Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 33
Surface Coating

Hello and welcome to the thirtieth lecture of the course on corrosion, environmental degradation, and surface engineering. In the previous lecture, we introduced the topic of surface engineering and highlighted surface coatings as a method to reduce surface degradation. Today's lecture will focus on surface coatings, which is a vast and complex subject. There are entire books, such as those published by ASTM, that cover a wide range of coatings. However, we will aim to provide a comprehensive overview in this single lecture. For those interested in more in-depth material, additional video resources, including NPTEL lectures, are available for further study.

So, what exactly is a surface coating? It can be thought of as a barrier or interface between a system and its environment. The thickness of a coating can range from just a few nanometers (nm) to several microns.

Therefore, the metal or ceramic, which can also include the polymer metal or ceramic, is typically deposited on a substrate. Now here we are using a new word, substrate; initially we were using only the surface. So there is some sort of surface in the absence of the coating, but when you consider the coating, that becomes a surface, and that has been shown in this figure. As you can see, this surface exhibits irregularities, and in a previous lecture, I discussed the concept of surface roughness.

I say this is one of the very critical parameters; we want an extra smooth surface, but to enhance, may be to reduce a corrosion or reduce a wear rate, enhance some efficiency, we may go ahead with the surface design also. So for the coating also we require surface design and surface preparation, and that has been shown over here. If you look at there is a substrate, if I remove the coating it will have some sort of exposure of the surface, which has a surface, and this roughness is often required for the coating. Therefore, a strong bond forms between the coating and substrates, ensuring that the coating remains intact for an extended period. If we don't have an interface, we may create an intermediate layer between the coating and substrate. We typically deposit the metal or ceramic powder on the substrate material, one layer at a time, or layer by layer.

There are many similarities between additive manufacturing and coating deposition. Both involve building layers, but coatings are primarily used to protect the substrate from wear, corrosion, and erosion. Erosion can happen due to exposure to elements like water, ice, sand, or debris. However, using an erosion-resistant coating can greatly reduce the damage caused by these factors. This brings us to the concept of tribocorrosion, which is the combination of wear and corrosion. Coatings can also act as insulators to protect the material from high temperatures.

For a coating to be effective, proper surface preparation is essential. A strong bond between the coating and the substrate is needed. In some cases, an additional interlayer is applied to improve adhesion and increase the coating’s lifespan.

There are various types of coatings and application methods. Physical Vapor Deposition (PVD) is a broad category, as is Chemical Vapor Deposition (CVD). Thermal spray coatings also offer multiple options. Sol-gel is another method, where a solution is transformed into a gel coating. Different materials can be used for coatings, including nanomaterials, metallic alloys, ceramics, glass, and polymers.

The primary purpose of the coating is to minimize production costs, preventing the product from leaving the cycle. By incorporating the material back into the cycle, we can at least lower the cost. Even at the cost of the raw material, we do not have to extract it from natural resources; the same material, by reconditioning or refabrication, can be utilized and enhanced. Therefore, the coating plays a crucial role in reducing production costs by eliminating the need to fabricate new parts. Now quite possible we may invent a new coating and then it has a different kind of functionalities, or if we are going for the PVD or CVD, which are thin film coatings, we can go ahead with some multilayer coatings also. So even what was not achievable in a previous component, previous subsystem, or previous surfaces can be also achieved today by doing a just a few micron coating on the surface, and then you find the product has become totally new or maybe ready to move in a cyclic manner. So those things are possible when we can really apply coating in a more meaningful way.

Another point to consider is that recently invented materials, especially nanomaterials, offer superior coatings. Therefore, they can be used to extend the lifespan of certain components, such as those that have a 5-year lifespan. Now the components can last 10 years and 15 years, too. So for those additional purposes, coatings are essential. Now I can say slowly the move on a world is moving from 3D to 2D, while this is just reverse; we moved from 2D to 3D.

Currently, we don't really need 3D systems, as most processes occur on the surface. So why not convert everything in 2D? Or maybe whatever bulk material is available has a mass; it has some other thing, but if we go ahead and use the best coating, then whatever substrate material we use will be fine. We can use even outdated materials, and if we can manage the corrosion or enhance its resistance, the material could potentially have a lifespan of several years. So those things are possible with the help of the coating. The easiest way to think about the coating is a painting.

When we spray a liquid onto a surface, processes like oxidation or polymerization cause it to harden into a solid. This is shown in Figure 1, where a coating is applied to a substrate using a stream of liquid droplets. Over time, the liquid—similar to paint—solidifies, forming the coating. This is why coatings like paints, varnishes, and epoxy resins are applied in liquid form.

One of the advantages of applying coatings in liquid form is that it helps maintain a uniform thickness. The surface tension of the liquid allows it to spread evenly, much like how water spreads across a surface. This spreading can also help fill in any small gaps or bubbles, ensuring a smoother coating.

This foam undergoes polymerisation when exposed to atmospheric oxygen, maybe UV treatment, or maybe sunlight, and then this liquid gets transferred to the more robust solid coating. So that is the easiest way to protect the surface from the environment itself. However, we come to the complicated coatings that are like in a gear surface here. So for bad purposes, we really require a very good holistic manner of coating. What are those things? In this case, we need to look at whether the substrate should be compatible with the coating.

If the surface substrate is not compatible with the coating, there will be delamination, and the coating after application will get removed in a short span of time, which we do not want. Therefore, it is crucial to carefully consider the substrate's thermal expansion. If the thermal expansion of both the coating and the substrate are nearly identical, this will be beneficial. Similarly, whether they have a similar kind of elasticity, it will be very good; they need to have high fracture toughness and relatively good hardness. So that it is really gelling well. However, if the coating has a very high hardness and the substrate does not have a very high hardness, then depression will come, and then the coating will really get fractured very fast.

Naturally, if the high thermal conductivity aligns with the coating, it will serve the overall purpose. So compatibility between coating and substrate is very important. The next step concerns the interface. What is the interface between the substrate and the coating? If this interface is indeed present, we should consider its addition. The coating must adhere to the substrate and possess a high shear strength, ensuring that it cannot be easily peeled off. This needs to have a high shear strength.

So good addition and good high shear strength are very important, and in fact I will be preferring the shear strength of the coating to one shear strength of the substrate. But if the shear strength of the interface is more and higher than that of the that of the coating and substrate, that means coating will never ever come. It will be getting punctured, or the coating will get punctured, or the substrate may get punctured, but the coating will not be removed from the substrate, and that is also possible. So we can think from that point of view. Now coming the coating property, we require good hardness, good elasticity, very high fracture toughness, and good thermal stability.

The coating should be stable even at high temperatures, possibly ranging from 400 to 500 degrees, or even higher. It should also have good thermal conductivity, ideally comparable to that of the substrate. Additionally, the coating's surface should have low shear strength to minimize friction, making the coefficient of friction nearly negligible.

However, this creates a challenge. On one hand, we want very high shear strength at the interface between the coating and the substrate for strong adhesion. On the other hand, when exposed to the environment, we want low shear strength to reduce wear. These are opposing requirements that need to be balanced.

The coating should also have minimal chemical reactivity. If it reacts with the environment or nearby materials, the wear rate will increase significantly, which is undesirable. Moreover, the coating should be extremely smooth to provide a better surface finish. Instead of relying on super-finishing operations, a high-quality coating can achieve the desired surface smoothness, ensuring minimal roughness, low chemical reactivity, and reduced shear strength.

So this whole box should be a minimum quantity, or it may be a value. There are a variety of coating methods available today. The topic of coating is vast and complex. Therefore, we will not be delving into a detailed discussion of coating as a subject at this time. Instead, we aim to provide a concise overview in the form of a lecture. While coating methods can be classified into various categories, we will be focusing on the solid state, solution state, or even the molten state. Here the molten state you require the temperature in this case gases stage also you require the temperature, but not the melting points may be want to go at the next phase of the gas form, means we are talking about the atoms, we are talking about the ions. There are two important coatings, or the period method, a CVD coating and a PVD coating. These are the best coating methods; the only limitation is that you require a vacuum chamber, and whenever there is a vacuum chamber, the sample size has to be restricted, so you cannot become the infinity very big vacuum chamber.

Therefore, the cost of PVD and CVD will be relatively high. When it comes to the solution state, we have two options: chemical solution deposition and electrochemical deposition. Based on our understanding of corrosion, we know that there will be a transfer of the anode surface to the cathode, which can be achieved in this manner. The last one is a solution to the gel formation, which is very cost-effective; almost whenever we do not have much in the way of affordability, we can go with the sol gel. Thermal spraying is one of the very popular coatings; it has been researched a lot. The dip coating is also used in a number of industries; they are really going hard, but again, the dip coating really required good skills. So, we required good skills, particularly in the dip coating.

Let’s start with the basics of CVD and PVD. In these processes, we work with atoms, molecules, or ions. The material is evaporated and carried by an inert gas, which then deposits the material onto a substrate. Essentially, the material is converted into a gas, atom, or molecule form, transported, and then deposited on the substrate, which may be a few millimeters or centimeters away. This method is ideal for thin film coatings, especially when you need coatings of around 10, 20, or 30 microns. PVD and CVD are popular choices because they offer excellent control over both the coating thickness and composition, thanks to the use of an inert gas and a vacuum chamber.

If you need a high-quality, uniform, and thin coating, PVD or CVD is the best option. However, if cost is a concern and you're looking for a faster, more affordable solution, you might consider methods like dip coating, sol-gel coating, or hydrothermal methods, which follow similar procedures but are more cost-effective.

Now, let’s focus on PVD, or Physical Vapor Deposition. In PVD, there is no chemical reaction involved—just a deposition process. Electron guns, usually one or two, release atoms or molecules from the source material, and these particles are carried to the substrate by an inert gas. This creates a coating, and titration may be needed for a perfect result. PVD is effective for applying a wide range of materials, including titanium-based coatings, which offer excellent corrosion resistance. In fact, titanium coatings can provide strong protection even in highly acidic environments with pH levels as low as 1, 2, or 3. This information is based on research published in 2019.

Therefore, titanium nitrate PVD coating is applied to the surface of stainless steel equipment. While we are aware that stainless steel materials are resistant to corrosion, we also understand that their resistance to corrosion is limited in an acidic environment. So, we really require extra coating, or may be say additional coating on that. In other words, the titanium nitrite PVD coating has the ability to enhance corrosion resistance and protect the equipment from corrosion over an extended period. Now, in this we say the PVD coating has enormous applications including aerospace, automotive, biomedical, even the arms, or may be say the forces those kinds of things can be utilized, it has a very good hardness, and good resistance against the corrosion. So, the second one is a CVD, and then CVD also we try to use the materials, and then we do the same sort of vaporisation, and then we go ahead with some sort of heating arrangement; that is what the heater has been shown over here and heating arrangement.

In CVD (Chemical Vapor Deposition), the material is heated, causing it to react chemically with other substances. This chemical reaction is key to the CVD process, and it results in a longer-lasting coating compared to other methods. CVD is widely used in the semiconductor industry, where very thin, high-quality coatings are needed, such as on wafers for chips. These coatings provide high resistance and are formed when the material reacts with the hot or heated surface.

It's important to note that chemical reactions in CVD produce byproducts, which are typically removed using a pump system to keep the process clean and efficient.

So, this is what we say: the byproducts of the chemicals are eliminated by vacuum pumps; that is what we will be using. One of the advantages of CVD is its enormous flexibility, which allows it to accommodate a wide range of materials in various compositions and shapes, including complex ones. Therefore, we can proceed with CVD, but the only limitation is the size of the chamber. We need to make a bigger chamber to accommodate; however, for smaller shapes or smaller sizes, there will not be much problem. Now it can go ahead with the carbide coating, nitrite coating, oxynitrite coating, silicon oxide, and may be whatever the range of materials are there. Another benefit is the widespread use of DLC coatings, which have become increasingly cost-effective in recent times. It also can go ahead with the graphene coating, it can go with a nanotube or nanofiber coating, or nanomaterial coatings, and not only this, they go ahead with the different kinds of crystallinity, including the monocrystalline, polycrystalline, and amorphous materials, and then the different forms of the material can be utilized and they would have a different kind of microstructure.

Polymer CVD is also possible, but I believe that for polymers, PVD is generally more preferable than CVD. PVD has been widely used in biomedical devices, particularly where long-lasting solid lubricant coatings are needed. These solid lubricants provide durable protection and are commonly used in the semiconductor industry on a large scale.

There's also ongoing research aimed at improving these processes. For example, instead of using a vacuum, atmospheric pressure coatings are being explored. Atmospheric CVD is now possible, although it tends to be more expensive and isn't very common. In fact, I haven't encountered this technology in my own lab, but it's an option today.

As we continue to explore coating technologies, there's a growing trend toward hybrid methods that combine different approaches for greater flexibility and improved performance.

Therefore, aerosol-assisted CVD, liquid-injected CVD, and plasma-enhanced coating are now viable options. So, these are the various methods that have been added where the CVD plays a secondary role, and that is why these are the second-hand categories. Then we're trying to hybridize two different methods and come up with better results. Now, this material is embedded in the polymer. So, that is what is a really problem in this case. Basically, we try to heat the substrate material, and in some materials we try to heat at 900 degrees Celsius, and then the polymer, particularly being a very temperature-sensitive material, we should not go hard with this, which is why the PVD will be more preferable for that.

However, one good thing about the CVD is that material wastage will be the minimum reason being, because multivariate we want to deposit the coating you go with the localised heating of that there only chemical action will happen. So, because of that, material waste will be low while in PVD, where there may be a word overshot. Now when you are really vaporizing the material, it will go and get deposited on the substrate, but there is no restriction; on this other side, it will not go. I just try to show the previous in this case. In this case we are saying this material will go and get deposited on this surface, but what about other surfaces? It can go on this side; it cango on this side even if it can go to an electron gun, and it may be on other sides also. Therefore, there is no such restriction; we attempt to focus it from a geometric perspective. However, in PVD, there is a possibility of material waste, whereas in CVD, this can be controlled in a much more patterned manner.

So, this is what about the CVD and PVD I am trying to describe in a short. So, we can cover other methods too. Another method is chemical solution deposition, or, in short form, we can call it the CSD. The advantage of CSD is that it utilizes the liquid phase. Why is the liquid phase used here? This ensures that the liquid spreads uniformly and we don't have to worry too much about controllability.

Liquid has unique properties due to surface tension, which helps with spreading. In this process, we typically start by preparing a solution in a beaker. The precursors are mixed into the solution, which is then deposited onto a substrate. This is a common method where the solution is spread and allowed to solidify over time.

One advantage of using liquids is that the main material is easily carried by the solution, even at low temperatures. Since it's in liquid form, there's no need to convert the material into atomic or molecular form, making it easier to apply, especially for complex shapes. Another benefit is the control you have over the process. You can adjust the pH, viscosity, composition, and concentration of the solution, which allows for better control over the morphology of the deposited layer.

So, this also provides a good flexibility to us, and then we can vary even the same chemical composition, but changing the solution concentration we may get a variability in a coating itself. So, we will also get good flexibility with a CSD. As I mentioned earlier, we are conducting a study on electrochemical processes related to corrosion. There is an anode, and the red colour has been shown that this is a sacrificial anode; it will be losing the material and getting deposited to the cathode, and the green colour will be getting added material on that. So, those things are possible now that this is an edge-old technology; it is not a new technology, and we know very well that nanostructured gold plating has been done by using this method of electrochemical deposition. This is why the well-established example of nanostructured gold plating has been cited.

Now, it has a time efficiency, the efficiency is on the higher side; it is a very fast process; it is cost-economic; we do not really require a vacuum. Everything is happening in solution one material is you getting lost, and other material is getting those surfaces, and then we have a good control because electricity also, and then maybe current which is passed we have this we can really keep a good control on that. Another thing is that we have a good simulation related available, that what time what current and how much will be on the thickness will be getting deposited if we know the structure of the material or the shape of the material. This allows for a uniform coating to be achieved. Therefore, electrochemical deposition offers numerous benefits, one of which is its high flexibility. Now, because we can change electrolyte composition, we can change a pH, we can change applied current, and we can change a temperature. The temperature is also two: one is an electrolyte temperature, and the other is a substrate temperature. On top of that, we can use additives from the new research we can keep adding, and then we get better and better results.

As I mentioned earlier, sacrificial electrodes have traditionally been used, but nowadays, non-sacrificial electrodes have become more common. With these, we can use permanent cathodes and anodes, and apply the electrolyte in such a way that we continuously form coatings on the desired surfaces. This method is now widely available.

For more detailed information on electrochemical deposition, you can refer to literature from 2018, and for chemical solution deposition, there are sources from 2017. In the same category, we also have sol-gel techniques, where a solution is prepared and agitated in the initial steps. Special attention is needed for the use of surfactants during this process to ensure the desired outcomes.

So, whatever we are mixing that is not getting settled down remains in the floating condition, and then we go ahead with a different type of exposure. So, that liquid maybe, to some extent, the liquid phase comes down and the gel formation starts. So, that is why the gelation has been written, and then we go ahead with the various temperatures. Additionally, it's possible for the gel to solidify into the final coating. More detail has been given in this reference. In this case, we are referring to the sol-gel coating. This is primarily due to its versatility, as it can also be used to repair existing coatings.

Reason being it is a liquid permeable nitrate; if there is some coating and there is some sort of damage in a coating, there is some sort of crack in that. So, we can use a sol-gel coating, and that coating can be repaired even if there is a suppose existing coating. I can deposit another coating on top of another sol-gel coating on that. We do not have to scrap previous coating; it can be really refurbished with this kind of technology. So, sol gel coating can improve already existing coatings; maybe the coating has become porous and become damaged. Those coatings can be really repaired using the sol gel coating methodology.

There are various solutions used in this process, one being a calcium phosphate $Ca_3(PO_4)_2$ precursor. The choice of precursor depends on the specific application, and it's typically dissolved in ethanol or distilled water. With agitation, a mixture is formed, and surfactants are added to prevent the precursor from settling. As the temperature rises, the viscosity increases, transitioning the mixture from a liquid phase to a gel phase, a process known as gelation.

Next, ethanol or water is removed by heating the solution to a higher temperature, allowing the liquids to evaporate, which eventually leads to a dry coating. The sol-gel method can be applied using various techniques such as dip coating, spray coating, or even spinning technology, all of which are effective for creating sol-gel coatings.

Despite our division into distinct categories, such as sol gel and dip coating, they are essentially the same and can be combined with each other. Despite the cost-effectiveness and relative affordability of this technology, it necessitates a high level of skill. Now, skills are important in this situation, and whenever we really require a high production rate, only skilled labour can do that, the reason being that it takes time, and then we cannot go ahead with the high deposition immediately. You need to dip it for some time, remove it, and then keep it in the environment for some time, then again dip it, then remove it, and then give it some time to get a solidification of the liquid over the surface. Therefore, the process is akin to an iterative procedure, where a skilled individual can perform more effectively than the method itself. However, since the sol gel lacks automation, its production rate is relatively low. Additionally, it may exhibit some porous characteristics or features, necessitating further repair through repeated recoating.

Therefore, it is important to conduct checks on this coating whenever it occurs, as it is cost-effective and comes in a thick film form, unlike PVD and CVD, which are classified as thin films. Another commonly used coating technology is thermal spray coating, which involves converting a liquid into a solid. We are bombarding the liquid under the specimen or substrate, and then based on the control of air mass flow rate, we can really control the thickness of the coating and properties of the coating. We can use two to three different materials, including nanostructure materials, to create the best coating possible. So, a lot of research is concentrated on this kind of topic, and it has again a very high flexibility from a thickness point of view. We can achieve a thickness as thin as 20 microns, and we can also achieve a thickness of a few millimetres.

It has been observed that particles bombard the surface, creating the possibility for a layer-by-layer structure to form. In some coatings, a single pass can result in a 50-micron (50 µm) coating. If a 100-micron (100 µm) coating is needed, two passes are required, and for 150 microns (150 µm), three passes may be necessary. This flexibility allows for precise control over coating thickness.

Unlike PVD and CVD, which are done in small vacuum chambers, this process may not always require such strict vacuum conditions, though some vacuum might still be necessary depending on the specific method.

So, thermal spray coating can be done, and particularly from a designer, I can really design the coating in the environment in a way we want. However, because of these particles, which are small, it will be causing some sort of air pollution. So, we need to really collect, and then it may be kept in a proper environment. We may be keeping a check on that. However, as I say, the best thing is that it covers a large surface area of the substrate. Therefore, when discussing the benefits of thermal spray coating, we can define it as a broad term.

Here, I can also refer to plasma coating or electric coating because we're using a thermal source to increase the temperature of the material, allowing it to liquefy. This can be achieved through various heat sources, such as chemical combustion or even diesel, which melts the material. A spray gun system, with different variations, is then used to apply the coating.

In thermal spray coating, the process typically involves two main components: a heat source and a spray gun, which is directed to ensure proper coating. Additionally, there's potential to incorporate manipulators to enhance the coating application.

So, the more and bigger areas can be really covered also. So, those things are also possible in this case, and then, as I said, there are a lot of coatings because we have a big domain: the possible plasma coating, the detonation gun, which is very well known, and then the high-velocity air fuel, which is also in my lab. At IIT Delhi, we have access to high velocity oxyfuel, as well as popular thermal spray coating categories such as flame coating and wire arc spray coating. There is also a cost-effective method known as dip coating, which is relatively simple. What is the process? Is it similar to gel coating? In this scenario, we immerse a substrate in the solution, and when we remove the used precursors, we observe a deposit of liquid on the surface. A knowledgeable individual will be able to determine the number of seconds or minutes required to maintain an air gap. So, the deposition happens again inside the back and maybe increases the deposition of the thickness as such. So, this is what a simple one is: we try to immerse the substrate in a colloidal substance; this is a colloidal substance; we draw it, and then liquid will adhere to the surface. That is what has been shown here. This process will create coating, and any excess material may leak from the surface. The solvent used to make the solution will evaporate within a few seconds or minutes, depending on the solvent's volatility. For example, if ethanol is used, it may evaporate in just a few seconds, leaving a coating deposit on the surface. However, this type of coating may be slightly porous or less precise compared to methods like PVD or CVD.

Despite this, it is a cost-effective coating solution. The thickness of the coating depends on how many times the surface is dipped and the withdrawal rate. The more times it's dipped, the thicker the coating becomes. In our lab, we use the high-velocity oxy-fuel coating method, where surface preparation is key. A rougher surface is often needed to ensure good adhesion of the coating.

Rougher surfaces will cause more and more adherence to the coating. So, you can see here we are blasting it with a grit, and then after blasting we get this kind of surface. Now this surface is ready to get a coating deposition, and while in this case we do a ball mill, and whatever the powder we want to really coat, it is utilized with a use in a ball mill. Maybe we try to reduce the size of the particles, and this is a gun where we supply oxygen and fuel. We supply the carrier gas, which is an inert gas with a powder and some sort of air assistance. So, the flow is also coming, and this and then the coating material gets deposited and into the substrate. So, this is substrate, and this is a coating. Now that you expose more and more time, thicker and thicker coatings will come. So, maybe this gun will move from bottom to top; it will cause a one-pass, and if you want more and more coating, then again we need to come down in the reverse direction.

This allows for the application of progressively thicker coatings. In this case, our approach involves layer by layer addition of material. We have provisions in place for both the aluminum powder coating and the alumina coating. So, for metallic coating, we can do ceramic coating, and then, particularly when we use aluminium powder, we use powder with some sort of LPG gas that can be used for the burning purpose. This allows us to achieve the critical temperature of 2000 degrees Celsius. However, this can be utilized, or maybe temperature can be increased to 3000 degrees Celsius when we are going for the ceramic coatings, which are the high temperature coatings.

So, if it is aluminium coating, we will go with a 2000-degree centigrade temperature when we go for the ceramic coating. For alumina coating, we go for the 3000 to 3500-degree centigrade. This is my attempt to provide a general overview of the coating. Now, the question comes when you have more than one like kind of coating available, which coating will be suitable. So, again, we will go with a digit logic method, and then we will try to say which coating should be selected. For this purpose, we require a table that outlines the comparative characteristics of various coating methods, including PVD, CVD, chemical deposition, electrochemical deposition, solid gel, and thermal spray. Of course, we also use dip coating, but I am using dip coating and solid gel in one category as such. Key parameters to consider include deposition rate, component size, thickness control, coating uniformity, and bonding mechanism. It's important to evaluate whether the method provides strong adhesion and if there's any potential for substrate distortion. These are just some basic features, but you can find more detailed information in books or catalogs.

Regarding deposition rates, PVD typically has a rate listed as around 0.5 kilograms per hour (0.5 kg/h), though in practice, it is often lower. CVD tends to have nearly double the rate compared to PVD. Chemical deposition methods usually have lower rates, as they are more controlled. Keep in mind that these values may vary between different labs and literature sources.

Coming to the thermal spray, this rate is very different; we can go with a high rate. Also, high velocity guns are generally used. So, we can also go with a high rate of almost 10 kilograms per hour (10 kg/h). In this case, the component size restriction is determined by the PVD and CVD, which vary depending on the chamber; on the solution side, it depends on the solution bath and thermal spray. If we use a manipulator or robot, we may not encounter any limitations. Of course, the powder that will be getting released to the environment will have restrictions because of that. If some say that it has to be a closed chamber or we use a gas mask, then there is no issue, no problem as such.

If not managed properly, the coating process can affect the environment, so it's important to have restrictions in place or additional measures to minimize the impact.

When it comes to thickness control, CVD and PVD offer very precise control. Chemical deposition and electrochemical deposition provide fair to good control, while thermal spray methods can vary. However, with the use of robots or manipulators, the control of thickness in thermal spray processes improves significantly.

In terms of uniformity, PVD offers good results, and CVD is considered the best among all coating methods. Chemical and electrochemical depositions provide fair to good uniformity. Thermal spray coatings also offer similar results but can depend on whether the process is manual or automated.

These guidelines help in selecting the right method, but the choice ultimately depends on the availability of coating techniques in-house or nearby, so adjustments may be needed accordingly.

When it comes to bonding mechanisms, both PVD and CVD offer excellent bonding at the atomic level. However, in solution-based coatings, there is a possibility of delamination due to surface forces. If excessive energy is applied, de-bonding may occur, and chemical or mechanical methods may be used to address this.

Distortion is mainly an issue with CVD, as the substrate is heated during the process. If the substrate is temperature-sensitive, it can deform, which needs to be considered during the selection process.

Further details on this topic are provided in the 2009 literature on coating tribology. The literature illustrates how to choose and apply the appropriate coating methods.

When selecting a coating, it's essential to consider the specific application, functional requirements, the components being used, and the necessary surface treatments.

Coating is common in many applications, and almost every component may require one. However, sometimes the coating may be for aesthetic purposes only, without any functional requirement. For example, if the goal is to achieve a specific color or pattern, such as a pink coating or a flower design, this is considered a non-functional, purely aesthetic requirement. In some cases, the coating is used for reconditioning or to restore the appearance of a component.

The surface is already there. Functional is already there, but only we want the surfaces to be clean, or the pores should be in the bridge, or maybe we do not want any surface roughness on that that can be done. Now, in this situation, we need to select the process; we also need to select the material, because there is a huge category of the process available, and we also have enormous material available. So, those needs to be checked, and then if we really require a specific requirement, then we need to give weights to the requirement, and finally, a solution will emerge out of that. Therefore, we have a process, a material, and a set of requirements, all of which need to be listed in order to arrive at a final, effective solution, which may involve a selection procedure. Let's begin by selecting the coating for the piston ring.

The piston ring is a system that endures high temperatures. Therefore, it is expected that the required temperature will be extremely high. Furthermore, it is exposed to a high rate of wear. So, we also require high hardness. In the automotive industry, we need coatings with specific qualities: minimum thickness, high hardness, and the ability to withstand high working temperatures. When choosing a coating method, we also want high productivity, meaning faster deposition rates. Finally, keeping the cost low is crucial.

So, when selecting a coating, we look for high hardness, a thin layer, high-temperature resistance, efficient deposition, and low cost. We can also add extra features using mathematical tools to adjust as needed. For now, we are considering different types of coatings, such as chromium plating, AMOS, and HOF, which we've just discussed.

In this case, there are two distinct types of coating: a PVDS coating and a chromium-based coating. We have sourced this coating and its corresponding number from existing literature, which is scheduled for publication in 2009. This, we say, the hardness of the chromium is very high, 800. Currently, the hardness of PVD chromium nitride stands at 1500, while that of PVD titanium nitride is at 1700. While these are the high hardnesses coming to the minimum thickness, in this case we are able to keep in mind that the minimum thickness of PVD titanium nitride is almost 10 microns, while others are generally 40 plus.

While in this case in HVOF and all in one pass, maybe what we have in a lab is a 50 micron, but maybe what they have coated is like 100 micron. So, in my lab, whatever we have, we cannot make anything less than 50 microns, while in this case maybe they cannot make a less than 100 microns, which is why it has been given. However, it depends on the technology and what facilities we have, and this number may change also. Coming to the maximum temperature, you can see here that the PVD chromium nitride has a high temperature, and they can really sustain on our 850 degrees Celsius. Then comes HVOF; it can really sustain 800, but again, these are the numbers depending on what kind of materials we are using, and then what kind of technology we are choosing, and whether it has some sort of assistive device or not. Whenever there is an assisted device, the temperature ranges may also change.

Coming to the deposition efficiency, this chromium plating deposition efficiency is low, PVD CVD deposition efficiency is low, but only the restriction here we do not have many data we say either low and high. So, we have two numbers, while in this case we use a digit logic, and we try to give rank between 0 and 10, while in this case low and high we have to give only 1 or 2. However, we say low, medium, high, then 1, 2, 3, low or ultra low, medium, high, and very high, then up to 5. Those things are possible; however, for the demonstration purpose, we are keeping it to only two levels, 1 and 2.

In this instance, we've assigned a deposition rate of 1. Now in a high cost, and we are giving it to; however, we can also give a reverse ranking. We are aiming for a minimum cost, which we can set at 1. However, to achieve this goal, we will need to make a slight modification to the formulation. In my previous lecture, I discussed using a range of 1 to 10. However, if a minimum score is reached, we will need to subtract it from 10. This will serve to demonstrate and possibly illustrate the possibility of such outcomes in this lecture. The way we formulate, these numbers will happen, and based on that, we need to select them. Therefore, these numbers have no inherent value or meaning. However, the mathematical model we choose, along with our evaluation and coding methods, will significantly impact these numbers.

We are currently using MATLAB codes. In this scenario, our goals are to achieve high hardness, low thickness, high temperature, high deposition efficiency, and low cost. Therefore, we will base all these factors on these criteria. A high score will be based on a scale of 1 to 10, while a low score will be calculated by subtracting the specified formula from 10. Now this table that has been recorded in h, which is a transpose of you can see 800, 400, and 790. We have given 8 values in this. Then T in the thickness has been given the nomenclature T, and the coming capital T is basically temperature. This comes from the cost and deposition efficiency that have been given in this manner. So, this is what we are trying to do. This has been tabulated in this manner the way we enter, and then we have a digit logic. We are trying to figure out whatever the weighting factors are.

We need to assign weighting factors to various factors such as hardness, minimum thickness, maximum working temperature, deposition rate, and cost. These factors are important when making decisions about coatings. For example, we might decide that hardness is more important than minimum thickness, so we assign hardness a value of 1 and minimum thickness a value of 0. This is a digital logic method, which we've discussed before.

Then we compare hardness with maximum temperature, deposition rate, and cost. If we prioritize hardness, it will get a higher value, and others like temperature or cost may receive lower values. We also include a "dummy" parameter, which doesn't have an actual value but is used for mathematical purposes. This ensures that all parameters have some value and aren't completely ignored. If we didn't include the dummy, one of the parameters could end up with a value of 0 and be removed from the analysis.

Similarly, we compare minimum thickness with maximum temperature, deposition rate, and cost, assigning values based on importance. This process helps us figure out how much weight to give each factor. For example, we may decide minimum thickness is more important than cost and assign it a higher value.

Finally, we calculate the total weight for each factor. For instance, hardness might have a total of 5 (from 5 factors), minimum thickness 3, maximum temperature 4, and cost 2. These totals help guide our decision-making process.

So, this will provide a weighting factor, and with that MATLAB code, we can really figure out those things also. So, what comes out is that hardness has a weighting factor of 0.333, minimum thickness has a weighting factor of 0.20, and then max temperature has a weighting factor of 0.2667. The deposition efficiency is 0.0667, the cost is 0.1333, and the dummy value is 0. Now step 3 is basically establishing the utility score. So, first case is the hardness or the parameter 1.

We are using this formula has been already explained in a previous lectures. So, I am not repeating it you can see that whatever the value which we got the chromium plating is getting something like on 1 to 10 scale around 2.9 something. MO spray is getting 0.26 in from hardness point of view, because most of the time MO is used as a for the friction point of view not from a wear point of view. And coming to the other coating, the highest number in this case comes around the PVD titanium nitride which has a very high hardness as such.

This can be calculated in whatever the formula can be incorporated here; we require a high hardness. That is why we are using this complete formula; we are not subtracting it from a 10. However, if we want anything on the on the minimum side or lower side, then we will be subtracting from 10. So, this is the output to which we are getting a utility score output, particularly for hardness. Same utility score for the minimum thickness. Now here we want minimum thickness. That is why this formula has been subtracted from a 10. After subtracting this formula from 10, we arrive at a maximum value of 9.9. And other values are less than those that have been mentioned over here, along with all these factors. So, everything has been done in a similar manner to the way we are done with hardness. Now, third is a minimum maximum working temperature. Again, you can see here we are not subtracted from a 10 because we want a maximum working temperature. And in this case, you look at the maximum working temperature of a PVD, which was able to handle 800 plus degrees Celsius; it is getting a maximum value of almost 8.7. The PVD, which scored highly in the first two features, now only receives a score of 3.7. Again, these are the subject of one. The way we have given the ranks, we have values that can vary a little bit and then compare if we get slightly different numbers. So, that has been for the third number, maximum working temperature, coming to the last, and the next one is the time, that is, the time is related to the deposition efficiency. We can quantify deposition efficiency from both the perspective of material utilisation and time. Here we are focussing only on the time point of view; we are not looking at the material utilisation point of view. And then you can see that the faster we get a MOS spray, the much faster HOVF is, because thermal spray has an automation system.

So, this will be getting much faster, or it may be the higher rank compared to the other case. In this case, our goal is to achieve a high level of deposition efficiency. So, do not get confused many times we want minimum time, but here we are talking about the time. So, we want maximum efficiency, and we are not. If we had seen the minimum time, then we would have subtracted from a time of 10, but in this case we are going for maximum efficiency. So, that is why we are not going with subtraction from a 10. And then here you can see the huge variation values. Another one is a cost because, again, we are giving only 1 or 2 numbers; we do not have discrete numbers available. That is why the values are either 1.58 and/or may be 9.2. So, there is a kind of only 2 numbers because we got only 1 or 2, and we are using the same kind of formula for this also. Now based on this, we get all the ranking, and we have a weighting factor available on that; we say the overall ranking can be with a multiplication of the factors. It will come out in this form. You can see here that the highest number comes from something like PVD chromium nitrite and PVD titanium nitrite, missed by the few numbers. So, it does not mean that PVD nitrite or iron nitrite cannot be utilized quite possible when we go for this kind of selection procedure, and maybe we try to eliminate it instead of the selection procedure. So, if I have a 10,000 coating, I will try to eliminate maybe keep a top 50 or maybe top 25 and then do a detailed analysis and study about those.

This methodology helps in selecting the best process, material, or a combination of both. Based on the analysis, we can conclude that PVD chromium nitride is the most suitable coating for piston rings and should be used. However, since the difference between options is minimal, it’s also possible to consider both options. Further detailed analysis or even a pilot project could be conducted, especially considering that piston rings are produced in large quantities, not just a few units.

Such in-depth analysis can provide more clarity on the best approach. I hope this lecture has provided you with a useful overview of coatings and the process of selecting the most appropriate one. We will continue discussing surface engineering in our upcoming lectures (31 and 32). Thank you for your attention.