Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 15
Fractography

Welcome to the 12th lecture of the course on corrosion, environmental degradation, and surface engineering. This lecture will focus on the topic of fractography. As it has been mentioned, fractography over here is something new that we are going to learn. To some extent, I say no, it is not new; we have learned a number of times about fractographs, and one of the fractographs has been given in this case, which has also been covered in the earlier lecture. We previously showed that the cleavage is over here; in this case, you can see the division, and we also showed the dimples. We have briefly discussed this subject in our previous lectures, but we aim to produce more significant outcomes from this one.

Fractography, in essence, constitutes a comprehensive examination and evaluation of fractured materials. It involves a dual pursuit: understanding the intricacies of this study while actively engaging in its analysis. The analysis at hand is focused on discerning the morphology, characteristics, and patterns exhibited by fractured materials. It's essential to underscore that our scrutiny is specifically directed towards material fractures.

In light of our preceding discussions on wear, fatigue, and fractures, it's imperative to note that fractography transcends mere fracture analysis; it encompasses a broader spectrum that includes fatigue and wear. Consequently, the conceptual groundwork laid in the preceding 11, 12, or 13 lectures serves as a foundational framework that intersects seamlessly with the subject matter at hand.

As we immerse ourselves into the realm of fractography, our primary objective revolves around investigating and deciphering material fractures and their associated definitions. A fracture, conventionally defined as the separation or disintegration of a solid body into two or more parts, is a consequence of diverse stresses such as fatigue, tensile, or bending stress. Despite the diverse origins of these stresses, the common outcome remains consistent: the material undergoes segmentation into multiple components.

In a previous lecture, we also covered topics related to fractures. We say the fracture process involves crack initiation and crack propagation. Again, in the context of crack initiation, we have discussed the presence of various discontinuities in every structure. This is due to the fact that most structures are polycrystalline, characterized by varying grain sizes and grain boundaries. While there may be indications of a crack, even a minute one, we need sufficient energy or a mechanism to initiate a crack that can propagate further. Many small cracks cannot be propagated. Therefore, we are focusing on the initiation of the crack and its subsequent propagation, as these factors will ultimately lead to its failure.

We've already discussed these topics to some degree. Now, what is the really new thing that we are trying to address in fractography? In this case, there are many new things that will be addressed. However, I am attempting to gather prior knowledge for this lecture to ensure a smooth and cohesive course flow. In this instance, we are observing through magnification, as we frequently present figures as small as $10\ or\ 5\ \mu m$, which are invisible to the human eye. In the earlier lecture, I mentioned that if we are less than $50\ \mu m$, we will not be able to see anything.

Throughout our presentation, we predominantly utilized SEM images, which are subject to magnification. Even if an optical microscope were employed, it would yield similarly magnified images. When scrutinizing these magnified images, our aim is to discern the fracture initiation sites, propagation paths, secondary cracks leading to further failure, and various patterns such as dimples, benchmark beach marks, striations, and cleavages. Thus, fractography necessitates the utilization of magnification instruments like optical microscopy, SEM, or transmission electron microscopy (TEM) to elucidate the topography and morphology of fracture surfaces. Additionally, sometimes it's imperative to analyze the chemical composition of the fracture surface to ascertain the presence of oxygen, chemical reactions, or other phenomena concurrent with the wear process. Such instrumental analyses are indispensable for comprehensive fractographic investigations.

Regarding the dimple microstructure, commonly observed in metals and alloys subjected to fatigue loading, it manifests as microscopic depressions or indentations on the surface. Under cyclic loading, small cracks or flaws within the material can act as stress concentration sites. These cracks propagate with increased surface loading, eventually manifesting as dimples. Moreover, cleavage fractures, observed along weak planes or grain boundaries, result in smooth, flat fracture surfaces resembling a knife cutting through butter.

The production of cleavage fractures involves the propagation of fractures along pre-existing cracks, following paths dictated by weak planes within the material. This process is solely attributed to fracture propagation. Cleavage fractures are particularly influenced by the presence of grain boundaries and polycrystalline materials, often exhibiting cleavage and ridge steps. Here, "ridge" is a term introduced to denote a feature slightly more intricate than cleavage. While cleavage fractures manifest as relatively straightforward breaks, ridge fractures demand slightly more energy and exhibit protrusions. This distinction is crucial; ridges are characterized by their elongated, narrow, and elevated nature, differing slightly from the characteristics of cleavage fractures. Consequently, the fracture of damaged material along ridges necessitates a slightly higher energy input compared to cleavage fractures of similar size.

So let me start with this lecture by naming something like a multimode fracture, because most of the time we find a multimode fracture, it is not a single mode fracture, and this is also an SEM image, which I showed in an earlier lecture. But we showed there that for the microvoid fracture, we showed an intergranular crack fracture, and we also showed the cleavage of the fracture. Therefore, on a single fractured surface, we can observe the micro-voids, the cleavage, and the intergranular crack. In the previous slide, I depicted a type of dimple, but in this instance, I am referring to it as micro voids, a term that bears some resemblance to both dimples and micro voids. However, there is a slight difference in this case; dimples can also occur in parts of brittle fractures, but most multi-void fractures occur in ductile materials.

Hence, the prevalence of micro void fracture predominantly characterizes ductile materials, such as copper, aluminum, and steel, among others, owing to their inherent plastic deformation capabilities. When subjected to tensile stress, any initial discontinuities or gaps within the material trigger the development of micro voids within its structure. This phenomenon arises due to the plastic deformation incurred by the material under loading, allowing for slight alterations in shape and resulting in the generation of micro voids within its surface. Subsequently, these microscopic voids proliferate and coalesce, ultimately leading to surface degradation. While resembling dimples, micro voids are distinctly situated on the ductile side of material behavior. Conversely, dimples may exhibit elements of brittleness, with micro voids showcasing relatively higher ductility.

The distinction between micro voids, dimples, and craters lies not only in their morphology but also in the magnitude and material properties associated with each. Craters, occasionally perceived as enlarged dimples, denote sudden and intense failures akin to the impact of a large ball on a surface, resulting in significant cavity formation or deformation. This phenomenon, observed in fracture surfaces, demands considerable energy and manifests as distinct from micro voids and dimples.

Furthermore, regarding cleavage and intergranular crack fracture, cleavage predominantly occurs at grain boundaries, which serve as inherent weak planes within the material. Consequently, when a crack follows the path of least resistance along these grain boundaries, cleavage fracture occurs. Comparatively, intergranular fracture is characterized by its propagation along grain boundaries, contributing to material failure. In assessing these three types of failures—micro void, cleavage, and intergranular fracture—we note varying responses to loading conditions. Micro voids persist even under relatively low loads, while cleavage fractures necessitate higher loads to initiate, indicating their respective endurance to cyclic loading.

While coming to an intergranular crack fracture, that can be instantaneous also, and because of that, there will be a significantly high load. It is really penetrating the grains themselves; it is not looking at only the weak side; even the strong side is getting damaged because of the very high loads. So if I write from a load point of view, I say the microvoids will have a minimum to a minimum load; even a minimum load will cause some sort of fatigue because of the loading. There will be some sort of microvoid; it may not lead to the final failure, but there will be some sort of void formation, kind of a slight porosity in the material, but coming to the cleavage fracture, it really requires a load and then kind of weak sides. The grain boundaries represent the weak sides, where a concentration of stress may be present. If nearby microvoids connect, they can intensify the stress on the upper side, leading to a failure. In the case of the intergranular, we really require a larger load, or maybe much more load, compared to the cleavage fracture. These are the essential requirements.

In the subsequent slide, we revisit a concept previously discussed: hydrogen embrittlement. We elucidate how an increase in hydrogen content can instigate the formation of hydrogen blisters, evident in the observable swelling across the material's surface. This swelling, indicative of hydrogen embrittlement, serves as sites for crack enlargement. Upon closer examination of the fracture surface of a material affected by hydrogen embrittlement, we observe numerous discontinuities, depressions, and microstructural alterations. These features, facilitated by hydrogen embrittlement, predispose the material to crack propagation. For instance, a crack may originate from a site of hydrogen embrittlement, extend through the material, and potentially cause detachment between surfaces. Such occurrences are not confined to specific materials but are observed across various substrates, including titanium and steel, with particular prevalence in marine environments.

Continuing our discussion on fracture modes, we introduce the concept of multimode fractures, where brittle and ductile fractures coexist. Despite conventional categorizations distinguishing between brittle and ductile fractures, reality often presents a combination of both. An empirical assessment of fracture modes entails evaluating the probability of each type based on observed features. This probabilistic approach allows for a more nuanced understanding, acknowledging that surfaces may exhibit characteristics of both brittle and ductile fractures simultaneously. Therefore, absolute classifications of fractures as purely brittle or ductile are challenging, necessitating a probabilistic assessment to discern the dominant fracture mode.

Further exploration into fracture mechanisms reveals the multifaceted nature of failure processes. Micro voids, cleavage fractures, and intergranular fractures are indicative of varied initiation points and propagation pathways. Micro voids, often initiated by discontinuities such as inclusions or grain boundaries, undergo elongation under increased loads, potentially culminating in stress concentration and subsequent cleavage fracture or propagation along grain boundaries. This multimode fracture paradigm underscores the complexity of failure mechanisms, wherein various factors contribute to diverse fracture modes, making definitive classification challenging. Ultimately, understanding these multifaceted fracture processes aids in elucidating the intricate nature of material failure and guiding mitigation strategies.

However, we have also seen the ridges. So if I break the stone in two parts using this cutting blade, then I will find the flat surface is kind of a regular flat surface, while if erosion is happening on the surface, then we will find a number of ridges happening on this. So even though the overall result is that the same parts are getting divided into two parts, or that the system is dividing, or that the surface is dividing into two parts, the action will be slightly different. In this case, this is more dominant at the abrasion site, while in this case, more domination occurs because of the erosion site. More energy is really required, and there will be a situation. Now coming to even erosion itself, erosion again will determine whether there is abrasive wear or fatigue wear.

Even with this type of wear mechanism, they maintain a connection with each other. I am merely attempting to demonstrate that when the impingement angle per check reaches 30 degrees, we detect a plowing component in this process. What is the meaning of ploughing? It is something like a building of age, or there may be some sort of more deformation, or plastic deformation will occur when the angle is 90^0 . This is what we call fatigue wear in this case, the reason being that the pits will be much bigger in size. As has been shown here, in this case, pit formation will be there even though the area is smaller, but the depth will be greater. Now, as the surface attempts to sustain more energy within a smaller area, As a result, the penetration depth will be greater than the area.

In scenarios of abrasion or erosion, the angle of impingement plays a pivotal role in determining the dominant wear mechanism. For instance, at a 30-degree angle, the cutting action predominates, leading to abrasive wear dominance. Conversely, when the angle increases to 90^0 , fatigue wear or impact wear becomes more prevalent. It is crucial to conduct a thorough analysis of the worn product to discern the characteristics of the debris. By examining debris size, composition, and morphology, we can infer the underlying wear mechanism. For instance, the presence of fatigue wear debris suggests a likelihood of impact wear, especially at a 90-degree angle of attack. Additionally, the material's properties play a significant role in wear resistance. Ductile materials are more resilient to cutting at lower angles, whereas brittle materials are prone to failure, particularly at higher angles. These observations underscore the importance of understanding material behavior and wear mechanisms to predict and mitigate wear-related failures. Subsequently, in the upcoming slides, I will elaborate on the connection between wear and fracture mechanisms to provide a comprehensive understanding of material degradation processes.

In a previous lecture, I presented a slide featuring a disc composed of MR brick, denoting a magnetorheological material. The intention was to eliminate the need for a traditional brake shoe in the braking system, opting for this innovative unit. However, upon closer examination, we encountered multimode failures within the system. Multimode failure refers to the coexistence of various failure mechanisms, as evidenced by the embedded particles on the surface, indicative of embedment, and the presence of crevices. Fractographic analysis has proven invaluable in elucidating these failure modes, underscoring the complexity inherent in developing new systems. The comprehensive understanding gained from such analysis revealed the necessity to enhance surface hardness. Consequently, efforts were directed towards hardening the surface to ensure that particles in contact were harder than the disc material itself. By adopting this approach, the propensity for spherical particles to embed and transform three-body abrasion into more damaging two-body abrasion was mitigated, necessitating adjustments to material hardness for improved system resilience.

The concept I'm illustrating here pertains to multimode failures and their connection to surface fracture. When I mention "fracture," I'm referring to the occurrence of grooves or material removal from the surface. In my perspective, any instance where material is separated or removed from a surface constitutes a form of fracture. Therefore, the presence of grooves or material removal serves as evidence of surface failure.
Moreover, I will delve into two additional slides covered in previous lectures. These slides focus on identifying fractures through the observation of fracture lines, which can manifest in seven distinct patterns. By discerning these fracture lines, we can deduce the predominant fracture mechanisms at play. The presentation of these fracture lines serves to illuminate crucial details about fracture mechanics, including crack propagation routes and material behavior under various forces. For instance, the appearance of chevron-shaped lines indicates the occurrence of high-energy impacts, leading to immediate crack formation and propagation.

In essence, the discussion centers on the interconnectedness between multimode failures, surface fracture, and the identification of fracture mechanisms through the observation of fracture lines. By understanding these concepts, we can gain deeper insights into material behavior and failure processes, essential for effective system design and maintenance.

Another prominent fracture line we observed is known as a beach mark, commonly associated with fatigue failure. This distinctive pattern signifies extensive plastic deformation and typically requires numerous cycles to develop on the surface. As I mentioned earlier in this lecture series, when the plastic limit surpasses a certain threshold due to continuously increasing loads and decreasing stresses, ratchet marks may emerge. These marks manifest as sharp, distinct depths resembling gear teeth on the surface, indicating exceptionally high loads.

In summary, the beach mark exemplifies a typical fatigue phenomenon, whereas the chevron pattern indicates a high-energy impact event leading to surface failure. With these patterns elucidated, we've covered three of the seven fracture lines. Moving forward, we'll delve into the remaining four: ridge cleavage, ridge, and cleavage, with a focus on comparing ridge and cleavage, as previously discussed in this lecture series. Through this comprehensive analysis, we aim to deepen our understanding of fracture mechanics and the factors influencing material failure.

Upon further examination, let's ascertain the clarity of the concepts discussed regarding ridge marking or lines. These markings represent elevated ridges, akin to the patterns observed when two stones or parts of a stone separate due to water erosion, leaving behind distinct patterns on the surface. This process resembles the display of martyrs, where portions remain attached, forming elevated surfaces. Conversely, cleavage presents itself as a smooth, almost knife-like separation, reminiscent of cutting butter with a knife. Although there may be some curvature, the overall surface appears smooth, characteristic of cleavage marking.

In contrast, shear lip denotes a ductile fracture accompanied by significant plastic deformation, resulting in the material separating into surfaces, forming what is known as a shear surface. This type of fracture, termed multi-crack, is the most common, where various crack types and paths coexist. It's essential to discern the dominant path among these multi-mode cracks to understand the primary failure mechanism. For instance, if corrosion or hydrogen embrittlement induces stress, addressing the root cause becomes imperative to mitigate further damage.
By clarifying these distinctions between ridge marking, cleavage, and shear lip, we deepen our comprehension of fracture mechanics and enhance our ability to identify and address material failure effectively.

Now, if it is coming from a from a very high shear lip, or, may be, a kind of plastic or excess plastic deformation, we naturally need to think about the load in this case. Now if there is some sort of brittleness increasing and fracture is happening because of that kind of ridge mark or may be a cleavage mark, we need to think about why the brittleness is increasing, is there any sort of environmental impact, or do we need to change a material? Once we understand this type of line, we can make informed decisions about changing materials, altering operating conditions, or modifying the environment. It's crucial to create a closed system that allows us to control the environment, rather than relying on an uncontrolled one. So this kind of understanding is important whenever we are thinking about the kind of surface engineering or mitigation of surface failure, surface degradation, or, may be, corrosion degradation. Therefore, this kind of understanding will be important from that point of view.

Now, transitioning to the central theme of this lecture, we delve into the comparison between fracture and wear debris—an aspect often overlooked or inadequately addressed by many authors. The primary focus here is to dissect the interplay between fracture and wear debris, as they represent significant facets of mechanical system failures. Fracture, inherently, signifies a higher-level failure, whereas wear debris, though also indicative of failure, tends to manifest at a more granular level within mechanical systems.

In my perspective, both fracture and wear debris offer valuable insights into system behavior and potential failure modes. However, understanding wear debris can provide early indicators of system malfunction or deterioration. By closely monitoring wear debris, one can glean valuable information about the underlying issues before catastrophic fracture occurs. This proactive approach allows for timely corrective measures, thereby expediting the troubleshooting process and enhancing system reliability.

Furthermore, it's crucial to recognize that wear debris is inherently linked to fracture, albeit often at a micro or nano scale. By scrutinizing wear debris on such fine scales, we can unravel the intricacies of material degradation and failure mechanisms. This emphasis on the microscopic or nanoscopic level elucidates the underlying processes driving system failure, facilitating a more comprehensive understanding and effective problem-solving strategies.

In the diagrams presented, we illustrate the interaction between a stainless-steel shaft and a carbon graphite mechanical seal. When these components are in contact, the carbon graphite layer from the seal transfers onto the surface of the stainless-steel shaft. This transfer forms a black layer that serves to reduce the coefficient of friction. However, with continued operation and exposure to water, this layer undergoes gradual removal or delamination.

This phenomenon involves the addition of material through transfer, followed by its subsequent removal over time due to operational wear and environmental factors. While material transfer occurs as an addition mechanism, the eventual removal of this transferred layer represents a form of detachment from the surface, akin to a fracture.

Consider, for instance, the bearing previously depicted, exhibiting numerous scratches. These scratches indicate material removal from the surface. While this removal may occur at a nano or micro scale, rather than at a visible mm or meter level typically associated with fractures, it still constitutes a form of detachment. Thus, it's pertinent to recognize such micro-scale or nano-scale material loss as potential indicators of impending failure or degradation.
By preemptively addressing these micro-level or nano-level wear phenomena, system performance can be optimized, and the occurrence of more severe forms of wear or fractures can be minimized. This proactive approach enables the reduction of wear-related issues, contributing to the overall reliability and efficiency of mechanical systems.

So, this is what we call adhesive wear; this was abrasive wear. When it comes to fatigue wear, we often find that 70 to 80 percent of failures occur on the surface due to surface fatigue, which plays a more significant role than subsurface fatigue. In this instance, we also demonstrated the presence of a material defect, which serves as an initial site for the formation of cracks. As these cracks grow in size, they may merge and agglomerate, potentially leading to a larger fracture. And slowly, because the stress intensity has increased significantly on the site of this kind of crack, it will slowly propagate to the surface, and this chunk will come out. Now this chunk itself can be a micron size; I am not saying that this is a big size; it can be $20\ \mu m\ or\ 15\ \mu m$. Also, it is not necessary that it has to be a mm level, but this is a fracture in my view, and when we say this is a fracture, we should not utilize a fracture mechanics approach to analyze how and why this gets into the debris that is coming out. Can we really reduce or minimize this kind of failure?

So, this is what we will call its formation, which we already covered in a fatigue case that is also a type of fracture. I also showed in the case of the abrasion mechanism what has been shown. I took this as an example of the bearing, but a sketch was also shown because of the sliding motion between surfaces 1 and 2, there is a possibility of microcracks, which are there inside a surface, and then finally, they come up in a particle, or maybe say that this hum or this asperity gets disintegrated into a number of parts. Therefore, this phenomenon can be considered a type of fracture. Therefore, this fracture can be used for this purpose. Now, if I try to figure out what the morphology of these particles will be, I can judge what kind of load condition is happening inside the surface, how many particles are coming, and what the chemical composition of this debris is. I will get complete information.

The analysis of particles, including their size, morphology, and chemical composition, provides crucial insights into the functioning of a system. By closely examining these aspects, we can discern the underlying mechanisms at play within the system without necessitating its physical disassembly. Rather than waiting for a complete fracture to occur, the presence of even a few particles or debris can signify potential issues such as corrosion dominance or chain thickness degradation. By quantifying factors like particle density and wear coefficient, we can make informed predictions about the remaining lifespan of components like chains. This proactive approach, facilitated by Fault Detection and Diagnosis (FDD) techniques, aligns with the core objective of this course: to mitigate surface degradation and prolong the operational lifespan of mechanical systems.

Through the meticulous analysis of debris, we can effectively achieve our objectives. For instance, the distinction between two-body and three-body abrasion, as illustrated in the diagrams, provides valuable insights into the nature of surface wear. By examining the resulting debris, we can discern whether the wear process is characterized by rigid deformation or plastic deformation and brittle fracture. This comprehensive understanding of wear mechanisms enables us to implement targeted mitigation strategies and minimize surface degradation effectively.

The wear debris serves as a valuable source of information, offering insights into the condition of a system. Our primary objective in this lecture is to view wear debris as a micro or nano-level representation of surface fractures. By treating wear debris with the same level of scrutiny as fractures, we can extract meaningful data and take appropriate precautions. Utilizing techniques such as scanning electron microscopy (SEM) allows for detailed analysis of wear debris, including examination of grain structure and application of etching mechanisms.

In a previous slide, I discussed the adhesive wear mechanism, wherein molecular attraction leads to cold welding between surfaces. This phenomenon results in the transfer of material from a softer surface to a harder one, as depicted in the accompanying image. This transferred material can induce work hardening on the receiving surface, potentially leading to further material transfer between the surfaces. As material transfer continues, junction growth occurs, resulting in the accumulation of transferred material and the formation of interfacial bonds.

This ongoing process of material transfer and junction growth exemplifies the intricate dynamics at play in adhesive wear mechanisms. Understanding these mechanisms is crucial for devising effective strategies to mitigate wear and prolong the operational lifespan of mechanical systems.

The observed phenomenon entails the gradual accumulation of a lump on the surface, which progressively enlarges until it reaches a critical size. This enlargement is often rooted in a weaker section of the material, ultimately leading to detachment from the surface. Upon detachment, the lump undergoes crushing, potentially transforming into a plate-like structure with an expanded peripheral area and possibly negligible thickness.

This characteristic is indicative of adhesive wear, particularly when plate-like debris is observed. Such debris suggests a higher likelihood of adhesive wear, with the possibility of transitioning from adhesive wear to abrasive wear. While initially, the particles may be transferred from one surface to another without a net loss, as their size increases, they eventually separate from the surface. This separation results in a fracture, conforming to the definition of fracture as the separation or disintegration of a solid body into two or more parts.

Thus, this process can be aptly labeled as a fracture phenomenon occurring within the context of wear. Even though the material transfer initially resembles adhesive wear, the eventual separation of particles constitutes a form of fracture, albeit on a micro or nano scale. To further study and characterize this phenomenon, it is imperative to collect samples for analysis.

We gather the debris and subsequently examine its microstructure, morphology pattern, and potentially its chemical composition. Once we have this type of information, we can accurately assess what is actually occurring within the system. Therefore, it will provide an increasing amount of information about potential failures before they occur. Currently, I am merely attempting to display this slide, and nearly all the figures have already appeared in earlier lectures. Therefore, I am not presenting any new figures per se, but rather I am attempting to illustrate them. Now, take a look at this wear debris. It is completely irregular, lacks any discernible shape, and appears to be a three-dimensional figure.

Now, this debris is something like spherical, and at the micro level, this is like a kind of plate or maybe slightly curved plate debris, and then the question comes: how do we get this kind of spherical debris as such? So, we can relate here that in a three-body abrasion, if the particle has come out of the surface, then it will be subjected to three-body abrasion, and in an earlier lecture I mentioned that three-body abrasion is much less harmful, the reason being that the loose particle will revolve a larger number of times, I mean the larger time may be almost four times compared to the sliding. So, rolling compared to sliding is more dominant for the third body, which is coming out as a particle, and because of this rolling action, it is quite possible that the spherical particles become spherical in this situation. So, another thing that is coming is this particle, which has a lot of corrosion or oxide formation. Therefore, we urgently need to conduct an analysis. We understand that every material is susceptible to contamination; an oxide layer will form on the metal surface. When it comes to debris formation, we can conduct an analysis to identify any oxide or contamination, or perhaps a lubricant mixture.

So, that will give a good indication of whether I get a completely virgin surface or a fresh surface, which means something is wrong. So, the system is not behaving correctly; it is not getting enough oxide or lubricant sufficiently, and we need to work on it. Therefore, examining and analyzing the wear debris, whether it is intact or fractured, can yield valuable insights. Look at this wear debris, which was also presented in a previous lecture. In this case, the wear debris size is almost an mm.

We have already presented something: if the wear debris size is more than $100\ \mu m$, of course, everything is relative. If the size of the whole system is much smaller, naturally, I will say $10\ \mu m$ itself is much bigger, but like a thumb rule, if the micron size of a particle size is more than $100\ \mu m$, that means wear is significant, and then material is going to degrade. I mean, the surface is going to degrade at a at a much faster speed. So, that is what we call severe adhesive wear. As I mentioned, this is a plate stripe, which is a kind of adhesive wear. Sometimes we use the word spalling, and then this is much bigger than because this is $10\ \mu m$ while this is $254\ \mu m$. So, naturally, this size is much bigger, and we say that size also matters, shape also matters, number also matters, and chemical composition also matters. So, these four characteristics are required for analyzing the wear debris, and that gives us good information. Now, however, another thing comes: if the number of particles is many, but the particle size is almost negligible, may be less than $2\ \mu m$ or less than $1\ \mu m$,then I will be very happy. It is quite possible that I am going to get this kind of surface, which is very good from the mating point of view; it is not really going to damage the opposite surface.

Indeed, the surface in question can effectively function as a repository for numerous micro grooves, resembling a dust bin in functionality. Such a surface configuration is likely to extend the overall lifespan compared to a flat surface. Flat surfaces lack these valleys, preventing the retention of particles; instead, they tend to expel particles immediately from the surface interface. Conversely, surfaces with discontinuities, like micro grooves, offer a space for particle storage before eventual removal.

While it's plausible to argue that these discontinuities may serve as stress concentration points, the reality often manifests differently. Rather than sharp edges, these features tend to adopt rounded edges over time, especially after a few cycles of operation. This rounding can occur due to material properties, the presence of lubricants, plastic deformation, or increased stress, all of which contribute to the natural deformation of the surface.

This understanding allows us to connect the observations of wear debris and surface features from previous lectures. By aligning these insights, we establish a cohesive framework for the course, demonstrating how wear debris analysis can effectively be treated as a form of surface fracture analysis.

This is another interesting thing. We say that there is three body abrasions, and we mentioned that the particle sizes are much smaller. It is quite possible that even the very sharp, irregular-shaped particles are getting rounded. So I will be happy if the number of particles is so small that the number of particles per size is almost negligible. I can be very happy from that angle and say that this is a good thing. However, I may be unhappy. Also, to some extent, look at the fretting movement kind of fretting failure, which we have studied, and we know that fretting wear will cause this kind of surface, or it can cause this kind of surface very difficult surfaces, and then it happens like a silent depth. That is what I used a word for last time: that this is a silent depth kind of thing and happens mostly for joints like a nut, board joints, riveted joints, or something like that. So when this kind of joint is there, what will happen is that there will be some sort of micron-level vibration, and that is why we say that fretting wear debris, often composed of extremely small particle sizes, is that the amplitude of vibration is much smaller, like, say, 1 micron or 2 micron, and then there will be adhesion mechanism, abrasion mechanism continuation, a particle will get separated from a surface, and a particle will get separated from a surface and it will have a lesser oxygen than if another particle gets separated, then there will be adhesion mechanism between the particle itself, and then if there is some sort of close loop in this case. We say that when two particles join, they may initially have a spherical shape, but the deformation caused by the joining may cause them to take on an irregular shape, and it's possible that this shape may also emerge. Because of the continuous action, we say that extremely small particles range in size from nanometers to microns due to the interaction of corrosion, as moisture can easily pass through this type of joint.

Despite the strong molecular attraction between the particles, there is a possibility of corrosion. So there will be a possibility of adhesion, and then when they join together, there will be a possibility of body abrasion because there is a microsliding motion in this case. This interaction could potentially lead to the formation of irregular, complex debris, which could range in size from nanometers to microns. However, in this particular scenario, I should be concerned. Initially, I say that if I am getting too many small particles, I should not worry, but if there is a fatigue phenomenon, I should worry because there is a possibility the particles are leaked. I should gather information that indicates a potential issue, such as joint wear or the possibility of fatigue wear. If there is fatigue wear, I should stop it or maybe tighten it. That is why we often say that whenever there is a nut and bolt connection, there should be regular maintenance.

Regular maintenance refers to the systematic process of inspecting, lubricating, and tightening components within a system to ensure their optimal functioning over time. This often involves tasks such as opening bolts, applying lubrication, and securely re-tightening them to maintain the required torque. By doing so, the risk of bolts loosening, which can lead to increased vibration levels and amplitudes, as well as larger particle sizes, is minimized. These considerations are crucial for ensuring the reliability and longevity of the system, particularly in cases where minimal maintenance is desired.

While smaller particles may contribute to a smoother surface finish, an excessive accumulation of such particles, especially around joints, raises concerns about potential fatigue wear. Therefore, a balance must be struck between achieving surface finish goals and mitigating the risks associated with particle accumulation, particularly in areas prone to fatigue wear due to joint stress.

The discussion also extends to the phenomenon of crevice corrosion, as illustrated in stainless steel surfaces. While not directly related to fractures, the presence of distinct patches and protective layers on the surface prompts further investigation into their chemical composition, including elements such as iron, chromium, and nickel. Understanding these chemical properties is essential for assessing corrosion resistance and ensuring the structural integrity of the material over time.

So those things were also shown. So many times when we do a kind of study of the debris, it can really provide very good information, and then if there is some sort of debris and then it says that particle size is more than 100 μm, and particularly there is a corrosion chance, we should act immediately so that corrosion can be halted; otherwise, there will be a brittle fracture, and then the whole system will collapse. So if we get even or smaller chips, we should start analyzing those chips, look at the chemical composition of those chips, and then say that this is the situation of the system, whether it is working perfectly, not working perfectly, or if we really require some sort of strategy for that purpose. Now that we have discussed debris, it's time to examine the correlation between it and surface degradation. What is the correlation between surface degradation and debris? If we can establish such a connection, it would be truly remarkable. If we are able to determine the extent of surface degradation and the type of debris that is expected, can we effectively interconnect and predict how the shape will develop, or can we make accurate predictions well in advance?

So I'm just trying to demonstrate three different types of completely abrasive mechanisms in this case, which include micro ploughing, micro cutting, and micro fracture or spalling. What is the meaning of that? In this case, you can see that the various debris are very small; it is shown over here as a kind of thin, two-dimensional chip that does not have much thickness. So, in this case, the particle size is much smaller in both the length and width directions, as well as the thickness direction in all three directions. In the case of microcutting, a continuous chip formation can be observed. This continuous chip formation typically occurs in the cutting cases or machine tools, indicating a potential issue within the system.

When it comes to spalling, we often attribute this type of failure to adhesive wear. However, finally, it has to be fractured from a surface, which is why it has been given the microfracture, or, maybe, action, in such a manner that abrasion is finally happening. So initially it may be a kind of adhesion or material is getting deposited on one surface, and finally it is coming as a form of the complete spall, or the complete fractured surface is happening, a major particle is coming out of this one. So this size is much larger than other dimensions, too. This is just one dimension; if I were to describe it as another, both dimensions would be substantial in comparison to the other two debris dimensions.

In this context, micro ploughing isn't posing significant issues. However, it does induce some alterations at the edges or creates enriched systems on the material surface. In contrast, material displacement occurs here, while groove cutting is evident in another scenario. Although material removal occurs from the main groove, remnants remain attached to the surface, indicating incomplete removal. Consequently, there's more plastic deformation in this instance compared to lesser plastic deformation in another, where micro cutting predominates, or a complete fracture occurs from the surface. Therefore, the resulting spoilage is more pronounced, signaling a potential concern compared to scenarios involving cutting or micro ploughing.

Decohesion occurs when wear debris is detached from the surface due to abrasive action, such as micro ploughing, micro cutting, and spoiling. These phenomena were extensively documented in a reference from 1981, highlighting the enduring importance of understanding the relationship between surface conditions and wear debris. This connection between surface degradation and the generated debris is crucial for modern research, as it allows us to anticipate and preemptively address wear-related issues.

It is imperative to establish a link between surface degradation and the characteristics of wear debris. By doing so, we can develop strategies to mitigate wear effects proactively. This entails analyzing the correlation between the worn material's surface properties and the features of the resulting wear debris. Factors such as surface topography, composition, and morphology significantly influence the properties of wear debris.

By comprehending this correlation, we can gain deeper insights into the wear process and optimize maintenance strategies accordingly. Understanding how surface conditions impact wear debris characteristics provides a clearer understanding of wear mechanisms, enabling us to devise more effective maintenance approaches.

Micro ploughing occurs when abrasive particles displace thin layers of material on a surface due to mechanical action. While some material is displaced, it's not completely removed; instead, it undergoes plastic deformation or displacement. In terms of wear, the non-dimensional wear constant, which we've discussed in previous lectures, typically remains below 10^{-7} in such cases. This value is considered acceptable given the nature of micro ploughing.

On the other hand, micro cutting involves the cutting action of harder asperities on a surface. Here, the hardness of the materials involved, as well as the angle of the asperities, play significant roles. In micro cutting scenarios, the non-dimensional wear constant may be even lower, potentially falling below 10^{-3}. This emphasizes the importance of hardness and surface characteristics in determining wear rates during micro cutting processes.

So, when the micro cutting rate is below 0.001, it raises concerns, prompting us to investigate the root causes and methods for prevention. While micro ploughing may not be as worrisome, micro cutting demands our attention. Additionally, the occurrence of spalling, as observed in two dimensions, indicates a more significant issue. Unlike micro cutting, spalling involves movement in two directions and often leads to brittle failures. Hence, understanding why ductile materials experience brittle failures is crucial. We must assess potential weak points and crack formation to address this concern effectively.

By analyzing wear debris, we gain insights into the system's loading and operating conditions, allowing us to implement appropriate remedial measures. To illustrate, let's explore a few examples that demonstrate the correlation between wear debris and surface conditions, particularly in dry environments.

What is the importance of dry-condition adhesion? will also be there. If I make it to the lubricated condition, it is quite possible that adhesion will be removed. So, in this case, we want to really look at what the correlation is, how the debris will come out, and what the relationship is between the surface and the wear debris. In this case, particularly the steel specimen, we say that there are two heat treatment processes that have been utilized, and then we want to know which heat treatment procedure is going to give better results compared to the other heat treatment procedures. So, we have two heat treatment procedures, and then we want to test which heat treatment will give better results. Again, under this testing, we can go ahead with normal conditions, but in the accelerated condition, the loads were increased significantly, and this detail was given in this paper in 2016.

I am just trying to summarize what is interesting to us and how surface and wear debris are related. You are able to see here that there is some sort of groove here, and then the corresponding wear debris that has come out has been shown over here. So, they are trying to establish wear debris and then the microgroove, which has been cut on a surface. A similar kind of thing has also been shown instead of the complete microgroove. We are able to find out some sort of pit formation over here, and then the wear debris has also been shown in this case.

And of course, in this kind of wear, debris has also been shown in this case. So, there is a heat treatment one and a heat treatment two, and the natural question will be which heat treatment is better. And again, I use the word both are operated under dry conditions; it is not a lubricated condition. So, which treatment is really better? So, we need to look at it in a slightly different manner; we need to examine the wear on the worn-out surface, and we need to really analyze the wear debris, and then we are able to find out in both cases that there is a plastic deformation. So, in an absolute sense, even though we have done an accelerated test, if the load is beyond a certain limit, plastic deformation is happening.

So, is it really correct? If there is a possibility, we should reduce the load. However, if we have to just compare the kind of heat treatment procedure, we do not have to really worry about any other mechanism. Then in this situation, we are able to see the micro-cutting; we are able to see the micro-peeling because plastic deformation is also visible; micro-cutting is also visible; and micro-friction fracture is also visible because, when you look at the chip, there are some sort of mark on it, and all three are happening because of abrasion. So, fatigue is also related to abrasion; these are not connected. In both cases, we are able to find some sort of scratch mark; we are also finding deep marks, and we are also finding the white grooves.

So, in both treatments, we observed similar phenomena. However, upon closer examination, we noted variations in particle size. Specifically, specimens from heat treatment one yielded larger or longer debris compared to those from heat treatment two. This discrepancy suggests that heat treatment one may not be as effective as its counterpart, heat treatment two. In fact, when considering the overall comparison, both treatments appear inadequate, indicating the need for alternative heat treatment methods that can offer improved results and longevity. Thus, based on our observation of the lengthier debris associated with heat treatment one, it becomes evident that further evaluation and adjustment are warranted.

So, when comparing it to heat treatment two, an observable phenomenon across all three cases is the occurrence of micro ploughing, micro cutting, and micro fatigue processes. Even upon adjusting the load—whether increased or reduced—these phenomena persist, albeit with varying magnitudes. For instance, under minimal loads, micro cutting may occur, albeit at a very low probability, perhaps around 0.1 percent or even lower, say, 0.05 percent. Similarly, micro fatigue becomes more apparent with increased cycling. Thus, in each case, the multimode fracture mechanism described in the previous slide manifests. The key lies in identifying which characteristic dominates overall and devising corrective or mitigative measures accordingly.

Now, let's delve into another example sourced from a reference published in 2010. In this study, researchers employed a reciprocating wear tester to evaluate behavior under dry conditions—no lubricant was used. They subjected the samples to a sliding distance of approximately 1 kilometer or 1000 meters and compared the results. In one case, they utilized the best material available.

In another scenario, researchers have developed a nanostructured material and are evaluating its performance compared to the conventional material. However, their analysis is centered around debris. What does this mean? In this case, under dry conditions, both adhesive and abrasive wear occur in both materials. Upon closer examination, it's evident that the chip sizes in the conventional material are significantly larger than those in the nanostructured material. Nevertheless, chips are generated in both cases. Now, considering a three-dimensional perspective, can we reattach this debris back onto the surface and assess if everything integrates seamlessly? This approach allows us to gauge the system's longevity more accurately.

This concept is pivotal, often referred to as a digital twin. Can we push the boundaries further and reconstruct the entire structure from debris alone? If achievable, it could revolutionize our approach to service and maintenance, enabling proactive interventions before actual failures occur. Imagine a scenario where we monitor the condition of gear teeth meticulously. Even the slightest debris separation, be it at the nano level, can subtly alter the involute profile, potentially exacerbating pitting failures. Instead of waiting for these failures to manifest, why not take preemptive measures well in advance? This proactive mindset forms the crux of our approach, utilizing digital twins to anticipate and address issues before they escalate.

So, let me explain in my way that we say the wear debris worn out surface and digital twins are three maintenance-related concepts. I am using the word because a degraded surface is a maintenance-related concept; wear debris is a concept related to maintenance; and digital twin, which is a new one recently started, is also a maintenance-related concept. Now wear debris has been explained in detail, and then even the surface that gets roughened and material loss has been detailed and then explained in detail, and then we say that when we see the surface degradation, the remaining useful life of the component will be. We can think about plant maintenance, or maybe we can make some sort of strategy for maintenance purposes, and then we can prevent unanticipated failure in this case. So, we need to establish a relationship between wear debris and surface degradation. As I mentioned, the digital twin is slightly different, and what is the digital twin? Maybe a number of sites will explain it, but what do I think and what is my way of understanding it?

A digital twin essentially functions as a virtual replica of a physical object or system, incorporating data from wear debris sources such as sensors, IoT devices, or simulations. By merging this data with the structure or physical system under consideration, we can create a simulated version of the deteriorating system. This entails modeling the removal of wear debris from surfaces, such as gear surfaces, within the digital replica to understand the evolving dynamics of the physical system.

While some may categorize this approach as a cyber-physical system, I prefer not to delve into the realm of computer-intensive services or cyber-physical systems. Instead, I emphasize the practical utility of digital twins in maintenance operations. They serve as valuable tools for tracking, evaluating, and enhancing performance, offering real-time insights into the condition of physical assets, whether they are gears, bearings, or even costly medical equipment. With a digital twin, we can predict wear patterns and impending failures, enabling proactive maintenance planning well in advance. This proactive approach ensures that systems can operate smoothly for extended periods, with faults promptly diagnosed and corrective actions taken either in situ or according to pre-planned schedules.

In essence, wear debris and signs of surface deterioration serve as visible indicators of system health, akin to traditional fractography analysis. However, in the virtual realm of digital twins, these indicators facilitate real-time monitoring and analysis of the system's condition, providing a comprehensive understanding of its behavior and performance.

So, that is a very new and good concept. I know it is difficult to really rebuild a complete structure from a wear debris point of view, but I am sure that research will be enhanced in this area, and soon we will be able to look at and find out a complete maintenance strategy completely based on a digital twin. So, now let us take a look at the two more examples. We said earlier that two examples we covered would be in the absence of lubricant in a in a dryer case, while in this case we are going to cover it with some sort of lubricant. In this case, what has been mentioned is something like, you know, a case study has been given a kind of hip simulator, and this paper was published in 1996. and What is the kind of dynamic load or fatigue load? In this case, the maximum load was applied around 2450 Newtons, and an overall comparison was made for the 5 million cycles as completely fatigued, and then we say that they use three different kinds of samples: a raw sample, a treated sample, and one that is exposed to radiation. So, three samples were compared, and here the comparison between the two samples has been given, and in this case, you can see that debris generation has been shown.

In the first case, there appears to be a higher quantity of debris observed. However, the authors argue that these particles do not qualify as debris; instead, they describe them as fibrillation, suggesting that they may be necessary to reduce the wear rate. Conversely, in the case of radiation exposure, numerous voids are present on the surface, which is deemed unfavorable, especially for hip simulators. Consequently, it is predicted that the wear rate will be significantly higher in this scenario compared to the other. To investigate this further, the authors conducted a thorough statistical analysis, necessitating a larger number of experiments. Consequently, they utilized a total of 18 cups, all made of ultra-high molecular weight polyethylene. Among these, six cups were left untreated, while six were treated with ethylene oxide (ETO), and the remaining six were exposed to gamma radiation.

Two treatments were administered alongside an untreated control group. The experimenters conducted testing six times to ensure reliable results. To facilitate lubrication, all samples were pre-soaked in bovine serum for six weeks. This ensured adequate saturation of lubricant or bovine serum in the samples. Upon comparison, it was found that the cups subjected to gamma radiation exhibited significantly higher wear rates, with values around 5.3×10^{-6} mm^3/Nm, compared to the untreated cups, which showed wear rates of approximately 1.68×10^{-6} mm^3/Nm. Meanwhile, cups treated with ethylene oxide showed minimal wear, with rates around $1.6 \times 10^{-6} mm^3$/Nm. However, this difference was not considered significant compared to the untreated group.

The study concluded that gamma radiation, known to be detrimental to human health, adversely affects the performance of ultra-high molecular weight polyethylene materials. Under gamma radiation, wear rates increased by threefold, suggesting the unsuitability of such materials for optimal results. Despite observing slightly increased wear debris, the presence of fibrillation was noted to be higher, potentially contributing to effective wear reduction. Overall, attention must be paid to factors such as wear rate, wear debris characteristics (including number and size), and the impact of treatments on material performance.

So, there are more and more dimensions, or maybe more and more parameters related to wear, coming. Now, we will just take one final example. In this lecture, we say we are trying to take another example from one of the references from 1985. What they mentioned about the wear debris generation due to abrasion, and then they compare hard particle versus soft particle, and they use two different kinds of steel, which are again A and B, and then this is in the image that has been shown for material A and this has been shown for material B, and then you can see here that the 120 grit size has been used. In this case, 180 grit size has been used, and we know very well that as the grit size increases in the core, the hardness of the abrasive particle will reduce. So, this B is subjected to more hard for harder particles, and what they are able to find out kind of very long kind of micro cut has been shown in this case while slightly this is a different. So, we can see here that D and E are something like a microcut in this case, while coming to the A and F, AF has been shown as a micropulling, while C and the B and C have shown something like a fragmented, small, or kind of brittle failure, particularly happening, and that is what they interpret. So, if I think slightly differently, we say that even though the materials are different, and even the abrasives for which they have used a different material and different abrasives, they found the characteristics in a in a more or less similar manner. So, what they wrote was something like a similar type of debris obtained. In both cases, whether it is a softer abrasive or a harder abrasive, they have found a similar kind of debris, and then only the number changes and the size changes. What they found is that a softer abrasive produces fewer micro-cuttering chips and smaller pieces of debris compared to the harder abrasives.

So, number is really reducing and then what we say that overall type of the chips are not changing sizes are different if we go for the softer abrasives size is lesser number is lesser number of debris are lesser, but more or less shapes are more or less shapes are same. So, we need to really look at all four: what is the size, what is the shape, what is the composition, and if we are able to find out what the wear constant, or dimensional wear constant, will be, that will give us really good results overall. So, these are important aspects, and then, as I will ask in this case, they say the S-PAL. As I mentioned earlier, we generally find a multimode fracture; it is not only a ductile fracture or brittle fracture; there will be some brittle fracture; there will be some ductile fracture, whose fracture is going to dominate, which has a higher probability that we need to look at from that angle. However, if there is more domination of the brittle face fracture, we actually need to look at the weak sites, the grain size, some sort of inclusion, or the polycrystalline structure to see what the real problem is, and then we need to address those kinds of problems. So, I hope this lecture helps you understand fractography, and I will say thank you for your attention.
Thank you.