Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 09
Fracture surface degradation

Welcome to the 7th lecture of the course on Corrosion, Environmental Degradation, and Surface Engineering. The topic of this lecture is Fracture Surface Degradation. We already highlighted in lecture 1 that we will be covering what a slow fracture is and what a sudden fracture is. Furthermore, slow fracture has two divisions: fatigue and creep. Fatigue is further divided into two categories, depending on whether it is caused by mechanical forces or thermal loads. These topics will be covered in this lecture, and we will try to cover all these topics within one hour.

Now, as we start discussing fracture surface degradation, a question arises: Do we really need to understand fracture, considering we are focusing on surface degradation and fracture is a well-established domain? There are numerous books, mathematical models, and experimental techniques available on this subject. Do we need to cover this in a course on surface degradation? It is important because we are specifically talking about surface degradation related to fracture. What does that mean? When a material fractures, it creates at least two surfaces. What will happen to those surfaces? What kind of deterioration will occur on those surfaces? This is the topic and related phenomena that we need to concentrate on in the present lecture.

When a material fractures, it creates at least two new surfaces, both of which are exposed to the environment. Because of this, there is a chance that the environment will affect those surfaces. Additionally, there may be residual stresses or higher external temperatures. Previously, thermal insulation may have protected those surfaces, preventing temperature increases, but once a fresh surface is exposed due to the fracture, it may be subjected to such variations. This is why we say that newly exposed surfaces of a fractured material may undergo various changes.

We need to identify these changes and understand how they affect failure analysis. If the fractured material surface is degraded by the environment, stresses, or temperature, we might not reach the root cause of the failure. Instead, we could be misled by secondary factors unrelated to the original cause of failure.

Therefore, it is crucial to consider environmental factors. We know that ultraviolet (UV) rays can affect the surface of a freshly made material. For instance, a freshly exposed surface may turn yellow or develop more cracks. Initially, there might have been few cracks, but UV radiation can significantly increase the number of surface cracks.

In this case, the cracks are not due to the fracture itself but to UV exposure. If we do not account for UV radiation exposure, we cannot accurately detect the root cause of failure. We must either prevent UV exposure or create an environment that shields the surface from UV rays.

Moisture is another environmental factor to consider. Humidity can cause freshly exposed material to absorb moisture, potentially leading to swelling and further complications. This can also obscure the root cause of failure, making it difficult to analyze accurately.

Sometimes, we expose a fractured surface for several hours, leading to additional surface degradation, which we call slow fracture surface degradation. Understanding these processes is essential to ensure accurate failure analysis and to prevent misidentifying the root cause of material failure.

There is a possibility of changes in the microstructure if the material is left exposed for some time. Exposure to oxygen or other environmental factors can lead to microstructural changes. Harmful gases reacting with the open surface, virgin surface, or surface exposed by fracture can also cause these changes. In such situations, microstructural changes will occur, potentially weakening the material further. Additionally, as I mentioned about creep, it is possible that even after fracture, the material continues to follow a creep path, leading to different conclusions about the cause of failure, with creep not being identified as the primary cause.

Another possibility is that pre-existing cracks may follow different paths, resulting in more cracks under slow fracture conditions. It is crucial for us to understand these aspects, which is why we emphasize that fracture surface deterioration must be understood and characterized for accurate failure analysis.

For a correct failure analysis, we should consider these points and take appropriate measures. Sometimes, we need to suggest a maintenance strategy, which can only be accurately proposed if we understand the failure correctly. If there is surface degradation, we might not reach the right conclusion.

We will not be able to suggest the right maintenance strategy, and if we do not reach the right conclusion, the durability of the material cannot be enhanced. This is why understanding fracture surface deterioration is crucial. Sometimes we use the term "fractography" to describe the process of examining a fractured surface and identifying the changes that have occurred. This topic will be covered in the present lecture.

Let us start with some common examples. When discussing fractures, we often use technical and scientific terms. In the case of a fracture, there is typically some form of segmentation, separation, or fragmentation.

The surface itself may fracture into several pieces, or a solid body may fracture. Both possibilities exist: the surface may be removed, worn out, or normally worn, resulting in a new surface, or the solid body may fracture, as shown here. In this solid body, if the area of reduction is less than 5%, it is termed a brittle fracture. If there is necking, and the area of reduction is more than 5%, then this type of failure is called ductile failure.

This topic is a common subject in mechanical engineering, and many people have studied it.However, whether the failure is brittle or ductile, we are primarily interested in the surface. Sometimes, we observe brittle and ductile failures happening simultaneously, or a failure that starts as ductile and transitions to brittle. There are numerous cases like this, and we will study these scenarios.

In brittle failure, fracture stress is equivalent to the yield stress. In other cases, fracture stress can be less than the yield stress, or fracture stress can be equal to the ultimate tensile stress. To summarize, brittle material failure or rupture occurs without much deformation, as indicated by the percentage elongation or the area reduction.

In the case of brittle failure, there is no substantial deformation, so we will not get an early indication of brittle failure. For ductile materials, which include most metals and some polymers, plastic deformation occurs before failure. This deformation can be observed as a change in shape or form. Ductile materials bend and show significant plastic deformation before they fail, and failure often occurs when the stress exceeds the yield strength.

The failure mode depends on the type of strain: compressive, tensile, shear, or ultimate tensile strain. The relevant equations will vary based on the specific situation.

Another point to consider is that material defects can lead to different types of failures. For example, in ductile materials, if the load increases suddenly, the material may not have time to undergo the typical percentage reduction in area, resulting in spontaneous failure. This failure might appear brittle, but it is essential to determine whether it is genuinely brittle or a sudden ductile failure. Sometimes, ductile failure can occur spontaneously due to a significant change in load.

For example, if a braking system suddenly applies very high torque, such as a 400% or 500% increase, the system will fail immediately. It will not undergo long plastic deformation before failing.

These are important points to consider. High load and high stress can cause both brittle and ductile failures, or a combination of both. The type of failure depends on the history and the kind of stresses or loads acting on the surface.

Fracture behavior can change based on these factors. Many brittle materials will become ductile at higher temperatures. Conversely, many materials that are ductile at atmospheric temperatures can become brittle if the temperature is reduced.

What is the difference between brittle and ductile fracture? Brittle fracture has a smooth, flat fracture surface with little or no plastic deformation and no significant reduction in dimensions. This type of fracture is spontaneous, resulting in a flat, smooth surface without multiple circles or signs of plastic deformation, such as necking.

Understanding these differences is important. Let's look at different examples to illustrate how brittle and ductile failures can occur even when the material and process are the same. Despite these similarities, the behavior can still change.

We have covered that a fracture can be either brittle or ductile. Both types of fractures generate new surfaces, which we refer to as fractured surfaces. When a material fractures, it typically creates at least two new surfaces, but it can result in many more pieces. A single component or subsystem might fracture into multiple pieces, not just two.

These fractured surfaces can be investigated using fractography, as mentioned earlier.Fractography is important, and there are many books and ASM standards that include chapters on fractography. Fractography is the study of broken or fractured surfaces.

There are two primary methods used in fractography: macroscopic and microscopic. Macroscopic fractography involves visual observation and is guided by specific rules and guidelines. These guidelines help determine whether a failure is brittle, ductile, caused by high stress, high temperature, or creep. This method relies on the physical appearance of the fracture surface.

In some cases, microscopic examination is necessary. This can involve using a microscope with up to 1000x magnification or a Scanning Electron Microscope (SEM) with magnifications up to 10 million times. This approach focuses on metallurgical features, which we will also discuss.

I have shown two pieces here, referred to as shaft 1 (S1) and shaft 2. In one case, we observe a ductile failure, and in the other, a brittle failure. The text indicates that one piece is subjected to maximum shear stress and the other to maximum tension.

Now, why does this change occur even with the same material? For example, if we consider cast iron, I assume it is in some sort of powdered form. This means that in one case, we are using the casting method of manufacturing, and in the other case, we are using powder metallurgy. We can obtain shafts from both processes. If subjected to tensile or torsional loading, we may find that one case results in ductile failure, while the other results in brittle failure.

What causes this difference? How is the manufacturing process controlled? Are there voids present? If there are voids, the fracture behavior may change, possibly shifting from ductile to brittle failure. Additionally, whether the material has been properly sintered after the powder metallurgy process is crucial. If it is not properly sintered, the failure may shift from ductile to brittle.

These factors are important to consider. Assuming that a particular metal or manufacturing process will always result in ductile failure is not necessarily accurate.The type of failure depends on various factors such as the composition, the manufacturing process, and the steps involved. It also depends on the purity of the powder or metal used. This is why we say that predicting fracture is complicated and not straightforward. Thorough knowledge is required to accurately predict failure. It depends on numerous conditions, including the state of the stresses involved.

The shape of the surface also plays a significant role. For example, if a rectangular piece is modified into a more complex shape with very thin sections, what would typically result in a ductile failure might instead lead to a brittle failure.

It also depends on the loading method, the types of loads applied, and the interaction between different loads, all of which affect the fracture. The connection between the material properties and the presence of defects, as described in the context of casting and powder metallurgy, is also crucial. The potential for defects and the type of manufacturing process used play significant roles in determining the final type of fracture, whether it will be ductile or brittle.

Another important factor is the microstructure of the material.

I can convert ductile fracture to brittle fracture by changing the microstructure, or vice versa. These possibilities highlight the importance of understanding microstructural changes. Another critical factor is how the material interacts with its surroundings. A ductile material subjected to corrosive conditions can change from ductile failure to brittle failure. There are numerous examples in literature where ductile failure has turned into brittle failure due to moisture, corrosion, or rust.

We will continue discussing this topic. At the macro level, we can identify the type of failures by observing fracture lines on the new surfaces that emerge from a fracture. By analyzing these fracture lines, we can predict the type of failure that will occur.

So, this is how we are able to see that this kind of V grooves, or within the V lines, are what we are calling the fracture lines. Chevron, so this is what was mentioned about the V-shaped fracture lines. In this case, the V-shaped fracture lines are essentially indicating a high-impact failure, which could be caused by a high velocity or a sudden release of stress at a high magnitude. If this occurs, we can observe a specific type of line on a fractured surface. This line can indicate the possibility of a high-velocity impact failure or a sudden increase in stress levels, which is typically associated with brittle failures. Maybe when we are using ductile material, there will be a brittle failure like this.

There is also the possibility of observing circular lines, known as beach marks. Beach marks are a clear indication of fatigue-related phenomena. In many fatigue failures I have observed, beach marks are the first sign. The presence of beach marks typically signifies a fatigue failure. These marks resemble clamshell patterns or concentric rings, though not necessarily perfectly concentric. You may also see vertical ridges, but in this case, we are discussing circular ridges. This pattern is caused by fatigue and generally indicates a ductile failure.

These kinds of lines provide a good indication of the type of failure: brittle or ductile. For example, impact loading often leads to brittle failure, while repetitive cycle loading tends to result in ductile failure. By observing these lines, we can predict the type of failure the surface has experienced.

Another type of mark is the ratchet mark. Ratchet marks appear as asymmetric lines resembling the teeth of gears. These marks typically occur due to cyclic loading.

We can again say that this may be a type of fatigue loading, possibly indicating a ductile failure. To summarize, fracture lines reveal important details related to fracture mechanics and crack propagation. For example, concentric rings and ratchet marks indicate crack propagation and how the material responds to external forces. By observing these lines, we can gain significant insights.

Understanding the meaning of these lines requires knowledge:
- V-shaped lines indicate a certain type of failure.
- Concentric rings suggest another type.
- Gear teeth-like forms (ratchet marks) indicate yet another.

These observations help us understand what kind of failures the surface has experienced.

We will continue discussing microscopic and macroscopic fractography observations. By examining the fracture lines, we can gain further insights. In the previous example, we saw circular ridges, while here we observe vertical ridges. These elevated ridges indicate fracture and can signify impurities in the material.

When impurities are present, cracks can form. This type of crack formation is not necessarily due to repeated loading but rather due to inclusions or specific microstructural characteristics. Initially, the fracture may start as ductile, but it can eventually lead to brittle failure. This contrasts with the circular ridges seen in fatigue loading, indicating that impurities, inclusions, voids, or gas bubbles are contributing to the failure.

Another well-known example is the shear lip, which is a characteristic of ductile failure. Whenever we see this feature, it is a clear indication of a ductile failure.

Shear lips are curved or wavy lines that indicate shear deformation in a material, which has undergone ductile fracture or plastic deformation. When these shear lip lines are present, it clearly indicates a ductile failure.

Another type of failure is characterized by cleavage marks. Cleavage lines are straight or slightly curved fracture lines, which often suggest the presence of impurities and indicate brittle failure. These lines are favored by crystallographic planes in brittle materials.
In summary:
- Shear lip lines indicate ductile failure.
- Cleavage lines indicate brittle failure.

Finally, the presence of multiple cracks can also be an indication of brittle failure.

When there are many cracks, it is difficult to determine which one started from a ductile failure. Often, when multiple cracks are present, the failure likely began with some sort of ductile failure and then led to brittle failure. This change can occur due to variations in loading, misalignment, or changes in temperature.

For example, if the temperature rises significantly and there is insufficient thermal conductivity, or if a pump or lubricant stops working, these conditions can lead to such failures. This indicates severe problems in the system, not just in one component but across multiple components simultaneously.

Therefore, we must examine all related components to understand the full scope of the failure.
Now, as I mentioned, we covered macro-level fractography in our previous two slides, but we also need to cover micro-level fractography. At the micro level, we need to consider composition, crystal structure, and process history. Understanding whether the manufacturing history was correct or if something went wrong is crucial.

The process will affect whether a failure is brittle or ductile. The type of failure can change based on different conditions such as load, temperature, and the speed at which the load is applied. For instance, under high impact loads, ductile failure can quickly shift to brittle failure. Conversely, if thermal softening occurs, a brittle failure might transition to a ductile failure.

Understanding each case is important for making informed judgments. It is clear that we need a deep understanding and extensive knowledge to make accurate decisions in failure analysis.

If we lack the necessary knowledge and need to draw conclusions, it is essential to consult experts who specialize in this field. We must adopt practical approaches to ensure accurate results.

For example, under low temperature conditions, even ductile materials can undergo brittle failures because the microstructure changes in such situations, causing the material to become brittle. Another important concept is creep deformation. Creep deformation is time-dependent; even under a constant load, the failure will continue to progress. We are not changing the load or any other condition, but the behavior of the material is such that it will continuously increase in strain rate or plastic deformation.

Creep deformation is characterized by the continuous expansion or stretching of material subjected to constant stress or load. The figure illustrates a creep failure. In the case of gear teeth, which are typically subjected to fatigue and pitting and usually fail in a ductile manner, a significant crack indicates a different failure mode. This large crack is more characteristic of a bending failure, which, in my view, suggests a brittle failure.

So, what we mention here is the deep crack in a gear tooth leading to a brittle fracture. This is a brittle failure that likely started because the material was previously subjected to some stress. Suddenly, due to certain conditions, the stress increased more than five times, causing the failure. Initially, the material might have experienced fatigue loading or fatigue failure, which then transitioned to a bending failure due to the sudden increase in load.

Fatigue is a slow-paced crack formation and development process, typically occurring under lower loading and unloading cycles, which can number in the thousands, tens of thousands, or even millions. This process primarily causes micro-cracks to form. It is possible that some micro-cracks formed due to fatigue and merged with some inclusions, discontinuities, or voids. As a result, the remaining area became insufficient to sustain the load, leading to a rapid increase in stress and ultimately causing the complete failure of the gear tooth.

Regarding creep, there may be an initial crack, and even under the same load, if the material is subjected to creep (which often occurs at higher temperatures, typically between 0.3 to 0.7 times the melting temperature), the crack may expand. Creep results from atomic and molecular diffusion, which requires thermal energy typically provided at higher temperatures. Such high temperatures may result from high friction, inadequate lubrication, or insufficient cooling. These conditions can lead to an increase in temperature and subsequently cause failure.

So, it is mentioned that atoms and molecules diffuse from one surface to another, causing the material to gradually degrade, deform, and eventually fracture. In fractography, this involves both macroscopic and microscopic observations, indicating that fatigue can lead to a final bending failure.

In this case, initially, a small microscopic crack may have formed. Then, perhaps the temperature increased or was already high. Initially, the failure took longer, with the first crack formation occurring slowly, eventually leading to complete failure. These are the types of failures we need to observe, examining the freshly made surfaces after a fracture to determine the type of failure and its root cause.

Sometimes we use the terms granular or transgranular to describe the lines or crack paths. For example, in this case, three lines are shown: one where the crack initiated and followed the grain boundaries.

So, it is an intergranular failure when a crack starts at some grain boundary and expands across all the grains or boundaries, causing the material to fail. If the failure happens in this manner, it is termed intergranular.
Then, there is granular failure, which can occur across the grains. This can take two forms: crystalline or non-crystalline. In non-crystalline materials, the crack will not follow a specific path and will go through different grains without following any crystalline lines. However, in crystalline materials, the crack will go through the crystalline planes and follow a systematic pattern.

These cracks can also cause failures. In the cases we have observed, all three involved brittle material failures. While this type of failure can also occur in ductile materials, it is more common in brittle materials because their grain boundaries are weaker. If the grain boundaries are weaker, intergranular failure will occur.

Additionally, even in materials with grain boundaries, a crack can expand. For example, a crack may start here, but there was some sort of inclusion present, which could change the failure mode.

So, it can change path. It will not go through the grain boundaries but through the transgranular regions. It can be non-crystalline or crystalline. This is mentioned here: polycrystalline material fractures are classified based on the direction they take through the microstructure.

In microstructure observation, we divide fractures into two forms: IG (intergranular) and TG (transgranular). IG stands for intergranular fracture, where the fracture moves along the grain boundaries. TG stands for transgranular fracture, where the fracture penetrates through the grains. In transgranular fractures, the crack goes inside the grain. In crystalline materials, it follows the crystalline planes, while in non-crystalline materials, it does not follow these planes.

In the case of IG, the crack propagates along the grain boundaries, typically in materials with weak grain boundaries. Most of the time, brittle materials are subjected to this type of failure.

Now, even ductile materials subjected to corrosion or some form of embrittlement can experience this kind of failure. So, even ductile materials can undergo intergranular (IG) failure due to corrosion or some induced weakness in the material.

For transgranular (TG) failure, the crack propagation generally occurs through the grains. There are two types of TG failures:

1. Crystalline TG Failure: In this case, the crack propagates along well-defined crystalline planes within the grain. The fracture follows the crystal structure and crystallographic planes in highly crystalline materials. The fracture surfaces show cleavage, as observed in a previous slide. This type of failure generally occurs in brittle materials.

2. Non-crystalline TG Failure: This type does not follow any specific rules. The crack goes through the grains without following crystalline planes. This leads to abrupt failure due to impurities, voids, inclusions, or foreign materials in the microstructure.

This analysis helps in understanding the failure mechanisms and obtaining accurate results. I will now cover a few brittle fractures in the next two slides. In my last slide, I mentioned cleavage fractures. Here, the grains and their planes are shown. Additionally, this slide depicts an impact fracture due to a sudden high load, resulting in a large crater.

This is one of the brittle failures put with the cleavage-based or impact-fracture-based. Now, coming to the granular-based, in this case, intergranular, they are passing through all the grain boundaries. While in this case these are the transgranular sites, it is not really passing the grain boundary as such; it will be going through the grains, and more or less all these kinds of failures are brittle failures. Coming to ductile failure, we have seen well-known examples, like that neck formation, and we use a cup and cone shape. This is a failure. Shear lip is another term used to describe a type of failure that occurs during ductile failure.

While here we are showing that there is a void, not at this kind of necking formation, but there is some sort of crack formation or that there was a void that is really creating or initiating the cracks, and slowly the growth occurs. And this microstructure shows very clearly that there are a number of voids in the microstructure itself that are causing the failure or which will be enhanced to the bigger crack, and finally, the fatigue failure. Now this slide shows the combined, in this case we are able to see the cleavage fracture, we are able to see the micro voids, and then we are also able to see the intergranular crack formation. So, this is the intergranular crack formation we are able to see here. This is the cleavage fracture, and there is a void. This is happening when the load pattern changes, the temperature pattern changes, or because of the corrosion environment on the on the surface. If the crack was exposed to the environment, then suddenly the increase of water happens through the surface and goes on to enhance the failure rates inside the material itself.

So, what we can say is that the fracture is initiated by microvoids. So, in this case, particularly, the failure started only in a ductile manner; there were microvoids, and then it was expanded, or because there were some other inclusions, it could go through the intergranular failure as well. And then there is a possibility that there is some sort of structural discontinuity. Sometimes we design in a manner that we want to show very good ethical features, but sometimes that gives us some sort of discontinuity and causes a failure as well**.** So, if we want to really keep a very good feature showcased, we need to keep the stress level slightly lower than the tensile strength, or, may be, failure strength. If we don't do this, microvoids will form, leading to a discontinuity and potentially a faster rate of failure. So, there is some life that we were assuming may be say 10,000 hours; it may fail in may be say less than 2000 hours also.

Now, with the increase in load plastic deformation, these microvoids will be elongated continuously, and the remaining area will not be sufficient to sustain the load. So, that is why**,** as I say, in areas of high stress concentration**,** cleavage will occur**,** cleavage fracture will occur, and it will start a failure of the surface. So, we have covered ductile failure. We have covered the fractography, and we have covered the combination of ductile and brittle failures. Now there is a need to worry when the surface has come out; it may be that the surface of the material has a fracture, and then we are able to see the new surface. This is what we are showing: the original fractured surface is not exposed to the environment, and in this environment, we are able to see that immediately some sort of chloride formation happens on the surface that does not take much time.

And then this surface was exposed to the **very,** very mild HCL environment, and the HCL percentage was only 0.025%, which is negligible and insufficient for the failure. But we have seen the chloride formation happening on the surface, if I had to analyse this surface, I would come to some conclusions. In this case, if I analyse this surface, I will conclude something else. I will find out that maybe there is a chloride formation inside the surface; the chlorine has ingressed inside, and that has caused a failure. But this was not the right case right after the fracture of the surface, or fracture of the material surface, got exposure to this HCL, or, may be**,** aqueous HCL, and that is why it has changed to this form.

So, we need to really worry about the first, which is the fracture, and then, after the fracture, what surface comes out and whether the surface is handled properly or not. Because to get a microstructure to go ahead with the SEM, TEM, or some other analysis, we required equipment, and then we needed to take pieces to that lab. It will take maybe 10 hours, 15 hours, or maybe sometimes we get a slot after 7 days also. As a result, we must take appropriate care. So, what should we do, and what should we not do? So, I am just going to show only that you should not do. Aspects: try to avoid what are the things to be avoided. We should not rejoin the fracture surfaces.

Many times, when we attempt to reconnect fractured pieces, it may lead to additional failures or even alter the root cause of the failure. Therefore, it is advisable not to reconnect pieces or mark the crack surface. Writing numbers or labels on the fractured surfaces, as I've done here with "1, 2, 3, 4," should be avoided in real examples.

Furthermore, we should refrain from removing any pieces, even tiny ones, as doing so could obscure crucial evidence of the root cause failure. Similarly, using harsh equipment or sharp edges to clear debris from the broken surface is ill-advised.

Additionally, we should avoid touching fractured surfaces with bare hands, as the moisture and particles on our fingers may introduce further failure or alter the evidence of the original failure.

We should avoid cleaning it with acid or corrosive edges. So I am mentioning all: do not do rejoining, do not do marking, do not remove any piece, do not use harsh equipment, do not touch crack surfaces, do not clean the surface with acid or corrosion, do not utilise fabric, fibre, or mud paper, because these things will leave some sort of strain or maybe some sort of along with the sample or with the fractured surface, which will lead to a conclusion about something else. We should not do that, and finally, we should not mask. We should also not apply some sort of glue. So that you know and the PPCs remain intact, that will give a somewhat different result. So, if you want a true failure analysis, do not do this; that is more important. Now, sometimes we try to do a modelling. I am not going to cover the modelling; I am just trying to show only one slide and that people have another slide that, if you have interest, you can go through.

We often discuss fracture models in terms of two primary models. However, many people think of fractures occurring in three stages: nucleation, propagation, and final failure. We have already covered nucleation in some detail when discussing fatigue failure.

Propagation occurs even in the case of brittle failure, albeit at a much faster pace. Finally, there is the failure stage. So, we consider three stages: initially, there is no crack; then nucleation occurs, where a crack starts; and then propagation, where the number of cracks increases. This leads to either neck formation, as mentioned here, or complete failure.

These three stages are widely covered, and there are entire books and many mathematical formulas available on the subject. This slide provides a brief overview of this information.

We say the crack nucleation often there is a some sort of void as I mentioned earlier, it void may have occurred because of some sort of manufacturing defect also, or maybe because of the high stress or maybe some sort of inclusion that the many times we develop the product it does not have 100% purity, there will be some sort of inclusions or maybe some sort of other imperfection in making a microstructure, or when we are doing a hydrating process on the surface some sort of imperfection remains here. And if these are the there are voids there are some inclusions, or there are microstructured imperfections it will trigger the process of the crack nucleation. So if these are the things, maybe in some cases the crack was supposed to initiate after 10,000 cycles, and because of this void formation, inclusions or microstructure imperfection may start after 10 cycles. So naturally, life has come down significantly. So once the crack is started, we say that it is quite possible that the that the stress concentration at the defective regions will surpass the material strength.

What does that mean? When a crack is formed, critical zones with stress concentration will develop. The multiplication factor might be 1.5, 2, or 2.5, depending on the size of the defect and its proximity to the load or maximum load. This increased stress concentration will cause the expansion of the micro crack to a reasonable size. Often, micro cracks smaller than a nanometer are not counted as significant discontinuities. However, when these discontinuities reach a detectable dimension, they are considered micro cracks.

I mentioned void inclusions or microstructural imperfections. These imperfections, when smaller than micro cracks, can increase in size due to stress concentration, eventually becoming measurable micro cracks. These cracks have significance from a failure and fracture point of view.

Next is crack propagation. Once a micro crack is generated, it will naturally progress. This progression is shown here: the crack will propagate or increase in size and stress concentration near the crack will always be present, potentially increasing. As the crack propagates, the area preventing failure continuously decreases. Fracture can proceed slowly or jump across depending on the conditions. If load conditions remain stable, fracture will proceed slowly. However, if load conditions change significantly, such as a change in temperature or the introduction of water or acid, crack propagation can increase significantly.

Thus, depending on the characteristics and stress circumstances, cracks will usually extend slowly but can sometimes progress spontaneously.

If it is spontaneous, it is going through a brittle failure. If it is slow, then we can say it is a kind of ductile failure. The last one is a failure, as this is a material mentioned over here that breaks when the crack reaches a certain length. Now, it is very critical to understand what a certain length is. Here we say that the material remaining in the in the cross section or cross-sectional area is not sufficient to support the applied load. So, this is important because it will vary from design to design, from material to material, or from shape to shape.

So, it will not be the same. So, this is important to be considered, and what we say the material loses is load-bearing capacity, and it may suddenly or gradually again depend on brittle failure or ductile failure, causing fracture parts to separate and reduce load-bearing capacity significantly. So, this is what can be modelled; there are a number of mathematical models available. We can also generate some sort of empirical rule, but we are just providing some sort of understanding in the present lecture. Now some common examples are there, and I am just trying to highlight them. We say that in this case, particularly, we are shown some sort of failure of the complete tooth on the gear tooth, which has been fractured and is not visible.

It will naturally cause additional failure to other components, but in this case, the tooth has been removed. We can say it is a sudden or abrupt failure because the removal of a gear tooth is a significant failure. It may have started as a ductile failure but transitioned to a brittle failure due to being subjected to a very heavy load.

The material, which was expected to fail plastically or nearly so, failed drastically with less deformation and fewer warning signs. This could have been due to a lack of maintenance strategy. Failure occurred even when there should have been substantial plastic deformation. In such cases, a jamming action would occur, preventing the loss of the gear tooth.

So, in this case, it is essentially a brittle failure that may have started as a ductile failure. Then, the load changed significantly, leading to a brittle failure. Now, what we are showing is a fatigue failure, which is a kind of gradual, ductile failure. However, in this case, the fatigue crack is a delayed, slow process caused by exposure to variable loading.

Fatigue failure generally occurs at lower loads, often experiencing reversible loads much less than the ultimate tensile load. Sometimes, if conditions are not controlled, it can suddenly lead to failure. These points illustrate that while fatigue failure is typically a slow, ductile process, it can ultimately result in brittle failure under certain conditions.

In ductile failure, another important point is that the formation of pits can indicate the progression of damage. The process may start with one pit, then another, and so on. This gradual progression takes a long time, and we can monitor it by noticing increased vibration. When the vibration becomes very high, it’s a sign to stop and change the gear.

As such, this type of failure is manageable, and there are good theories to guide us. However, if the number of pits increases beyond a certain point, the vibration levels will rise significantly. Even if the gear hasn’t cracked or fractured, it may still lose its utility and should be replaced.
In this case, the gear hasn’t failed in the sense of breaking or fracturing, but the surface has deteriorated to the extent that replacement is necessary.

The last type of failure we’ll discuss is creep, which is a slow, time-dependent deformation process. Creep refers to the continual expansion or stretching of a crack, if present. As shown here, the bar subjected to load has expanded by some dimension, and this expansion will continue, potentially leading to neck formation and ultimately failure. Creep typically occurs at temperatures ranging from 0.3 to 0.7 times the melting point of the material. For instance, if the melting point is 1000 degrees Celsius, creep may begin around 300 degrees Celsius or higher.

When a material is exposed to such temperatures, the possibility of creep failure increases, and this must be considered. Creep involves the diffusion of atoms and molecules, similar to the diffusion mechanisms discussed earlier, but in this case, the diffusion occurs within the same material, from one cross-section to another.

As planes within the material weaken, expansion and stretching occur, leading to failure. These are three key points: sudden failure, slow processes, and temperature effects, all emphasizing the importance of considering fracture and surface degradation from various perspectives.

To conclude, let’s cover a case study from literature published in 2023, illustrating the significant role of temperature in changing failure characteristics. This case study involves the fracture of a brazed diamond abrasive grinding wheel. A company manufactured the grinding wheel using a brazing process, utilizing a nickel-chromium-phosphorus-silica active alloy powder as the interface between synthetic diamond and a steel substrate.

To analyze such a wheel, we need to study the complete process. The filler alloy, synthetic diamond grit, and other materials were used to create the wheel, which is referred to as a diamond wheel for cutting purposes. The cutting face was made using a laser welding process between the steel surface and the brazed surface. The wheel's diameter is approximately 355 mm.

The filler alloy and synthetic diamond grit were cleaned using ultrasonic cleaning with acetone and ethanol. This cleaning process is common in manufacturing. The cutting tool, or brazing diamond cutting saw, was made by following the diamond brazing process and kept in a vacuum furnace. The brazing temperature was around 1026 degrees Celsius, maintained for 15 minutes.

The authors followed the suggested process meticulously, ensuring that the temperature increase did not exceed a certain rate. They increased the temperature at 10 degrees per minute (10°C/min) and subsequently followed the cooling process under a high vacuum furnace. They maintained all conditions to prevent environmental interaction and achieve perfect brazing. After brazing, the blade was ready, but it needed to be welded to the main beam, which consisted of a steel matrix, to serve as a cutting tool. They used a laser welding process for this purpose.

The cutting tool, or diamond wheel, was then subjected to scanning electron microscopy (SEM) for fractography analysis. The SEM scans revealed that everything was in order: the diamond grains were fine, the grain edges were intact, and the binding with the filler material was perfect. The embedding of the diamond into the alloy or filler material was also flawless, indicating successful manufacturing and preparation of the diamond wheel.

The images revealed that both the cutting edges and the surface integrity of the diamond abrasives were in excellent condition, free from any visible cracks or holes. Even under SEM, everything appeared perfect. The boundary of the diamond grit was fully embedded within the active filler layer, indicating perfect adhesion between the diamond and the filler alloy. With everything in proper shape, they were ready to conduct trials.

The trials involved cutting cast iron pipes with a thickness of 18 mm. They used a water cutting machine for this purpose. The test aimed to assess the performance of the diamond wheel in cutting the cast iron pipes. One important aspect of the test was that they did not use any cooling agents or lubricants, as these are costly, and their exclusion aligns with sustainability goals. Avoiding peripheral substances like lubricants and cutting fluids is advantageous if it can be done without compromising performance.

So, from a from a sustainability point of view, the drawing action should be able to really give good results, but we need to check technically whether it is possible or not, and in this case, I mentioned that an iron pipe with a wall thickness of 18 mm was employed for the experiments. This is the complete process that has been recorded and shown. However, they found that finally, after cutting some section of the pipe, there were some sort of visible cracks on the diamond, and then the diamond was showing some sort of crack or some sort of marking on the in some sort of marking or cleavage planes, which indicates very clearly that brittle failure has occurred. That means, the cutting tool that we have made, we assume the diamond will be able to see it, and then the very high temperature sustained in the absence of the lubricant has not reached that level. That means, even the diamond that is really subjected to a high temperature may be to the to the tune of 1000 degrees, which was supposed to be because diamond can sustain this kind of temperature, but it has not really sustained, the reason being that may be the 18 mm thickness is too high, for this kind of heat rate of heat generation was very high and it has softened it, and may be the SP3 bond, which we see in a diamond, got converted to a SP2 bond.

That means the softening has happened temperature has changed, on the structure has changed from SP3 to SP2, and then that is why we find abrasive particles breaking in pieces, fractured in pieces, or initially, there was a thought that these pieces would come out of the alloy filler alloy, but that does not happen; it remains as it is in pieces, but the diamond itself has changed from SP3 to SP2 bonds. And then that is why we say that figure 3a shows a diamond abrasive particle fracture profile. This has been shown as a fracture profile, and then when you do an analysis of the microstructure, they find that the SP2 bond is there.

When they examined the enlarged view, they could identify the brittle failure of the diamond. Overall, this experiment failed, indicating that more research is needed. They need to determine whether lubricants are necessary, if a laser with a different thickness should be used, or if productivity should be sacrificed to some extent by reducing laser speed and allowing more time for cutting. These are the kinds of experiments that may follow, as this publication came out in 2023. I hope they continue this line of research.

Thank you for attending this lecture. In my next lecture, which is Lecture 8, we will discuss surface degradation mechanisms due to heat and radiation. Today, we covered some aspects related to heat. Thank you.