Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 01
Course Introduction

Hello, welcome to first lecture of course on Corrosion, Environmental Degradation and Surface Engineering. You may have heard a number of times the system fails because of the material degradation. However, in my experience, surface degradation tends to be a more dominating failure mechanism compared to material degradation. Material degradation is basically bulk degradation. As per my understanding or my experience, I have observed that most of the failures start from the surface. It can be a crack on the surface, surface irregularity, some sort of acidic attack on the surface, some sort of water attack, some sort of windfall attack. This kind of things will happen on the surface.

It does not go directly to interior or inside of material. That is why I give more emphasis to surface degradation. Roughly 70 to 80 percent of failure of the system happens because of surface degradation. Failure starts from a surface lead to the material degradation. Only very few cases, around 20 to 30 percent, see the failure starting from inside the bulk and then it slowly reaching to the surface.

Again we will not be in the situation getting much time as failure will be instantaneous, spontaneous. That is not something we are interested in dealing with. And as per my understanding if failure does not occur, that means surface engineering has already been done very well or at a very advanced level. That is why the surface damage has not happened or failure has not started from surface degradation. So, that is why we are offering this course to explore the topics related to corrosion and surface engineering. We will be having approximately 33 lectures in this course.

We will be examining various characterization methods because, when you review the literature, you find many characterization methods, many coating methods and many tools available in the open literature. Everyone tries to claim that their method, their coating is better than others. So, we want some sort of scientific understanding, we want some sort of mechanism to understand how the failure occurs. Many times, the failure happens because of one reason, maybe say, because of the surface crack on the surface and then first slowly it moves to the wear side and the wear has its own a number of mechanisms. Finally, failure is a combination of failures/factors. We will not be knowing how and why this kind of failure occurred. So, without a very good understanding of the damage mechanisms, we cannot comprehend why failure occur.

So, in this course, we will be exploring about all those damage mechanisms, what are the mitigation methods, how to avoid, how to save the cost. In the introduction, maybe in the proposal, I covered some sort of economic aspects, giving more weightage on the corrosion because of its significant impact on the cost, which is almost a 5.95% of the Indian GDP which is equivalent to 1.667 lakh crore. It is a substantial amount, especially considering that in 2023, the entire education budget was 1.13 lakh crore, which is lesser compared to the cost of the corrosion.

There is a need to understand corrosion mechanisms. There is a need to understand how we really can help India or contribute to the science or figure out to minimize this kind of cost. These costs have two components: direct losses and indirect losses. What are the direct losses? We require regular maintenance; regular cleaning of the system and the direct losses will be contributing roughly 2.3% GDP. That means, if I enhance and come up with a better science, if I come up with a better understanding of the method even these direct losses equivalent to 2.3% GDP can be significantly reduced. But more than the direct losses is indirect losses like a shutdown of the company or maybe the complete plant that is a very huge cost or with a regular usage of the system efficiency decreases over time. Initially, if the efficiency was 99%, after one year efficiency might drop to 98%, after two years efficiency drops to 95%. Actually, with drop in efficiency with time, there is energy loss, which does not justify good economics because it is going to cost a lot. Sometimes, we need to replace complete product, or we need to over design the systems, this adds further expenses.

We know that these kinds of situations are going to happen. Should we overdesign it by factor of safety 1.25 or factor of safety 1.5, which might be unnecessary? If we understand science in detail, we can figure out how to mitigate these situations more effectively even by reducing the factor of safety as well as reducing the cost. So overall, if we want economic solution or cost-effective solution we should understand this course in detail, and this applies across many different industries, different organization, different kind of services and that is why I want to show slide on corrosion, which accounts for 5.95% of GDP. It is evident that corrosion is significant in a number of sectors. Let us take an example of agriculture. Environmental dust and silica particles, coupled with moisture, are very harmful as such unless we do not use our surface engineering knowledge. So, agriculture alone accounts for almost 6% of the total corrosion cost, which itself is a huge amount. Similarly, in mining, the particles and sort of reactive gases pose challenges. Moisture or water content can cause some sort of corrosion, which adds up to huge cost.

In manufacturing, we have seen a number of times the manufacturing tool deteriorate with time, even becoming blunt and losing productivity. This alone accounts for about 5.7% of the total corrosion cost. We have found number of times of failures in oil and gases, which also contribute another 1.5%. Water management is another major, major problem because the water itself has a flow and moreover it is of corrosive nature. It has a rusting nature, so if we are using some sort of steel or iron materials, naturally the damage is bound to happen. Even if we replace it with a plastic pipe or some other kind of pipe, water flow will be a major problem. So, surface engineering solutions are essential here. Similarly, transportation including automobile, buses and even railway tracks pose major problems.

The corrosion also causes a lot of the failures in railway track and regular maintenance is the requirement. One of the major concern is high temperature corrosion which happens in most of the electricity related units because the temperature is very high and the presence of fly ash and other corrosive media which cause major failures in such cases. Of course, what we have discussed so far only shows 50% of the overall picture. There are a number of other sectors which may be facing problems because of the corrosion. Even concrete or even the structures, are also subjected to corrosion or environmental corrosion or environmental degradation. So, if you want to really increase the life of systems or components or subassembly, it is crucial to understand all the mechanisms, we need to understand surface engineering, we need to understand the characterization, we need to understand the root cause failure of the system and then we provide a best remedy or best solution for those problems. In my proposal, I covered one slide on the normal day to day example: if you keep a car unprotected in environment or maybe in one rainy season or one winter season, it is sufficient to cause a corrosion of that car body over time.

In the past, cars mostly had the metallic bodies, but now the industry has come up with the plastic or a composite materials which cause less damage but still considerable damage. It is quite possible that the environment itself is causing degradation to the system. Because the environment is causing a degradation of the surface and then we need to reject the complete system which contributes to environmental degradation. So, it is a two-way process: the environment causes failure of a system, leading to environmental degradation. This is a major issue because it is known that there are a lot of pollutants, there are a lot of pollutant gases which can be acidic in nature or when those gases interact with the water, they form acids and that causes or increases the corrosion rate. These factors are important to consider. We also covered the interaction of corrosion and oxidation.

Oxidation is a chemical process involving some sort of electron transfer or loss/gain of atom/molecules. Well corrosion is a broader domain, with the oxidation being just a subset of a corrosion. So, to explain corrosion in a better manner, we can think of oxidation just one of the phenomena, one of the portions of the corrosion. For example, we know how to protect a car from corrosion by simply covering the car. This highlights the concept of surface engineering: the means to protect surface from environment or by putting a barrier between environment and surfaces.

If you are able to put barrier between the environment and surfaces, surface is not going to cause any damage to the environment and environment is not going to cause any degradation of the surfaces. So that is a perfect solution, provide a separation, provide an interface and that is crucial. So, we suggest this kind of course to figure out the effective way to achieve this separation and increase the remaining useful life of the product or system and make it environment sustainable. Therefore, this first course on corrosion, environmental degradation and surface engineering is very important. Understanding mechanisms related to corrosion, related to environment, the interaction with the surfaces and corrosion/damage mechanisms of the surface will be essential for us.

So, this is the course, which we are endeavoring to provide in detail, divided in five divisions. Often, we observe surface degradation, which can be visualized, but for a deeper understanding, we need to integrate more mechanisms. So, surface visualization is the easiest one and then based on those observations, a number of mechanisms can be reviewed from literature. We will conduct a thorough literature review and impart basic knowledge. However, this basic knowledge will be applied in an effective manner, that too in cost effective manner. This means we will also assess which methods are going to be very useful for different situations and at what cost. So, if we know the severity of the problem or severity of the situation we can give different kinds of solutions. It is quite possible with solid fundamentals of the surface engineering, we can provide a better treatment, we can provide a comprehensive solution to the system.

As I mentioned earlier, the environment can also cause a failure of the system. So, we need to examine how the environment is really causing surface degradation. Water, in terms of humidity, is a one of the very common factors. The dust particle is another factor. Wind gusts are also another environmental factor which causes surface degradation. We need to really establish correlation or relation with a corrosion because the corrosion often plays a significant role in the surface degradation. Even though we know that wear phenomena and physical mechanisms are very important, in presence of corrosion that acceleration of the said wear phenomena is phenomenal, very high. So, that is why we say that corrosion is a lead factor, we will keep it in a lead way and then we will try to analyze the whole course from that perspective, focusing on the majority of damage caused by corrosion.

We have a number of characterization methods to measure surface degradation. There are a number of methods we will be exploring one by one and actually when we are trying to optimize the surface degradation identification measurement, we should have a understanding of the characterization techniques. Not every characterization technique will be useful in every situation. So, some situations may requires the application of different characterization techniques for effectiveness.

We will examine a number of examples to establish the correlations. We will emphasize that costly machinery should ideally be reserved for the final stage rather than using it at initial stages as immediate nano-level details may not always be necessary. Transitioning from micro to nano levels may be more appropriate in certain cases. So, we will establish a network and then try to figure out cost effective way to identify the failure. Once we have identified, then we can do good analysis related to failure.

Then virtually we need to find out what are the failure modes. There are number of failure modes and then we need to assess the effect of these failure modes on the lifespan of system. Understanding the relationship between lifespan and economic factors is crucial for determining overall success or failure. This will provide an overall competitive environment for us. Then we can choose different processes, different materials for improvement. By replacing materials strategically, we can provide better solutions.

It will result in lesser pollution. It will cause less damage to the environment. This way we will have the utility of the failure analysis and life cycle assessment analysis. Towards the end or towards the last, we will be thinking about how to modify surface to minimize surface degradation. What kind of the coating to be selected because there are soft coating, hard coating, and methods for some sort of surface functionalization. Recently we have started working on nanotechnology. In nanotechnology, we utilize nanomaterials in the form of coating or in form of some additives in the lubricant. With those nanomaterials water can provide a good surface protection and then overall cost-effective good solution to us.

So, this is the overall framework of the course. We will have 5 divisions in the course. Let us take a very common example to understand this. You have seen these kinds of stones that have gradually worn and I can say that these stones shapes are because of the surface degradation. Bigger stones erode to become smaller and smaller stones over a time, often due to heavy rainfall and constant chipping caused by the water flow, resulting in different shapes.

So, you can see that this kind of stones undergo surface degradation. Coming to metals, metals can become porous even after degradation. Different materials will have different kinds of impacts. Few materials are more reactive compared to some other materials. For example, plastic is less reactive compared to steel. We find a much faster degradation of steel in the case of the corrosion related phenomena, but in case of the physical related phenomena plastic will have much more surface damage. So, we need to determine the right method or right material for each situation.

Even the composites, composites are one of the very good solutions as such, but we know the defragmentation or delamination happens very frequently in the composites. They are very susceptible to UV radiation. If they are used in the presence of radiation, this lamellar may break into some sort of smaller pieces, leading to significant problems. So, if the fibers are broken, naturally the composite material will lose its structural integrity. Another factor is that composite are made layer by layer and if delamination happens, it will compound the problems.

So, we need to understand those concepts. The tool even from age old, people or civilization have understood that tools will work only for some time. They require resharpening. This degradation occurs because of the surface interaction and because of the corrosion nature of the fluid/water, leading to bluntness and eventual reduction in sharpness. Sometimes, tools even break under the forces and then wear-particles will come out. So, sharpness will slowly reduce.

Sometimes, tool even break, not just stone material tools or wood material tools, but also metal tools. Another major issue in a surface degradation is evident in historical buildings in India. Over time, environmental factors such as some sort of pollution and water erosion cause material loss from surfaces. So, we need to understand and comprehend these kinds of failures. In an earlier slide already, I mentioned automobiles. The automobiles have tires, which when interact with the environment, they release a number of particles.

That means the tire degrade with time and release particles that pollute the environment. So, if you are able to provide better and better material for automobile vehicles, whether two-wheeler, four-wheeler or trucks, can mitigate environmental impact and reduce costs. We do not have to really spend the money on this. Addressing such major failures is crucial; some occur suddenly, while others provide warning sign well in advance.

Let us consider examples of the bridge failures. It is well known that wherever there are nut and bolts, mostly made of the steel, they will get corroded, they will fail and that is a major issue with a number of infrastructures. Naturally, we require time management, or we say that we need to have a strong maintenance strategy particularly for those kinds of failures or to avoid that kind of failures. We know very well that many times we are able to avoid that failure by regular maintenance, but sometime failure occurs suddenly, leading to unexpected problems. Another structural concern is environmental factors like rusting, which can lead to cracking, especially under strong wind and heavy rainfall. We lose some pieces from the structure itself. Naturally, the strength will reduce, leading to fatal failure. Even in oil pipeline cases, we have observed a number of corrosion phenomena. The corrosion leads to make structure porous initially and then slowly erosion of material happen layer by layer and finally the open is fully open to the environment, causing a huge loss not only related to oil or not only related to the passing fluid, but to environment on a large scale.

We also have observed failures in the gears, bearings and number of components due to some sort of fatigue. Even though people can say it is a fatigue failure and mostly fatigue failure is a kind of material damage, material degradation, we have also observed fatigue failure originating from the surface. We have seen a number of cracks and then the pits on the surface leading to the material failure. So, this failure is basically related to surface leading to surface fatigue and causing material failure. We have highlighted in our earlier proposal also.

We know that rusting leads to surface damage. Even on attempting to polish or repaint, we will be losing the thickness. As we are slowly losing the thickness of the different parts, naturally the material is getting removed from the surface and that increases the risk of failure. So that is why we require good surface engineering to avoid bridge failure, to avoid a structure failure, to avoid corrosion failure or a fatigue failure. We require implementation of surface engineering in an effective manner. Let us take an example in more detail. Every surface has some sort of a core material, or what we call a bulk phase.

So what we are trying to cover is the surface damages initiate and progress to cause bulk failures. In fact, approximately 70 to 80 percent of failures stem from surface failures. It is not a bulk failure. Only in few cases, the bulk failure happens, where the failure starts from the inside because of some sort of the material defect and slowly it moved to the surface and causing surface damage. But mostly the failure starts from a surface.

Surface damage may manifest as some sort of sliding mark which happens because of the physical interaction, some sort of pitting or surface fatigue phenomena. It may have a corrosive phenomenon related to chemical reactions. In some cases. fatigue may occur just below just below the surface layer, sometimes originating from an intermediate layer used in coatings to bind with the substrate. Many times, for depositing coating, we need to have intermediate layer which can attach coating with a main surface or to substrate.

To illustrate, see this performance graph where the top blue line represents optimal performance with a significant safety margin. So, we are taking a very big factor of safety and initial performance is in the top blue color line. Now there are two possibilities: One is this black color line; other one is a blue color line. Now what we are saying in this case is a basically accelerated test which is happening in the blue color line. We are saying accelerated wear occurs or accelerated failure occurs, and this is a normal failure. Now if I bring effective surface engineering, we can see here there is a big difference. For instance, while without surface engineering, performance degrades 10 percent and if I made effective surface engineering I am losing only 2 percent. So, we are enhancing life by almost 4 to 5 times. Thus, effective surface engineering is crucial for minimize failures and sustaining performance.

So, over time, maintaining performance without deterioration is becoming increasingly important, leading to high demand for systems that can achieve this. We require surface engineering knowledge to effectively utilize such systems. This surface engineering knowledge will be only useful when we know the mechanisms, we understand the mechanisms, and we understand the science behind those failures' phenomena. We can categorize those failure mechanisms into three domains: physical domain or physical phenomena; chemical phenomena and biological phenomena. For our course we will not cover biological phenomena for the time being. We want to be away from bacteria, from algae and all which are also happening in agriculture cases, but we wanted to be away from that. So, we will not cover biological phenomena. We will cover physical phenomena; we will cover say chemical phenomena. Our coverage will encompass topics related to physical phenomena including thermal aspects, as well as wear phenomena, which may result from surface fatigue or under high loads. It is worth noting that wear does not necessarily occur solely due to physical phenomena; sometimes surface fatigue can also generate some spherical particles, which increase the possibility of the wear, increases the pit, contributing to wear.

These phenomena may also be interrelated. Sometimes radiation is also connected to it. It can be thermal radiation or some sort of other radiation or UV radiation from Sunlight that contributes to the problem. Moving to the chemical side, mostly it is a salt or kind of acid which plays a leading role. There is also an overlap between physical phenomena and chemical phenomena, such as physical failures assisted by corrosion and heat. Temperature also plays a major role; in almost every corrosion case we have seen the temperature plays a major role. With increase in a temperature and heat energy more and more sever corrosion occurs.

So, that is an important aspect. To summarize, this course will cover physical phenomena and chemical phenomena, but we will not cover biological phenomena in this course. Now, as mentioned, there are a number of mechanisms related to this. We will address chemical actions, and under physical actions, we will discuss mechanical action and thermal or heat actions.

In this context, "physical" encompasses a mechanical and heat aspects, while "chemical" refers to "chemical interaction". We are not going to cover biology. We will be covering the wear phenomena or physical interaction between the surfaces. There are a number of wear mechanisms, with adhesive wear being prominent. This kind of wear often occurs when surfaces experience cold junction or cold welding between the surfaces due to low speed or surfaces are in contact to each other and then suddenly friction increases significantly. This is an indication of adhesive wear which we will try to cover in detail. There is another wear mechanism known as abrasive wear. Sometimes, adhesive wear causes abrasive wear, sometimes particles which come from environment or even the water particle can cause the abrasive wear or erosive wear.

So we will address particle related issues which come from environment or from other wear mechanisms. Fatigue wear, caused by surface irregularities, will be covered comprehensively. Erosive wear is basically velocity-dependent; when the particles strike with a very high velocity and at some sort of impingement angle, they will cause erosive wear. Fretting wear is very dangerous. It occurs silently wear, often without notification. Two systems, which are connected with each other, may experience some sort of micron level amplitude or vibration, which is almost negligible, unnoticeable but lead to fretting wear over time. That is why we say that this is the kind of the wear does not give advanced information before failure happens. As per my knowledge many bridge failures happen because of this fretting wear.

Sometimes we observe that temperature increases significantly and that causes the diffusion and subsequently causing melting and diffusive wear. We will cover one by one these topics.
Coming to the fractures, they often provide early indications which mostly leads to fatigue failure. The process may be slow, but we are able to see the bending that indicates fracture is going to happen. Once fracture starts, if is challenging to reverse or mitigate the damage. So, we need to give a special emphasis to fracture wear, as it can sometimes occur suddenly.

So, we require good techniques to understand problems thoroughly. The more complex the issue, the greater the need for understanding, because we do not want any catastrophic failures that could result in significant national losses and even endanger human lives. So, that is a major issue, and we need to really think seriously about this aspect. Coming to heat or thermal degradation, they are important. Similarly, radiation is important. Sometimes, the combined effects of heat and radiation can lead to photochemical degradation, which is of paramount importance. Coming to chemical degradation, one of the most prevalent phenomena, which I have observed is aqueous corrosion. This type of corrosion is widespread due to the ubiquitous presence of moisture in the environment, leading to aqueous corrosion as a common occurrence.

When look at the entire structure, it is evident that it will have some sort of aqueous corrosion or any other surface degradation phenomenon that will create a significant problem. Another issue arises from localized fault, where corrosion may initiate due to increased stresses or acidic reactions in specific areas. Flow assisted corrosion is also a concern, particularly when water flow exacerbates corrosion process. Sometimes we have a connection between temperature and oxidation and the high temperature oxidation will happen much faster pace. In such a process, the surfaces undergo oxidation which is often referred to as "fatal oxidation" and it is crucial to understand those. Further, sometimes we say that mechanical, heat, and chemical actions all combined together can cause another kind of the severe failure.

So, we can identify total 4 domains. Mechanical action is the first one. The heat is the second action, the chemical is 3rd one and 4th is combined degradation mechanism. So, a total of four reactions are possible in this case. We will explore in detail these aspects. Let us look at some sort of risk analysis because this complete surface damage analysis is required from a risk point of view. We need to contemplate whether to utilize costly machine or costly coding. So at least we should have a clear idea about risk management. Risk management can be calculated based on two aspects: what is the probability of the failure and what are consequences of that failure.

If the failure happens, what will be the cost impact of that failure? So, we can use some matrix something like a probability and a consequence matrix, where we assess the probability on a scale from A to C but consequences, determining whether they're significant or not. For instance, if the probability is very low and the consequences are almost insignificant, there is no issue. However, extreme risks, represented by the top-right quadrant, the consequences will be very high impact factor. So you can see the B, C, D. With increase in probability, more red color appears that means the R need to be investigated in a depth. Conversely, if the consequences are not very harsh, as seen in this situation, only with increasing probability of failure then we are moving into moderate risk. So, we need to analyze all the system from a risk point of view, considering the potential damage possibility because surface treatment, while beneficial, incurs costs. In other words, due to cost economics, it is not necessary that every case need to be undergo through the surface treatment.

We need to consider the surface treatment and then determine which surface treatment will give a cost effective benefit analysis for us. So, we need to think from a risk management point of view. We will cover this in detail. Let us address three major issues, of course if you search the literature even using Google, you will find numerous such cases.

We are well aware of the Bhopal gas tragedy. We know that leakage of isocyanide in a huge quantity caused three major issues. To reduce the operating costs, they shut down the refrigeration system. This highlights how cost consideration in India can outweigh other factors, impacting decision-making even when the best solution may be apparent. The best solution may not work because people indicate it as very costly solution. In other words, operators decided to stop the refrigeration system to save the cost. Another issue was the gas scrubber, designed to filter out the harmful gases. In the case of leakage of cyanide, the scrubber prevents it movement and minimize its harmful effects. Although the scrubber unit failed, and operators knew about that but they assumed it would not pose a problem since no gas was leaking at that time. Lastly, another issue was a corroded pipe.

So it is not only one subsystem; when the three subsystems encounter problems together; it can lead to a major tragedy, resulting in death of many people as well as long- term and short-term human-injuries. Many people are still suffering even after the immediate danger has passed. So, we need to think from a risk management point of view, considering the potential consequences and making appropriate solution, considering strategies accordingly.

As I have mentioned before, bridge failure happens because of some sort of weak links such as bolt connection or the presence of some sort of crevices or some sort of crack. Identifying these issues early on can help prevent this kind of damage. We know the derailment of the Charminar express. If the tracks are not kept well, not maintained very well regularly there will be problems. Even the railway track undergoes the wear phenomenon, which leads to failure. We need to utilize the surface engineering in effective manner to mitigate this kind of failures.

These are the important considerations. Now, focusing on the micro level, as I mentioned earlier, I am just trying to show in figure 2, which is basically visual inspection. Even with the aid of a microscope, I can visually detect certain failures. In this case, you can see the evidence of pit failure due to the pit formation, and in another case, we observe the melting. During the four-ball test, we observe the melting and then solidification of the molten layer. These observations are visible to the naked eyes, but our interest extends beyond mere visual observations. We want to figure out the root cause. Now if examine this surface by magnifier, then we find significant surface roughness characterized by the peaks and valleys. These peaks and valleys bring a lot of discontinuity and leave a lot of room for the wear phenomenon. Moreover, if there is a water content or environment factors such as weathering to play on the surface, then this will enhance the wear rate significantly.

If there is a some sort of acid, then it can significantly increase the wear rates. So, these aspects are important to consider. Another one, sometimes we use a costly technique 3D optical profilometer, which is only required when we know the surface roughness is very critical, requiring detailed examination. How about performing 2D surface roughness measurement of 4 to 5 locations and generating the 3D profile from those 4 to 5 images. So, we need to know how to utilize available resources in a much more effective manner and that comes with understanding of science and practical knowledge. For instance, if we aim for more detail, such as at a 5-micron level, we may see here some sort of the salt formation or some sort of chlorine action happening directly on the surfaces.

In this situation, we know that this is the initiation, and naturally, there is a possibility that during the delamination, surface start disintegrating. It will create a wear, which many times leads to major failure. So even though we say that the wear is a very slow phenomenon, but quite possible that if we are able to stop wear, it would not lead to the major issue. So, this is very important, and we can show various mechanisms here. If I find some sort of long particle it will be called cutting wear particle but if find some sort of spherical particle which will be indicative of the fatigue wear. So, wear phenomenon can play major role, but it is important to note that there are multi wear factor at play. It is not just understanding only adhesive wear; we must deal with number of other phenomena. We need to figure out which phenomenon is the root cause and understand how it leads to the next phenomenon.

So, this involves interaction, and it is crucial to understand that. This will also be covered in this course. Let us look at our roles in a slightly different manner: What should the role of industry be? What should the role of the government be? What should the role of the user be? I believe the life cycle assessment should be done by industry, should be done also by government, and should be done by the user also. Why should it be done? Because whatever the product or process we launch, we need to understand its goals and scope. How much raw material will be required? How much energy will be required? Naturally, if I am able to enhance the life of any product, I will require less raw material in the long term or less energy in the long term.

This means I am aiming to extend the useful life and going towards a more sustainable solution. So, these are the important considerations. Another aspect is raw material and energy usage. If there are near net manufacturing processes naturally raw material consumption reduces. Reason being, after production, the final product is obtained in a near-finished shape.

I will not require many manufacturing processes to polish it and make it very useful. Naturally, the production process also plays a major role. So, with an understanding of surface engineering, we know the type of raw material needed, the amount of energy required, and the kind of processes that will be very useful in extending its lifespan without causing harm to the environment. By considering the environmental pollution point of view, we are able to enhance the product's lifespan and save or conserve the environment in a better manner.

When we produce this kind of product, naturally we also need to think about inventory analysis, including how much time it will be in store. Then what kind of distribution system, how the product should be distributed and then finally the end of the life of the product. How product will be disposed of. So, this aspect is important from a government standpoint. We need to evaluate whether the making product and associated surface engineering which we are using are really useful or not.

The reason this evaluation is important is because solid waste is continuously increasing on this earth, especially in country like India. We need many effective methods for disposing of solid waste in a favorable manner. By addressing this issue, we are able to determine how much raw material remains available for use and then ensure its continuous use.

Naturally we need to minimize the solid waste, as processing the solid waste sometime leads to various environmental emissions. So, we need to minimize the waste to minimize the emissions. So, life assessment becomes very important from industry point of view, from government point of view, the user point of view. We will take a number of examples to exemplify it. So, these points are the very important.

Now I will just show you the couple of practical examples from our research. We focused specifically on surface roughness. In the first case, the surface roughness was approximately 0.362 micron. We changed the surface roughness to 0.051 micron, and we found that failure could be reduced by 72 percent life, extending the lifespan by almost three to four times. This is an important observation, showing that just by treating the surface or even the polishing surface can significantly impact fracture behavior.

So these are the important to note that just changing one manufacturing process the life is enhanced by the 4 times. The raw material is saved, energy is saved, so life assessment will be much better. This is a good example from that point of view. I am just taking one example from the reference. The reference has been given in this slide. What researcher did in this case, they coated the surface and they found after coating, wear reduced to less than 50 percent. So, this is a very effective method. They could the material or it can be said that they enhanced the life by 2 times. As they reduce the raw material, which means they reduced processing energy, but there will be cost of the coating that needs to be accounted. So, we really require a good economic analysis. Effective economic analysis helps us to decide whether we should go ahead with this or not. For that one requires complete science, which requires this kind of course.

Thank you for attending this lecture. We will come up with the next lecture.

Thank you.