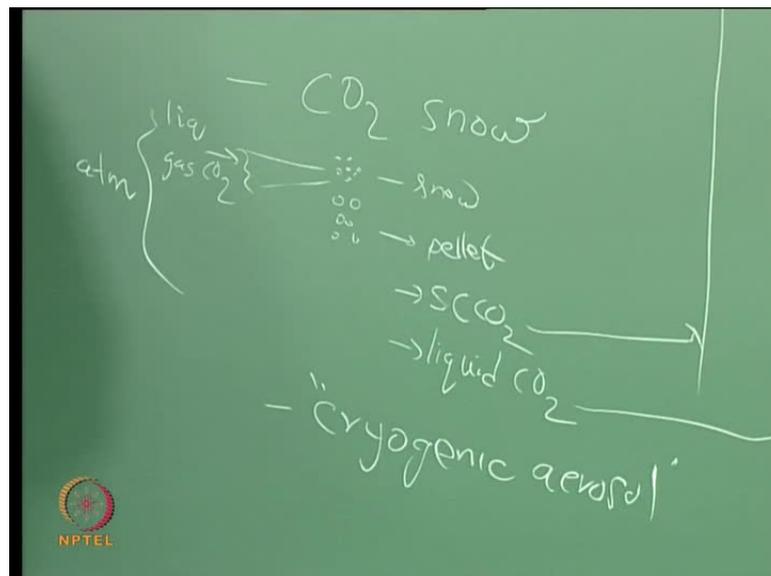
The pellet, for example, if you hit a surface with a carbon dioxide pellet, as soon as you hit the pellet, the CO₂ will start subliming. So, the solid pellet will get converted to gaseous CO₂ virtually, upon impact, after the contaminant has been removed. The CO₂ snow works in a very similar way; as soon as the snowflakes hit the surface, they remove the particles on the surface by line of sight momentum transfer, and also by the mechanism of rapid cooling of the surface. This, **this** process works exactly reverse of laser cleaning.

In laser cleaning, you increase the energy level of the substrate, typically by heating the substrate, and this temperature raise causes thermal oscillations to occur, which loosen the particles on the surface and render them removable. In the case of carbon dioxide snow, what actually happens is, as the snow sublimates from the surface, that is actually a rapid cooling of the surface associated with that. Now, this cooling of the surface has an interesting effect that again, it imparts a thermal shock to the particle, and also it makes contaminants brittle.

So, for example, if you have fingerprint; fingerprint is actually, one of the most difficult materials to remove from any surface. I am sure you would have seen it, if you are washing glass, if you get your fingerprint on it, **very**, very hard to take it off. Carbon dioxide snow can remove it very easily, and the way it does, it is, the flake hit the surface, it essentially liquefies momentarily into liquid carbon dioxide, which is a very good solvent for fingerprint, which is basically skin oil, and then it, again it sublimates. So, there is nothing left on the surface as a contaminant.

So, carbon dioxide snow is again, widely used in high technology manufacturing industries to do cleaning in situ, inside a clean, cleaned room manufacturing process. So, the carbon dioxide as a solvent is extremely versatile; it can be used in **many**, many forms, and it can be fine tuned to particularly the type of cleaning that you are looking for.

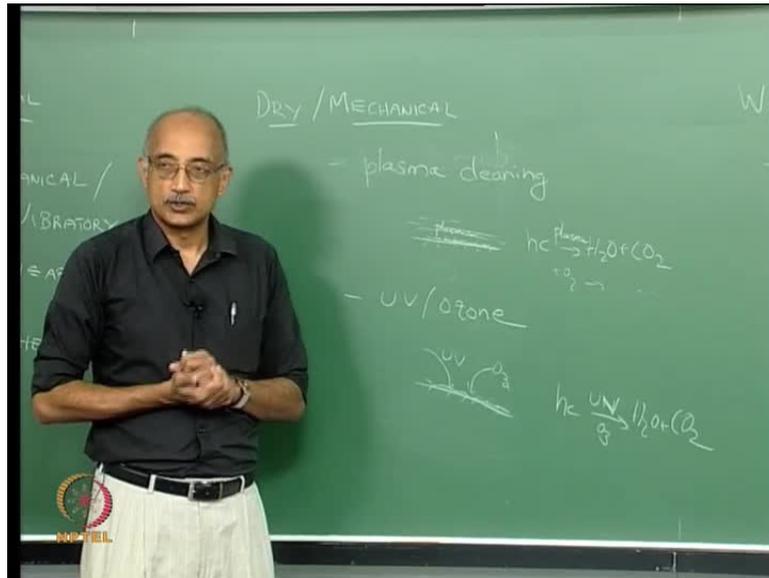
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Now, an extension of these, instead of using CO₂ snow, you can use virtually any inert gas. For example, you can take argon and convert it to argon snow. The general name given for such processes is cryogenic aerosol cleaning. You can take virtually, any noble gas and convert it to a snow form, or a pellet form, or a super critical form, or a liquid form, by processing it under appropriate conditions. Now, it is not just easy to accomplish as when you are using CO₂, but on the other hand these are much purer gases.

So, one of the down sides of using carbon dioxide is that the carbon can sometimes get captured as an impurity or contaminant on the surface, so you have to worry about how to remove the carbon afterwards; whereas, if you use the noble gases and do the same process, even if there is a residue, a few molecules left on the surface, they are chemically inert, so they are not going to do any harm to the functionality of the product.

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All right, so are there anymore dry cleaning processes? Another one, that again is widely used, which I have mentioned a little bit in the last lecture, is plasma cleaning.

In a plasma cleaner, you have a surface on which you have a film type contaminants, like an oil film and some particles also, and you have a gas **face** on top of it; you essentially, ionize the gas **face**, so that you turn the gas into a plasma. The plasma then interacts with the hydrocarbon contaminant on the surface, and as it does, it converts hydrocarbons into H₂O plus CO₂, by providing essentially, the energy that is required for this chemical reaction to proceed.

Now, when you want to convert a hydrocarbon into H₂O plus CO₂, you have to provide it some energy to make it happen. Now, typically heating will do it or oxidation will do it. Instead, in a plasma cleaner, you provide that energy h new, by using plasma and the plasma energy is sufficient to cause the hydrocarbon to be converted to H₂O and CO₂. Now, why do you want to avoid using O₂? Because, it may be, that the substrate itself is oxidisable. For example, if this is aluminum and you got oil sitting on aluminum; by

using oxygen you may be able to convert the oil, but then you will also be oxidizing the aluminum and forming an aluminum oxide layer on top, which you might not want to have for various reasons. So, plasma cleaning enables you to remove just the hydrocarbon materials on the surface, without having any interaction with the substrate surface itself.

A variant of this is called the UV ozone cleaning, and the idea here is very similar. You, again, you have a surface on which you have a film and some particles, you hit the surface with some UV radiation, but here, you also flow in some O₃, ozone. This process is suitable again, for substrates, which are not damaged by the presence of an oxidant. Now, in this case, what happens again is, hydrocarbons in the presence of UV energy and O₃ get converted to H₂O plus CO₂.

Now, the UV ozone treatment is done not only to remove contaminants from surfaces, but it can even be used to get pure water supply. If you look at, how, you know, high purity water is produced **in**, in large quantities? One of the ways, that the quality of the water is maintained, is by doing periodic UV ozone radiations of the water, because it can do two things - one is, it can remove any hydrocarbon material, that has built up and also the viable. You know, if you have bacterial accumulation, UV essentially, can kill the bacteria, convert it to a hydrocarbon, the O₃ will then oxidize it and convert it to H₂O and CO₂ and remove it from the system.

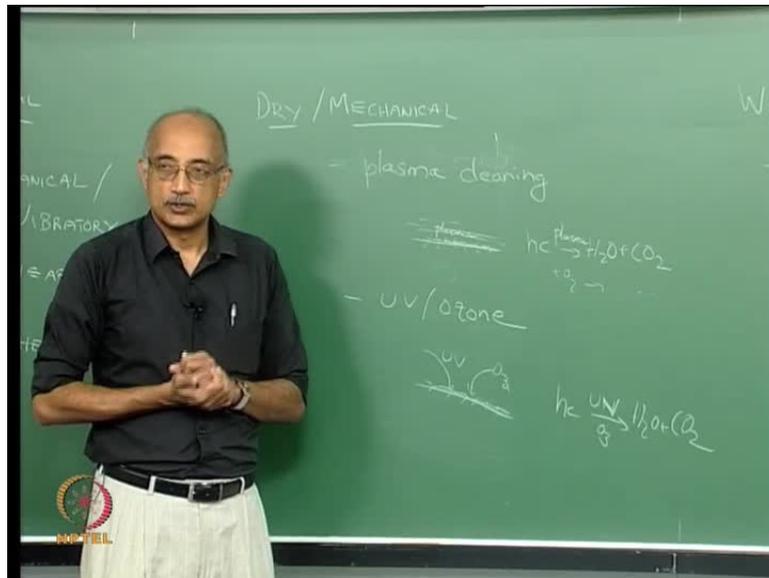
So, these are variance on dry technology, where essentially you are not using a liquid to promote the cleaning, you are still running it in a dry mode. Now, the biggest advantage of dry processing is that you do not require a drying step afterwards. Now, that the biggest problem with wet cleaning is the requirement of a drying step, now why is that a problem? The first reason is just the cost and the energy efficiency of the process; drying is an energy intensive process. When you have to remove liquid layer from a surface, you have to do either hot air drying, or you have to do just high temperature baking, or vacuum drying, all of these consume quite a bit of energy and also, they add to process time.

You know, in many of these manufacturing processes, **you have**, you have to maintain a fairly quick turnaround, so that you can maintain high throughput from your process. A

drying step essentially, slows you down, it is an extra step that the substrate has to go through; so, if you can avoid it, all the better.

And the dry processes offer the advantage of essentially, the single stage particle removal. The other down side of drying is that if the drying material, whether it is air or whether it is some kind of a displacement drying using alcohol, the drying medium itself can have contaminants in it. So, you might have cleaned the surface very well, removed all the particles from it, but if you are not careful, the air that you are using to do the final drying, may have particles in it, which deposit on the surface, and actually it is very dangerous.

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Because just before the drying, the surface is wet and as we have seen before, when you blow particles on to a wet surface, the adhesion forces can be much stronger than when you blow particles on to a dry surface. So, in essence, if you do incomplete cleaning or and you dry it, you have one problem, which is, that whatever particles are left over from the wet cleaning process, are now getting strongly bonded to the surface.

The other problem is, even if you have a perfectly good cleaning process, wet process and you have removed all particles from the surface, if your drying process itself is not maintaining the purity, then you can again re-contaminate the surface by dirt, that you are transferring as part of your drying process. So, in general, if you can get away with doing a dry cleaning process, you are better off doing that.

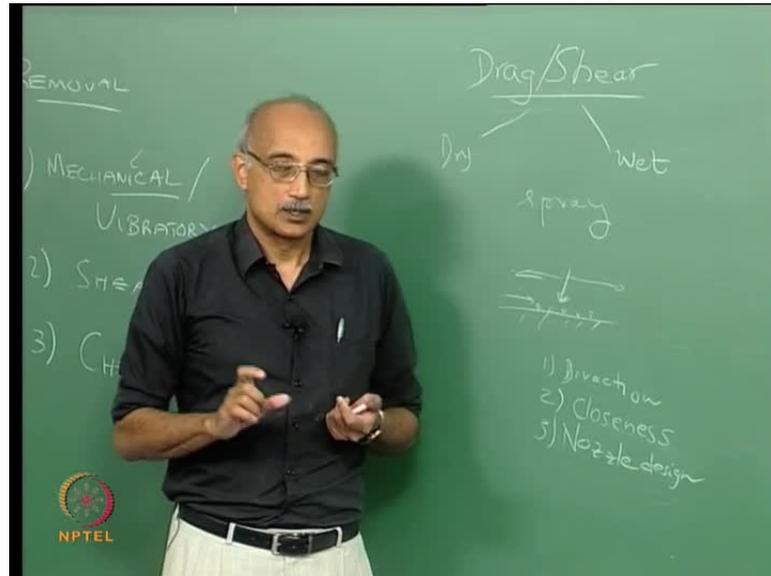
So, why do not we all just go for dry cleaning everywhere? Well, the down side of that is, a dry cleaning process is never as good as a wet cleaning process for the same amount of, for example, energy input. And the reason for that is again, as we saw, when you take a particle surface interface and you soak it in a liquid, you are reducing the Hamaker constant, the intermolecular van der Waals force of adhesion, you are reducing the static forces of adhesion.

So, you are essentially, lowering the adhesion force by nearly an order of magnitude, simply by the act of soaking the surface in a liquid. So, it is very tempting to use liquid media for doing particle removal because it is so much easier, and that is true; I mean, wet cleaning is a much more elegant process in terms of removing material from a surface.

I am sure, again from your household experience, anytime you want to clean something, the first thing you do is put it in water, detergent, you know, soak, scrub kind of thing. So, intuitively we know, that wet cleaning is more efficient than dry cleaning, but the thing that you have to keep in mind is just like with washing dishes, once you have washed the dishes, you have to wait for it to dry, or you have to provide some mechanism by which the drying can be accomplished faster; and more completely, all of that adds cost, that adds complexity, adds process time.

So, you know, it is kind of a balancing act. How much time can you afford to spend in particle removal? So, this again goes back to the question I raise, is to know, as in the earlier lecture, how clean is clean? Every product, every process has its own requirements for how much contamination is tolerable in the process? You have to design your particle removal process in such a way, that you do not under clean and you do not over clean, you have to set it at just the right sweet spot.

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All right, so, you have looked at several examples of dry cleaning technology, and a few examples of wet cleaning, all in the category of mechanical. When we extend the thinking to beyond mechanical cleaning, the first process that **comes into**, comes to mind is the process, that essentially, imparts a force to the particle and dislodge it from a surface. Now, this force can be applied using various mechanisms, and one of them is this drag or shear based cleaning, which can be done in dry mode as well as in wet mode.

Now, what do we mean by dry shear cleaning? Just blowing off dirt with air, you know, or if you just get close enough and blow on it; that is a dry shear based cleaning. And again, dry shear cleaning offers the advantage that there is no, for subsequent drying step necessary, whereas if you do wet shear cleaning, then you have to go and do some drying afterwards.

The most common method for doing drag or shear cleaning is using spray, so you can either dispense air or some gas from a nozzle at high velocity through pressurization; or you can dispense water or some other liquid, like a solvent, again through a nozzle through pressurization. And so, you take the surface on which you are trying to remove particles, and you direct the spray at the surface.

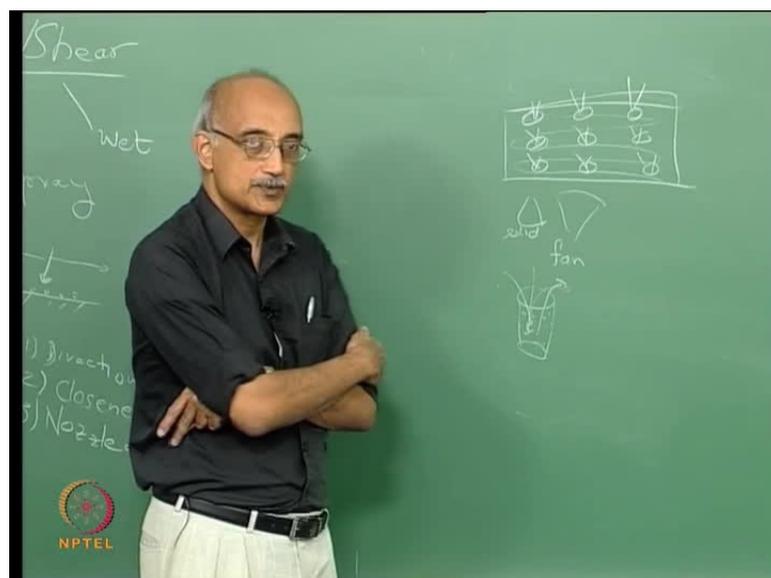
Now, in terms of, how do you optimize this process? What are the variables involved? I think it is obvious, that the direction of the spray is a critical variable. Whether you do

the spraying, even something as simple as, do you spray it in a normal direction, or do you do the spray in a horizontal direction, you know, which make more sense.

Horizontal is nominally better, although the advantage of spraying in this direction is, if you have the ability to move the nozzle and kind of train it, at various location on the surface, then this can actually impart more energy or momentum to the particle compared to this. So, it depends, whether you are essentially using a single nozzle or a set of nozzles at one end of the substrate and blowing air in one direction, or you have the ability to essentially, move the nozzle around.

In fact, the ideal way to do spray cleaning is to have some control over, not only the direction of flow, but also the closeness of the nozzle to the surface, because the third aspect is the nozzle design itself. For example, the nozzle can be a fan type of nozzle, in which the air, or the, or the water spreads into a fan when it comes out of the nozzle; or you can have a solid jet, where the water or air that comes out of the jet, is focused in a in a very specific area. Each has its own pluses and minuses - when you use a fan jet, you can cover a much wider surface area in much less time; on the other hand, when you use a solid jet, you can get much higher energy transfer to one specific location on a surface. So, when do you use which one? Is there one design that is inherently better, than the other?

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So, if you have a surface like this, which is, let us say, is perfectly flat, smooth, with no feature, no recesses, no grooves, then actually a fan nozzle makes a lot of sense, because all you are really trying to do is cover as much area as possible in a shorter time, as possible. So, you take a nozzle that gives out a fan or a spread spray, and just, you know, walk it over the surface several times; you can also keep changing the angles at which you are holding the nozzle, you can keep changing the distance of separation, and you can do a good job of removing particles from the surface.

However, if you have certain locations where contamination tends to accumulate, for example, let us say, you have screw holes - it is a plate that has certain locations where the threaded fasteners go in, you know, blind holes or through holes, then you really cannot clean these locations very effectively, if you are just using a common fan spray. So, then what makes sense is to supplement this with focus jets or solid jets, that can be customized for the design of the component.

So, the way I would try to clean this component is, first use a fan spray to remove most of the dirt on the flat surfaces, and then design a custom nozzle manifold, which has one dedicated nozzle for each of these. So, essentially, use nine nozzles, each of which are pointing towards one of these locations, and essentially, set of an alternating cycles. You first do a fan nozzle, blow off the entire surface, then use solid jets to remove dirt from these locations where they can accumulate or where they can hide, bring them out and then again, do the fan type of spray again. So, by using this alternating cycle, you can keep bringing out material from these localized areas, and making them available for removal, by using a fan spray.

So, this combination of a solid and fan jet type of cleaning works very well, whether you are using air blow off or jet cleaning using water or some other solvent. Again, the angle is important because especially, when you are doing cleaning of specific locations, for example if you have a hole, and you are trying to remove particles that are in this area, somehow, we have to bring them out. Now, if you just direct your jet this way, probably, would not happen very well; there will be a lot of recirculation, stagnation, material will get suck back in.

So, you want to do in such a way, that the water or air enter at an angle, and the air is then provided with an exit angle, and this combination can do a much better job of

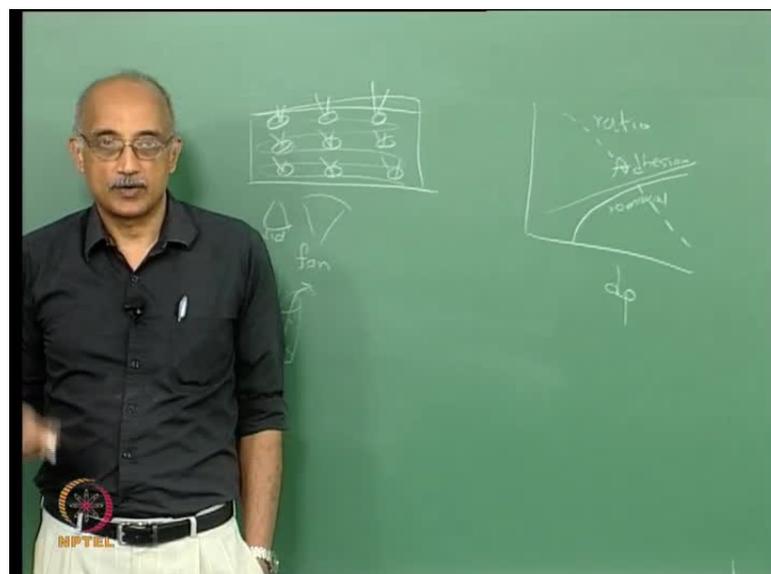
removing particles from the surface. And again, the distance of separation is also a crucial parameter because nominally, you might think that the closer you are to the surface the better off, but there are two problems - if you get too close to the surface, again, you can have unintentional physical contact between the nozzle tip and the surface, which can generate particles by damage.

And the second thing is, as you get closer and closer to the surface, the area that you are covering becomes smaller and smaller, and the potential for essentially, redeposition of the particles can actually become larger, if you get too close to the surface. So, again, you have to do some optimization to make sure, that the direction at which the nozzle is held, the velocity of discharged through the nozzle, the distance of separation between the nozzle and the substrate, as well as the physical design of the nozzle, are all optimized for these specific particle removal application, **that**, that you have in mind.

Again, typically, spray cleaning, whether you are using air blow off or you are using water jet, is limited in the smallest particle that it can remove; it is basically, a limitation of the mechanism itself.

When you are doing aerodynamic drag cleaning or hydrodynamic shear cleaning, what you are doing is imparting a shearing force to the particle, which essentially scales as the area of the particle or the diameter squared. So, as you can imagine, as the particle gets smaller, **the**, the removal force will also decrease quite rapidly.

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And by the way, that question I answered, why is it more difficult to remove fine particles from a surface compared to larger particles? The simple answer to that is - the adhesion force only drops proportional to the size, whereas the removal force drops as the higher power of the size. So, if you just plot d_p versus adhesion force, it might look like this. So, this is your adhesive force, whereas your removal force is more likely to drop like this. And what dictates, whether a particle is removed from the surface or not? It is really, the ratio between the two.

And if you look at the ratio between adhesion force to removal force, that ratio actually goes like this, and that is the reason, why finer particles are more difficult to remove from surfaces compared to larger particles?

So, let us stop at this point. In the next lecture, we will resume our discussion of spray cleaning and then also talk about other methods of cleaning such as, chemical cleaning as well as vibratory cleaning, a good example of which is ultrasonic and megasonic cleaning of surfaces.

Any questions?

See you at the next lecture then.