Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 02
Introduction to surface degradation mechanisms

Hello, welcome to the second lecture of topic Corrosion Environment Degradation and Surface Engineering. In my previous lecture, I provided an overview of this course. I emphasize that there is a difference between surface degradation and material degradation. As per my understanding, most of the failure occurs because of surface degradation. Surface degradation may lead to material degradation and that is very important to understand. I did mention about the importance of corrosion.

As I mentioned India loses almost 1.67 trillion rupees per year due to the corrosion failures and this budget is more than complete educational budget per year. Then I mentioned environmental degradation and surface degradation are related. And if you want to reduce this interaction, we should bring surface engineering related technologies to keep environment away from a surface or keep surface away from environment.

Towards the end of that lecture, I mentioned five subdivisions of this course. The first division was the surface degradation mechanisms and their relations to the environment and then I mentioned the different characterization techniques which will be explored in detail in this course. I did mention something about the failure analysis and its relation to life cycle assessment. And towards the end fifth division, I mentioned surface degradation mitigation approaches and how to mitigate surface degradation. So now we will start with the lecture 2 and the second lecture topic we have kept as surface degradation mechanisms.

Overall this topic will be covered in 3 to 4 lectures. Main objective of this topic is to increase the understanding of various surface degradation mechanisms and fundamental reasons behind those mechanisms. In an earlier slide, I mentioned the three main features mechanical, heat and radiation, and chemical action as sources of surface degradation. In the present lecture, I will be focusing only on mechanical aspects. Corrosion and heat and radiation will be covered in subsequent lectures.

So let us start with the slide. I mentioned that surface degradation is due to mechanical action, and we know very well what the meaning of the mechanical action is. What will happen under mechanical forces? Surfaces will get stressed or maybe say localized stress. We will come to now we will understand how localization starts and what are the reason how do we remove those things.

Once again, in this discussion of mechanical actions related surface degradation, we are going to cover two topics: One is wear, other one is fracture. Fracture refers to the breaking of a part or system into several fractions.

We will cover both slow and sudden fractures. But in the present lecture we will focus only on mechanical wear. We will provide an overview of mechanical wear. The adhesive wear, abrasive wear, fatigue wear, erosive wear, fatigue wear, melting and diffusive wear will be covered in next lectures.

We will focus only on understanding mechanical wear: what is the mechanical wear and how we define it. On this this slide, I have given four simple day-to-day examples which we have all likely observed. I believe that almost everybody has seen brake pads. Brake pads are ubiquitous even in bicycles. In the present case I have shown pads of automobiles. Another example of photograph I depicts tire wear, where we observe tire wear on the side and in some cases, the tread may wear down completely, becoming smooth.

Another example I am going to cover is something like a shoe wear and you can see there is a uneven shoe wear. This portion is much more worn out compared to the left-hand side shoe. So, in this shoe pair we can see the more wear. And finally, we examine spectacles as shown we are able to observe scratches on the spectacle's lenses. In all four examples, we observe surface damage without any fracture or division of parts into subsystems.

Let's start with the brake pads. This is a typical example where we want high friction, but low wear. So, this is a initial brake pad, while this shows the final image of a worn brake pad with a depth of approximately 3 to 4 mm. And we know very well that after 3 to 4 mm wear of this surface 1 and 2, this brake pad will be completely useless we will not be able to stop the wheels/tires of the automobile. So, it is very important to understand the mechanisms of this kind of wear. In this case we are aiming for high friction and low wear. So, it is a very good example considering tribological point of view.

Coming to the tire, as I mentioned, the tread depth is around 3 to 4 mm in this case. As the tread depth continuously reduces, and tire may become increasingly worn out and finally it become useless, and we need to replace the tire. Additionally, we have observed some sort of heat related issues, possibly resulting tire expansion or localized expansion, leading to very irregular surface. This irregularity increases sliding, resulting in_more efficiency loss. The decision to replace the tire and the urgency of replacement depends on various factors.

Moving on to shoes, they also give a pattern. The shoe wears out slowly, but it is possible that one side, such as the right-hand shoe, experiences higher mechanical force compared to the other side. Because of this unbalance, accelerated wear to one side showing more degradation than the other.

Coming to the scratches, we can see only scratches as part of surface damage, they still indicate a need for glass replacement for optimal visibility. However, these scratches also serve as design features, with operational considerations being more important. Now if the design is bad there will be immediate failure or material is a bad there will be immediate failure, but these failures happen over the time and that is why we say mechanical wear occurs gradually over time due to factors like how person is maintaining or how a person is operating. It depends on maintenance and usage habits. For example, frequent or irregular braking can accelerate wear on brake shoes and pads.

Similarly driving vehicles on uneven terrain or fluctuating between high and low speeds can subject tires to significant thermal cycles, leading to damage. Regarding shoes, uneven pressure distribution, perhaps due to walking habits or irregular terrain, can cause differential wear. That means again the person must change the habit of walking. Regarding spectacles, it is important to store them in a protective case to prevent damage. Regular cleaning is essential, but it is crucial to avoid using fingers to clean the glasses, as fingers can damage this kind of lens. So, we require a special cloth or a special liquid cleaning solution to maintain the lenses.

So, in all the four cases, we require proper maintenance. The maintenance is often more important than the initial design and initial material selection. So, we require understanding to maintain. While instructions are provided, adherence to them is essential for maximizing the lifespan of these products.

Now, we have described something about mechanical wear. It is important to define what constitutes “wear”. Often, we refer to wear as the undesirable removal of the material from operating solid. If the material removal is desirable, like in a manufacturing, then we would not consider it as mechanical wear. Only when it is undesirable then only, we are going to count this as a wear.

However, there is another distinction between zero wear and measurable wear. Zero wear refers to negligible quantity of the wear, or a very slow wear rate that is almost immeasurable.

Sometimes, what we think about wear involving surface cleaning or polishing in a way that does not result in material loss but rather improve surface quality and reduce stresses. So let us take an example in this case. Imagine two surfaces subjected to the mechanical forces in the tangential direction, resulting in relative motion. If particles from one surface transfer to the other at a nano or sub-nano level (particularly occupying the space of valleys without disturbing the interface), we may consider this as zero wear. However, if this wear turns out to be $0.1\mu m$, $0.2\mu m$ and generation of wear particles is continuous, then it becomes measurable wear and we need to consider it. We need to minimize this measurable wear.

Now, as I mentioned that we under mechanical action, surfaces experience localized stresses due to uneven distribution of load. These localized stresses means that there will not be uniform stress across a complete surface. Few asperities are subjected to very high load. This can lead to plastic deformation, breakage and elastic bending of asperities. As components move from one location to other location some asperities will be relieved some other asperities will get engaged, causing repetitive elastic bending and dynamic or fatigue loading. High loads or rough surfaces may induce plastic deformation, cold welding, or ploughing especially on softer surfaces.

In essence, mechanical wear depends on the relative hardness or softness of the surfaces. If one surface is significantly harder than the other, damage is more likely to occur on the softer surfaces. This is important to note that with more and more hard surface, wear will be lesser, but that does not mean that we can keep increasing hardness. High hardness also causes some sort of failure which be detailed in later chapters. Now, I am just trying to introduce concept akin to warranty. Many times, we buy product with a warranty period on the product. During warrantee period manufacturer or seller will replace or repair any failure within a specified time frame, typically seven days.

So, that is why the warranties are common with almost all the products. Many times, the warranty is for the one year, sometime we get a compressive warranty for 2 years to 3 years. So, these warranties are related to the mechanical wear. How are they related to mechanical wear? Let me show one graph, known as a bathtub curve.

Why is it called bathtub curve? Because its shape resembles a bathtub, and we focus on the initial portion called "infant mortality". That means, there is a possibility of instantaneous failures occurring at the beginning level itself. These failures are typically related to design or manufacturing flaws rather than wear failures.

During the infant mortality phase, often issues are related to design or manufacturing, the manufacturer may replace or repair the entire product. However, once this phase is over and then it has come to the normal wear and the product enters its normal useful life, the manufacturer is less concerned about failures.

This phase entirely depends on operating conditions and the use behavior. So, initial phase, "infant mortality" is responsibility of the manufacturer. Now, why does the warrantee period requires? Because we know nothing is 100% successful. Even if a product has 99% reliability, there is still a chance of one out of 100 components will fail. Rather than aiming for perfection, it is more cost effective to provide a warranty period. Quite possibly at the beginning manufacturers can go ahead with a more kind of warranty and then slowly they improve their design feature, they improve the material and then come up with a product which is not going to fail at all. So, that is also possible. If a failure occurs within a short timeframe, such as 7 days or 1 month, the manufacturer can replace the faulty component, benefiting overall. It depends on the product, market competition, and gradually improving design and materials, leading to products with minimal failure rates.

Now, let us consider the bathtub curve from the wear point of view. Earlier, we discussed the bathtub curve from the viewpoint of failure, and serviceability, but now we want to concentrate on bathtub curve from just wear point of view. If we see this bathtub curve, we can divide it into three segments AB (one segment), CD (another segment) and BC are third segment. If there is no wear and that there is no failure segment AB can be neglected. That means, there is no infant mortality. But wear in inevitable and ideal case of segment BC will be straight line, parallel to time scale.

In my opinion wear is unavoidable. Sometimes, we use the phrase "wear is a necessary evil that we must live with". This evil can only be controlled or minimized. The question then arises: how do we minimize it? So, in this case I have shown this A, B, C, D curve with B, C representing an ideal case. However, in reality, we may not achieve a perfect BC curve. However, we can get a B and C' like curve. This indicates ultra-mild wear. That means, wear coefficient is negligible, perhaps on the order of 10^{-15} or 10^{-16}. What does this mean? It means that the probability of success is something like one particle will fail out of 10^{15} particles. The wear rate is almost negligible.

So, we can think from this point of view. However, there is also the possibility that we cannot maintain the ultra-mild wear, leading to mild wear denoted by curve B C”. So, this BC” will be important. If we fail to maintain this level properly, it is quite possible to encounter moderate wear or severe wear. In the context of engineering or attending this course, it is essential to be able to transition from these undesirable wear patterns to more favorable ones. This is where understanding the reasons behind the significant increase in wear constants becomes crucial. For example, if wear constant is 10^{-1}, indicating one failure out of every ten, it is not satisfactory. We need to reduce it to the 10^{-15} or 10^{-16}. We will discuss in detail the wear constant in the next few slides and future lectures.

So, what is our aim? We assert that early failures do not play much role in our course because those failures mostly happen because of design, or because of the production, or because of the transportation. So, we do not have to cover those failures. However, we can make a difference in the B to C sector by reducing the wear rate in this domain to the minimum possible level. The ultimate aim of understanding the wear is to ensure a cost-effective, long-life span of the product or the system which we operate. So, this constitutes our aim, and we will now detail how we intend to achieve it.

Now, moving to the next slide, there is a discussion on the wear constants. You can see here this depends on the materials. For example, when copper rubs against copper, the wear constant typically ranges from 0.01 to 0.1. Increasing the hardness and changing from copper to mild steel, we get wear constant equal to 0.01 that is slightly less than the copper. However, if we increase the hardness and select hard steel then this constant reduces to 0.001 that means, a 10 times reduction than mild steel. Alternatively, when considering the transfer of layers such as hard steel against Teflon, the wear constant diminishes significantly due to the soft surface of Teflon. The Teflon is very soft and on contacting with hard steel it transfers a layer on the steel surface and because of the this transfer of layer the wear constant reduces almost 100 times compared to previous scenario. Similar outcome can be achieved with two hard steel materials, such as one stainless steel and other hard steel. The hardness of the steel surfaces needs to be very high. The tungsten carbide is also very hard and helps to reduce the value of wear constant. Additionally, utilizing polymer against hard steel can yield wear constant as low as 10^{-7}.

Nevertheless, these constants serve merely as initial reference points. Even if I try to make a component for pin on disc kind of setup and perform experiments on these materials, I may not get these values exactly. So, statistical analysis becomes crucial. These initial values provide guidance in material selection, we should not solely rely upon those values.

Furthermore, we acknowledge that surface texturing plays a more important role. I can choose any material and if I am really able to design surface very nicely, I can reduce wear constant. For example, for copper-pair material, we can reduce wear constant from 0.1 to 0.0001 by just by changing the surface roughness or surface texturing. As discussed previously, surface texturing can transition from severe wear to ultra-mild wear, as depicted in the bottom curve of previous slide.

In addition to wear coefficient, we also consider wear resistance, which is inversely related to wear coefficient. That is, higher values of wear coefficients correspond to lower wear resistance and vice versa. Extremely low value of wear coefficient, K can be 10^{-15} which indicates very high wear resistance. That means, a material or the product is very resistance against a wear. Understanding this relation is crucial.

To summarize, the wear coefficient is an important parameter that can quantify mass loss, indicating surface degradation, often referred to as mechanical wear or physical wear. We can conduct a number of experiments under different conditions, recognizing that wear constant given in tabular form are just an indication. By using the different surface texturing or operating situations, the wear constant can significantly be changed. For example, a few drops of lubricant can reduce the wear constant by 1000 times or 10000 times.

So, this depends on different conditions. It is not only material, it is not only the texturing that matters, but also different operating conditions and how the environment influences the material. Understanding, this is crucial for grasping the significance of wear coefficient. As mentioned earlier, a lower wear coefficient will indicate the more wear resistance, that means, 10^{-15} value of wear constant signifies very high wear resistance, whereas 10^{-1} suggests lesser wear resistance. This inverse relationship highlights that higher values indicate greater wear sensitivity, meaning materials with lower resistance will be more wear sensitive. Furthermore, the wear coefficient depends on material properties, as we mentioned copper on copper, steel on steel. In addition, surface hardness plays its role as we move towards harder steel, the wear coefficient tends to decrease, resulting in higher wear resistance.

We have discussed on surface softness or surface texturing, which we will elaborate in the next slide. Lubrication also affects the wear constant, on using lubrication wear constant will be reduced. Additionally, temperature plays a significant role. As we increase the temperature, the wear constant/coefficient tends to increase. So, it is important to consider the operating conditions. We say that the operating situation will alter the wear coefficient and we need to really find wear coefficient in real situations. I can pick up the material pair, I can consider surface structuring, I can account the operating conditions, but realistic coefficient values are obtained through experimentation, involving scale down models and various setups, to perform experiment and based on those experiment we need to come up with correct value of wear coefficient. So, question comes what are the different setups? What are the details of those setups like pin on disc machine, scratch tester, 4 ball tester. These experiments allow us to conduct a number of experiments and evaluate the values of wear coefficients by changing the surface, lubrication and the operating condition. In the next lecture, we will cover one example to indicate wear- coefficient can be changed by just changing the few parameters. We can really significantly reduce the value of wear coefficient.

So, moving to the next slide, we occasionally encounter the term “polishing wear”. You may have heard polishing wear term as it is utilized in a machining operation, where achieving shinning surface is often perceived as favorable. However, where this phenomenon is truly beneficial needs examination. While polishing may seem desirable for metal working machining and polishing optical lenses and mirrors are desirable, uncontrolled polishing can create more problems. Without proper control, excessive polishing can alter surface design and make it unsuitable for overall operations. So, it is important to understand whether the polishing is going to help or polishing is not going to help. As mentioned earlier, mechanical wear involves the undesirable removal of material. If polishing serves the purpose, polishing is good, but if polishing becomes undesirable then it is not favorable. For example, the engine liner depicted shows some sort of scratch marks from polishing. This liner was initially designed with textured surfaces, featuring peaks and valleys in a regular pattern.

Now, if we polish it, what will happen is that retaining the lubricant will turn out to be much lesser. So, texturing was required to retain the lubricant to minimize the wear rate and reduce the wear coefficient or increase the wear resistance. But, because of the polishing, those textured surfaces were cleaned, and eventually, the engine liner failed badly. So, this is important to understand that it is not necessary everywhere we do polish, and we get a good shining surface. From a wear point of view, it may be very bad and actually detrimental. So, we need to think whether the material removal was desirable or undesirable. Of course, as I mentioned if the removal is very low, like ultra-mild wear, then we will not worry too much. But if it is measurable and quantifiable, then it is a cause of concern. We will worry. This depends on the kind of material we select and the kind of process we select, and whether optimization was done appropriately.

Another aspect to consider is the type of liquid or fluid being used. Naturally, the textured surface will change depending on the material and process used. Different textures may be more suitable for specific applications. We will consider one example of the transfer layer phenomenon. When fixing a graphite seal, a mechanical type of seal, onto stainless steel shaft, initially black color graphite gets transferred onto stainless shaft. So, one of my research scholars used to think it is a bad phenomenon and he was polishing it again and again. After every polishing action of his was increase the coefficient of friction. The coefficient of friction was increasing to 0.5, but with time due to transfer of graphite layer onto stainless steel shaft, coefficient of friction was dropping to 0.2 or even lower. Despite the appearance of the transferred layer as black and undesirable, it actually seals and prevents steam leakage. So transfer of layer was done purposefully so that steam should not be able to come out easily. So, it is an intentional phenomenon. Removing this layer would be undesirable, leading to mechanical wear and increased friction. So, we need to understand that not necessary every time polishing is favorable; it can sometimes lead to a big failure. In the case described, the transferred layer reduces leakage, particularly steam. Additionally, if operating conditions change, such as increasing speed, the effectiveness of the design may be compromised. For example, if the operating speed of 300 rpm is suddenly changed to 1500 rpm, then this design may not be useful in that situation. High speeds can polish away the transferred layer, leading to failure. Similarly, sudden changes in process parameters, like steam quantity or velocity, can delaminate the layer, causing steam losses and mechanical seal failure.

So, everywhere we need to understand the physics behind these actions and why the design was implemented in this manner. We can understand only and only when we go through the complete wear mechanisms. So, we will be continuing this discussion, we can designate this as wear caused by fatigue loading. In my opinion, every loading is a fatigue loading. For example, if I want to operate something at 1000 Newtons, there will likely be variation, perhaps around ± 100 Newtons. So, it essentially constitutes fatigue loading. I have not seen any case where only static loading occurs; almost every situation is a fatigue loading situation.

Now, in case of fatigue loading, what occurs is the possibility of reverse cycling. In this situation, there is a possibility of some sort of nucleus formation or crack formation below the surface. I am just referring to depth of 20 to 50 microns only; I am not suggesting depth of 2 mm or 3 mm. It is a only 20 to 50 microns. Over successive loading cycle, this form of nuclei can get combined and then make a micron size particle, and this gets removed from the surface, leaving behind pits. Often pits are smaller than $50\mu m$. Why mention 50 microns specially? Because anything smaller than 50 microns cannot be detected by our naked eyes.

This means that even though a pit formation occurs, we will not be able to detect it visually. We classify it as subsurface fatigue loading, where pits may be only a few microns deep, and then cracks are getting connected, causing pit formation, which may only be a few microns in depth. Now, to illustrate with rollers; you may observe some sort of surface discoloration on rollers, indicating potential fatigue loading on these rollers leading to some sort of pit formation. When pits formed on the rollers, clearance increases, which is critical for rolling elements. Clearance plays very big role because overall rolling element bearing will have radial clearance of around $10\ to\ 15\mu m$. Pits of $15\mu m$ to $20\mu m$ can be fatal for the bearing and bearing loses its purpose.

So, this is important to consider this aspect. If roller wear out, sliding increases. So, even though rolling element bearing purpose is the rolling action no sliding or zero sliding, but because of this pit formation sliding to rolling ratio increases. Consequently, noise level as well as vibration level rise, rendering the bearing useless.

So, upon examination, we do not find any major failures or fractures. This is not a significant indication; even upon close inspection, we only observe some sort of discoloration, and it is possible that this could be due to accumulation of the number of pits. That means, even from the time of the first pit formed, which could have been more than 1000 hours operation ago, there has been a gradual decrease in efficiency. Additionally, the sharp position may have been affected, potentially leading to other failures.

So, we need to analyze this from a scientific point of view, considering micron and nano level details, to anticipate potential failures. If I can detect this kind of pit formation well in advance, I can promptly apply treatment, preventing further damage. This proactive approach could significantly extend the bearing's lifespan from 4000 hours to as much as 40000 hours. However, If I do not detect fault well in advance and there is some sort of failure which could drastically reduce the bearing life only 400 hours.

So, understanding load conditions, material conditions, and monitoring performance, such as oil content, is crucial. By doing so, we can significantly reduce the likelihood of unforeseen failures. When examining the surface at the micron level, it may appear rough and irregular. However, from a distance, it might resemble a polished surface as we cannot see the many peaks and valleys. We utilized a 3D surface profilometer for this analysis. However, in many institutions we use a stylus profilometer, which typically provides a 2D surface roughness.

In our case, this 3D surface profile has been overlaid with the 2D data, providing a comprehensive view of the surface characteristics. By analyzing a 5 mm length scan, we can clearly identify the peaks and valleys, indicating a very rough surface. We have calculated both the average surface roughness and the RMS value to assess the surface texture accurately.

In tribology, we prefer the RMS value over the RA value. The rationale behind this preference, as well as the detailed explanation, will be covered in subsequent lectures. In the realm of physics, we discuss why we assert certain aspects as right or wrong. While, in manufacturing, it is common to provide only the RA value. But it is crucial to consider RQ value. We need to give emphasis on RQ value. This provides a right indication of whether a surface is going through the damage, whether it occurs after a few hours or the few hundred hours of operation.

For instance, a 3D profilometer may reveal a surface that is rough, indicating a significantly smaller contact area compared to its apparent area. So, this is a very important aspect we have kept some area to sustain the load. Despite roughness being imperceptible to the naked eyes, we find that actual area can decrease to 1 to 15 percent of the apparent area. So, even in this situation if I keep a factor of safety as 6 to 35, the component may still undergo the plastic deformation. So, this is very important to note that the contact region experiences substantially high stresses, as the contact area is much lesser than what we intended. For example if intended area was X area and finally, we are getting only 0.15 X, in this situation the stress will increase by 6 times.

This high stress level increases the possibility of distortion. There is a possibility of crack formation, even there is a possibility of the fracture. So, the surface roughness plays a very important role. We need to think from that point of view. We must strategize ways to improve the surface roughness or surface structure to minimize mechanical wear and to increase the life of this component or system. So, this is very important to consider these factors. Now I am just trying to emphasize not only the product design, but also designing the surface roughness are important to consider.

Sometimes, people do not prefer surface roughness; they say texturing can help us design a surface texture. Now, let us consider the first surface roughness. When we manufacture, we can maintain horizontal lines, meaning peaks will only be in this direction. If we know this is also the lubrication direction, it will give one kind of response. However, if I opt for a cross orientation, it will give a different kind of response. When we measure cross surface roughness and find some sort of diamond shaped roughness, then we get a different response. Multidirectional roughness, being completely random, is generally not preferred, because it is not going to help us much. However, various research papers suggest that coefficient of friction can be changed.

Suppose the coefficient of friction in a specific situation is 0.2, It can be changed to 0.8 or something like 0.45, for same material pair. Consequently, if I want to apply this kind of texturing to the brake shoe, I might opt for a particular coefficient of friction depending on factors like the direction of the rotation and how it is fixed. So, the surface completely can really be designed with deliberate roughness, with the term “controlling surface texture” referring to the production of a desirable roughness to control friction, to control wear resistance and sometimes, aesthetic appeal. So this concept of surface roughness design it illustrated vividly in colorful shape/surface profiles, carefully crafted to achieve both functionality and visual allure. Referring to Patel et al., we observe their incorporation of multiple levels of roughness in Figure 1, aiming for hydrophobicity to prevent moisture from accumulating within the surface itself, to avoid corrosion. It gives good results. So, there is a possibility to design surface to mitigate environmental deterioration, ensuring their longevity and effectiveness.

However, I have seen a couple of other examples where we can observe this kind of segmentation on the surface. This kind of texturing on the surface can act as some sort of dustbin. Such a dustbin concept is a very good concept because mild wear can be contained within itself.

Why do we mention this? Because the presence of wear debris can lead to another kind of failure. Initially, wear debris is generated, and in its presence, the area of contact decreases, enhancing the plastic deformation and leading to additional failures. It increases the wear rate. To avoid wear debris from causing issues, we assume that wear debris dimension is less than $0.1\mu m$. As wear debris is generated, it is dumped in this. So, in this situation, we can maintain ultra wear as a ultra wear itself. We do not have to worry too much because the lifespan can be expanded to 10 years, 15 years, or 20 years until new technology replaces the old technology. So, there is a possibility, and that is why I use the word "surface texturing changes the contact mechanics completely". Now, how contact occurs between the surfaces or how debris interacts with the surface, can change mechanics completely.

Surface texturing refers to a small surface characteristic, such as grooves or dimples. We those surface features. If there is a dustbin or pocket, lubricant can be retained for some time. So that surface texturing provides significant advantage, and sometimes it is described as reducing, while other times, it is said to increase metal to metal contact.

Now, once again, it is subjective whether the peaks and valleys have been designed. This means there is no sharp peaks, and then if have been designed in a manner, it will increase the area of contact because the more contact will occur compared to the peaks and valleys. However, if this has been designed in a way where the contact area is gradually reducing, we achieve ultra-mild wear. So, even though the area of contact is reducing, the stress level is also decreasing we are introducing some sort of lubricant, which plays a role in reducing the metal-to-metal contact thus reducing the stress level. So, there is a possibility that by reducing metal to metal contact, wear reduces, and we can extend the lifespan by maintaining ultra-low wear. This is why I mentioned that either a lubricant can be introduced, or the debris generated can be dumped, acting as a dustbin, or it can repel the water, preventing water from causing any damage or rust to the surface.

So those things are also possible in the situation. Let us try to summarize where we started. We began with something like this, where we observed an irregular surface. Because of this irregularity, the surface area of contact will be much less. In one of the cases, we observed that the area of contact became only 1%. We can figure out the exact area of contact using a number of instruments, such as those that can find out the areas of contact at 1% or 5% compared to the nominal area intended from a design point of view. Now what happens when the nominal area is higher but real true contact area is much smaller? The stress level becomes very high. For example, if I consider only 1% as the contact area, then I am increasing the stress by 100 times. This phenomenon is akin to cold welding, where two surfaces experience very high load, making separation very difficult. Even if we assume the coefficient of friction of 0.2, the overall stress level increases significantly, leading to a significant increase in friction. So, high stress combined with high relative speed amplifies friction between surfaces moving against each other. The coefficient of friction also plays an important role. These factors together accelerate the wear rate. There is a possibility that two surfaces might adhere and get combined, leading to very high stress and potential deformation due to the combination of high friction (represented by the mu) and high stress. If the friction force is very high, frictional heating also increases significantly. These factors, when combined, contribute to a higher wear rate, as shown here. Because of the very high surface roughness and the less contact area, plastic deformation has occurred in the tool, indicating significant wear in this tool. So, surface roughness plays an important role. In the future we will consider a couple of examples to discuss this.

Thank you.