Corrosion, Environmental Degradation and Surface Engineering
Prof. Harish Hirani
Department of Mechanical Engineering
Indian Institute of Technology, Delhi

Lecture – 14
Synergistically combined degradation mechanism

Hello and welcome to the eleventh lecture of the course on corrosion, environmental degradation, and surface engineering. The topic of this lecture is synergistically combined degradation mechanisms. In other words, something like a surface degradation mechanism due to the combination of more than one failure action. The first question arises: why are we thinking about the synergy between two failure mechanisms? Is there really a synergy? As far as my knowledge is concerned, there is a lot of synergy between these kinds of failure mechanisms, and the overall degradation rate and damage progression are strongly impacted by the interaction of surface degradation mechanisms such as mechanical action, chemical action, and heat or radiation action. Mechanical activities such as rubbing or abrasion disrupt the physical barrier. Which is a kind of layer protection leaving material vulnerable to chemicals. Degradation is more likely to occur on newly exposed metal surfaces.

Mechanical actions, particularly fast rubbing or sliding, can produce a lot of frictional heat, which can lead to the thermal degradation of the surface. Increased temperature can cause thermal degradation processes like thermal cracking, which result in the deterioration of the surfaces. Alleviated temperatures can facilitate chemical reactions, speed up diffusion of the reactive species, accelerate chemical reactions, and encourage a more powerful or forceful chemical breakdown of material. Ionizing, or, as we say, ionizing radiation, can start or catalyze chemical processes and materials.

Reactive species that can further deteriorate the material through chemical reactions can arise as a result of radiation induced reactions. So, there is a very intermingle kind of synergy, one cause causes another cause, another cause causes a third action, a fourth action, or something like that, and there is a need to figure out which is the fundamental reason behind that, because what we really require is root cause failure. So, appropriate treatment can be given to the surfaces. So, for that purpose, we can think about the synergy among degradation mechanisms, as we have shown with three bubbles. There is a mechanical action, one ellipse, then a chemical action, another ellipse, and heat or radiation actions.

Now, there is a possibility that all three can work together, and there is what we call a synergetic action between these mechanisms. For that purpose, we need to analyze what the material properties are and what the operating parameters are. Operating parameters, as we already studied something like a temperature, ambient temperature, high temperature, or maybe the radiation temperature also increases. The mechanical loading, tensile loading, and fatigue loading that are important in an in an environment may be a dusty environment, a cloudy environment, or water contents. Very possibly, radiation intensity also plays a major role. If the radiation intensity is almost negligible, we may discard that, but many times the radiation intensity is significant and we need to count it.

And all of a sudden, it is more important what a contact condition is. There is some sort of stationary, static, or moving condition, and moving again is a rolling or sliding condition. Now, coming to the material property, what is the composition? Many times we change the composition of an alloy, and it may increase the strain but deteriorate from a fracture point of view. What is a microstructure? We have already studied something on microstructure. Microstructure changes significantly, and one of the major features that comes along with microstructure is surface roughness. Another point comes to mechanical properties; it can be the strain, it can be toughness, or we can say one of the surface properties, something like hardness. Thermal properties play another important role.

When we combine these properties and operating parameters, we can create a synergy that helps us understand the degradation mechanisms. Therefore, it is crucial to thoroughly understand the operating conditions, material properties, and our design requirements. If we want to operate something under high temperature, high radiation, high speed, and high load conditions, the design will naturally need to adapt to these factors. Understanding these elements—operating conditions, material properties, and design requirements—is essential to achieve optimal performance and lifespan. In other words, to prevent surface degradation, it is critical to review material composition, microstructure, and mechanical and thermal properties.

The chemical attacks we experienced in the previous lecture may overwhelm material compositions designed to withstand mechanical wear. Surface deterioration is influenced by particle size, grain boundaries, and phase distribution. Fine grain material may be more resistant to mechanical wear, but too many grain boundaries may cause corrosion or rupture. This is what we have mentioned last time: IGC will play a more important role in many materials that become very hard, which become very wear-resistant, but may fail because of rupture. As a result, it will also provide a site for corrosion. So, we can say high hardness is desired to prevent plastic deformation and abrasive wear, but it may increase the likelihood of erosion and brittle fracture.

We studied also something like erosion, and we say the angle of attack depends, and then it will affect the material property quite possibly if there is a hard material and the angle of attack is 90 degrees. We require more and more energy absorption, and then hard material will not be able to show, and there will be a failure because, we can say, the brittle fracture. Often, high hardness is required to avoid surface degradation. However, higher hardness is obtained through alloying or heat treatment. This is what we have already studied: that with more and more alloys, there are more and more possibilities of grain boundaries, and that may give some sort of weak point for the corrosion in the fracture as well.

So, thus, we can say that it may trigger numerous cracks that lead to the corrosion fracture. To effectively handle shock and impact loads, high toughness is essential, but high toughness will not come without sacrificing hardness. So, we need to decide which kind of hardness or toughness is going to give us the best result, and which combination is going to give the best results. We need to understand that. To dissipate heat efficiently and eliminate a localized hot spot that could cause wear, corrosion, or fracture, the material must have a good thermal conductivity. So, it is important that whatever material you use has a very good thermal conductivity, but sometimes we also require thermal insulation.

We need to clearly understand our intent and the situation. When applying a coating or adding a layer to a surface, we must consider the thermal expansion of the contacting materials. If there is a significant difference in thermal expansion, we need to change the material or implement some intermediate procedure. This consideration is crucial. Additionally, applying compressive force to bind a surface can lead to tension, potentially causing fractures or other types of loading. These factors must be properly accounted for to ensure the integrity of the surface.
Overall, thermal insulation, thermal conductivity, and thermal expansions are all important factors to consider. We need to think comprehensively about all degradation mechanisms and evaluate whether one mechanism will impact another. Therefore, we propose a framework to consider the combined effects.

In this framework, as mentioned previously, we need to account for mechanical strength. Surface hardness, although not a mechanical property, should be included as a surface property. Fatigue resistance is also crucial. Additionally, chemical properties such as solubility and wettability must be considered.

Thermal conductivity and expansion are crucial, and melting is particularly significant because it leads to severe wear. When the operating temperature approaches the melting temperature, ranging from 0.3 to 0.7 times the melting temperature, creep becomes a major factor. At higher temperatures or near the melting point, many degradation phenomena are eliminated.

In contact situations, microcyclic loading and motion, such as fretting corrosion with amplitudes around one to two microns, must be considered even though this motion is almost negligible. We need to account for cyclic loading, sliding, and rolling.

Our framework must include all these factors. Regarding loading, although we often refer to static loading, in reality, all loading is dynamic with inherent variations. Impact loading, whether from significant dynamic or cyclic forces, is especially important for erosion, as particles impacting a surface—whether solid or fluid—play a major role.

Service environmental conditions also need consideration. Humidity acts as a corrosive medium for most materials, and under pressure, cracks may expand or open up. Additionally, temperature variations can cause expansion, potentially accelerating failure at high temperatures.

When we think about an acidic condition with a pH value less than 7, sometimes it is a 4, 5 which is happening in most of the liquid cases. It is also important to account for this. Another one is if there are contaminants. Contaminants may be many, many, even the gases; gases may also be SO_2, and they may also be some sort of nitric oxide. So, that will play an important role overall, even if something is nothing. CO_2 itself plays an important role as a contaminants. Now, oxygen is sometimes very useful and sometimes very harmful. So, we need to account for those things.

Combining all these factors, we can identify a comprehensive failure mechanism. This mechanism will encompass a complete course of failure scenarios.

We'll cover a few examples to illustrate this. For instance, combining mechanical and chemical factors results in wear corrosion, which can be subdivided into abrasive wear, fatigue wear, and fatigue corrosion, among others.
Combining mechanical stress with heat leads to phenomena like creep failure and thermal fatigue. When we combine heat and chemical effects, we encounter oxidation, ionization, and hydrogen embrittlement, a common issue in marine environments due to hydrogen ingress. We'll include a case study on hydrogen embrittlement.

Combining mechanical, chemical, and thermal factors results in stress corrosion cracking, which involves mechanical stress (typically tensile), chemical corrosion, and potential cracking due to temperature or radiation.
To provide a comprehensive understanding, we'll cover several examples. In summary, a complete framework for synergistic failure and degradation can be developed by considering the interactions between material properties, contact conditions, and service conditions.

Surface roughness is a variable; as we have already mentioned, most of the time we can design surfaces. So, the surface roughness variable, which impacts wear and contact mechanics, plays an important role, and it becomes very essential, and we will deal with it in greater depth when we cover the topic of surface engineering. Service ambience includes, as you know, pollutants, gas, corrosive substances, pressure, and vibration. Your vibration also accounts because it is going to impart some sort of dynamic loading, one way or another, and maybe the radiation intensity, like in a UV, is very common, and most of the time that the materials are exposed to the sun and then actually deterioration or decoloration will be there, which will impact the overall failure analysis as well.

So, it must be considered. Combining many failure actions can have a synergistic effect where the presence of one failure action amplifies the effects of others and has an effect on degradation. Now, it will be interesting to see the combined effect and how they really act together. So, we will consider one of the cases and provide some sort of mathematical formula at the elementary level to aid understanding. Another one is that the big cracks, which are caused by mechanical stress, may provide some sort of site for the corrosion. We know very well that pitting corrosion becomes a very big issue, and then if there is a crack already available and the crack has happened because of the mechanical stresses.

And radiation induced or enhanced wear, stress-assisted corrosion, and thermal corrosion are important to consider. As a result of the interaction between the several failure mechanisms in the degradation process, one action may accelerate another, and that is what we want to understand. So, let us start with the verse first. We are talking about something like corrosive wear, and sometimes people can say corrosion wear. We are using the word corrosive wear. What has been shown in this case, particularly that I have shown some sort of two figures? Figure 1: In this case, you can see there is some sort of relative motion, there is corrosive media, there is some sort of oxide, and there is a metal.

Metals such as iron or steel are active materials. The oxide layer formed on these metals generally acts as a passive, protective film. In this context, we are considering sulphuric acid as the corrosive medium, which is known to be highly harmful.

Interestingly, higher concentrations of sulphuric acid do not cause as much corrosion as weaker concentrations. This occurs because strong sulphuric acid does not readily dissociate into anionic radicals and hydronium ions, so it does not act as aggressively. Conversely, weak sulphuric acid, which contains water, can dissociate and form ions, leading to more significant corrosion.

It is important to understand that sometimes weaker acids can be more damaging than strong acids, contrary to what one might expect. This example highlights this counterintuitive phenomenon.

What exactly is occurring in this particular case? We are stating that the sliding motion, coupled with the mechanical motion, is causing some sort of distortion or rupture in the oxide film. If the oxide film ruptures, a bottom surface that has not been coated will be exposed. If it comes into contact with oxides naturally, the presence of acid may trigger an immediate reaction on the surface, resulting in the formation of a new oxide layer. Mechanical action will remove it once more, but self-corrosion media will re-form it. So, removal and formation will be a continuous process.

Eventually, the metal will become useless, or perhaps we should discard it as it has reached a critical point where it can no longer survive and provide strength. The first figure illustrates this scenario. Now, let's move on to Figure 2, where the term "wear-assisted corrosion" is used. So, whether wear is assisting corrosion depends on what kind of railing mechanism is happening. So, what we say in this case we are comparing with a passive.

What we illustrated in the earlier diagram is a passive layer. In this scenario, wear is not occurring, only corrosion. This allows us to observe the passive layer or passive curve, where corrosion is unaffected by wear.

However, if corrosion is affected by wear, fragments of the layer will form and then rupture repeatedly. Over time, a layer will form, rupture, form again, and rupture once more, in a continuous cycle.

We need to further examine this process.The material was already present, possibly even in this location. Now I have to bring this material over here, and then next time I have to bring it on top of this. Therefore, we are observing a cumulative effect that determines the depth of wear. Similarly, as the depth of wear increases, the thickness of the material decreases, and beyond a certain critical thickness, it loses its usefulness. Therefore, we must consider replacing the material. So, what we see here is wear-assisted corrosion compared to passive or oxidized surfaces.

The new surfaces exposed by the wear are much more reactive and susceptible to corrosion, and that is what has been shown with this red color curve over here. We can build, and then the wear depth is continuously increasing.

So, if I say this is cycle 1, this is cycle 2, cycle 3. In cycle 3 itself, the wear rate has gone almost to the to the overall material that has been lost almost three times.

Therefore, it is significantly high. Now we can think about 3 mechanisms, or we say there is an abrasion wear mechanism, which is abrasive wear, or maybe this wear is erosion wear, or it can be fretting wear, and corrosion is common. Therefore, we have already studied a combination of these mechanisms: abrasive wear, erosion wear, fretting wear, and corrosion wear. If I want to elaborate, how do I do it? Sliding wear causes the mechanical removal or destruction of passive oxide films. Exposing fresh metal surfaces: these exposed surfaces corrode more quickly in corrosive environments because they lack protective coatings. Because the exposed surface is much more reactive compared to the protected coatings or may be a protective surface.

Abrasion-induced wear enhances the corrosion rate. Abrasive wear removes the oxide layer by exposing new metal surfaces through asperity or hard particles. This can occur as 2D, two-body abrasion, or 3D, three-body abrasion, making the surface more susceptible to corrosion. The corrosive environment then accelerates corrosion at these worn points.

Mechanical erosion, caused by the impact of fluid flow or solid particles, also removes the passive layer or protective coating from the surface, exposing the newly formed metal surface to corrosive media.

Therefore, the abrasion remains unchanged, while the mechanical action measures the erosion, which in turn eliminates the protective layer. Corrosion follows the same pattern; both abrasion and erosion have the ability to remove it. Therefore, the mechanisms involved are essentially the same as those we have previously studied. The development of fretting occurs when the two surfaces vibrate at a small amplitude in response to an applied force. So, it is an almost negligible amplitude, but again and again, that layer is also the fretting sliding there, or, may be, motion is removing the particle layer as such.

Even though there is increased force on the periphery, the particles are not being removed. This situation results in the protective layer being stripped away, allowing oxygen or corrosive media to interact with the fresh surface. A new coating forms, and the removed particles can contribute to further abrasion. Thus, fretting leads to both corrosion and abrasion.

These three mechanisms work together, and when the connection or joint is opened, a lot of debris is often found, indicating significant material degradation. This is the harmful outcome we wanted to highlight.

Now, let’s examine a case study from a paper published in 2020 that investigates erosion-corrosion of steel. We will use a simulated setup similar to what we discussed in a previous lecture, focusing on a three-electrode configuration. In this setup, the sample acts as the working electrode, and we also use a counter electrode and a reference electrode.

The setup involves erosion flow-assisted accelerated corrosion. Corrosion is studied separately, and then particles are added, and the flow rate is increased to observe particle impact on the sample. This allows for studying both erosion and corrosion together and separately.

A 100-electrode wire beam electrode setup is used, where each cell is analyzed individually. In the first condition, the sample is rotated at 1000 rpm in a 0.5% sodium chloride solution. In the second condition, the speed is increased from 1000 to 2000 rpm. In the third condition, erosion is introduced along with corrosion, with the propeller rotating at 2000 rpm. Each cell's wear rate is measured by analyzing the increase in current for corrosive wear and the material loss for mechanical wear.

This combined study of erosion and flow-accelerated corrosion uses a spinning cylinder as the test specimen (working electrode) with adjustable rotational speeds of 1000 and 2000 rpm. The experiment is performed for 20 hours, and the results are analyzed using a 3D profilometer to obtain detailed micrographs and profilographs.

Now, a significant aspect to consider is the total wear, denoted as T. Abrasion wear can be represented as W_a, while corrosion-induced wear can be denoted as W_c. However, when these mechanisms act together, there is a synergistic effect, represented as W_s, hence the term "synergetic effect". So, the total wear encompasses abrasion wear, corrosion wear, and synergistic wear. Evaluating the effectiveness of this synergy can be quantified by the ratio W_s/T.

If this ratio is notably high, such as 0.5, 0.6, 0.7, or 0.8, it indicates a significant synergy, where one mechanism may accelerate the failure of the other, or vice versa. This enhances the overall effect, leading to increased failure. We can conduct experiments to gain a deeper understanding of these dynamics. Alternatively, taking a slightly different approach, the method described in the preceding slide aims to examine the interaction between localized erosion and localized corrosion. Monitoring the potential and galvanic current distributions captures the dynamic fluctuation of anodic and cathodic sites, providing insights into the wear rate.

Localized metal loss caused by corrosion can be determined by examining the anodic current and the changing current of each individual electrode. This is achieved using a 100-electrode setup with a distributed potential meter and galvanic current measurement. Additionally, wear loss can be calculated using data from the 3D profilometer scans. By analyzing the 3D profilometer scan images, we can measure dimensions and use established formulas to determine how much material has been removed.

We use formulas to calculate total wear (T), which includes wear due to abrasive material, corrosion, and their synergistic effect. Consequently, metal loss from localized corrosion and erosion can be measured, and their synergistic effects evaluated.

Now, let’s examine the surfaces provided in this reference.

We are examining the surface morphology of the steel exposed to erosion corrosion or erosive corrosion. In the first diagram, which is a 50-micron (50 μm) micrograph, we observe micro forging at certain locations. This occurs when particles become embedded into the surface and are subsequently removed. This embedding and removal process causes damage to the matrix, altering the surface softness significantly compared to its original design specifications. Upon further zooming, three times closer, to 10 microns (10 μm), and then to 3 microns (3 μm), we notice dissolution and the presence of gaps in the surface.

In the earlier study, we observed that crevice corrosion or pitting corrosion can occur on such surfaces. Here, we see a large pit about 3 microns in size. When a particle is removed, it leaves behind a pit. This starts with erosion, and as particles get embedded and then removed from the surface, they leave pits, which naturally enhance both erosion and corrosion. The surface softness increases significantly due to this repetitive embedding and removal of sand particles, altering the surface matrix and causing further damage.

Additionally, this action removes the protective layer, which could be a work-hardened or oxide layer, depending on the original condition. The quick embedding and removal of sand particles under mechanical force lead to surface matrix changes and delamination, increasing subsurface fissures or cracks. These combined phenomena explain why erosion accelerates corrosion and vice versa.

Erosion can destroy the cementite network in steel, making pitting and corrosion more likely. Even the best material chosen for corrosion or abrasion resistance might not perform optimally under combined mechanisms due to their synergy. Therefore, it's crucial to study these interactions comprehensively.

Now, let’s consider another example involving mechanical and thermal actions together, such as temperature and mechanical stress causing failure. According to ASTM standards mentioned in the ASM handbook, aluminum alloys, particularly silicon-based ones, are treated to enhance strength. This involves solution treatment, quenching, and aging to precipitate small silicon particles, thus strengthening the alloy.

Akhtar et al. (2018) hypothesized that aging aluminum alloys at 120°C to 210°C would yield the strongest material. They found that aging at 170°C to 210°C produced the best results in terms of strength, not corrosion resistance. Using ASTM E8 for tensile testing and ASTM E23 for impact testing, they examined the material properties after aging.

Grain boundaries were analyzed under different conditions. Without aging, the grain boundaries appeared normal. At 150°C, semi-discontinuous chains formed, and at 175°C, continuous chains were observed, providing good strength. However, at 200°C, fragmented chains indicated more failure.

The study measured the hardening phase, finding 32% hardening without treatment, 35.5% at 150°C, and 38% at 175°C, which was optimal. At 200°C, the hardening phase decreased to 25%, worse than without aging. Thus, 175°C aging provided the best mechanical properties, while 200°C aging was detrimental.

Failure analysis, including tensile and impact testing, revealed that aging at 175°C produced the best results, showing continuous silicon precipitation and strong boundaries. The ductile failure observed showed dimples indicating good mechanical properties, affirming the findings.

This example illustrates the importance of understanding combined effects of mechanical and thermal actions on material properties, ensuring optimal performance under various conditions.

However, researchers observed some cleavage due to heating, while they noted the maximum dimple area in both E and F phases. Fracture resulted in a more ductile failure under uniform testing conditions, showing no significant variation even at 200 degrees Celsius. However, in impact testing, it's evident that the F phase exhibits the poorest microstructure, with nearly negligible dimples and increased rigidity and cleavage. This led them to conclude that particularly in the case of F, as depicted in figures 2F and 2F, this treatment yields unfavorable results, prompting consideration of alternative treatments.

This is what has been discussed in the paper. Now, let's delve into another intriguing example: hydrogen embrittlement. As mentioned earlier, this phenomenon often occurs in marine environments, where many failures stem from hydrogen embrittlement. This occurs when hydrogen infiltrates the metal, enhancing its brittleness. Hydrogen embrittlement can be categorized into two types: blistering, which affects the surface, and embrittlement, which occurs within or beneath the surface.

So, what distinguishes embrittlement from blistering? Blistering manifests on the surface, whereas embrittlement affects the interior or subsurface layers. Naturally, the question arises: what causes hydrogen blistering and embrittlement? This is the focus of our study—understanding the type of hydrogen degradation that arises when hydrogen atoms migrate within a material and accumulate at its surface.

So, from a hydrogen within a surface, they move to the surface as such and generate some sort of pocket, and that is what we use the word blistering, which is something like a bubble formation on a skin, which happens a number of times. Naturally, we encounter environments that contain hydrogen, such as aqueous solutions. Which has a hydrogen high-pressure hydrogen gas, which will be covered in one of the examples, where the high-pressure gas was exposed to the surface, what happened after that, and or maybe there is another kind of liquid or may be a solid available hydrogen sulphite? So, this hydrogen blistering will cause some sort of surface cracking, which will eventually lead to pitting, and then finally, if the whole layer may also get removed from a surface or maybe many pits are getting generated on the surface, we need to change the surface. So, it gives some sort of nucleation for the pit formation, or maybe something like, you know, a race surface that can be ruptured, which can happen when they are removed easily because of mechanical sliding, and that will cause a failure, but again, it will only be surface failure; it will not be within surface failure. Therefore, if hydrogen embrittlement transpires at the surface and the entire pit expands significantly, the pit formation will surpass the size of Figure 1, as depicted here.

In this scenario, we are referring to the infiltration of hydrogen atoms into a substance or their clustering within a lattice framework. Therefore, we are stressing that the presence of hydrogen will enhance the lattice structure, leading to an increase in brittleness and a higher likelihood of fracture. Hydrogen naturally infiltrates the material, leading to an increase in brittleness that triggers a crack. If this crack occurs on one side, it removes half of the surface, resulting in a more significant failure. So, that is what we mean by increasing the chances of fracture, and this kind of hydrogen embrittlement happens most often in steel, even titanium alloy, which is a very costly alloy. Very often, we use this alloy, but it is also subjected to hydrogen embrittlement.

This material is prone to various forms of deterioration. Often, electroplating introduces the risk of hydrogen embrittlement, necessitating precautions to prevent such failures. Let's examine a slide where you can easily discern the presence of bristles, resembling raised skin. Just like human skin, these raised portions, or bristles, are susceptible to damage upon sliding, leading to the collapse of bubbles or vessel damage, resulting in shallow pits on the surface.

Transitioning to hydrogen embrittlement, fractures are evident on the surface, accompanied by numerous crevices and a network of cracks. This type of failure can initiate surface pits, leading to overall surface failure or pitting. Additionally, it creates favorable conditions for corrosion, further exacerbating pit size.

What happens when we apply hydrogen to a steel surface under high pressure? This is an experiment conducted by one of the authors, and I aim to present the results. This is what we say, and then the surface without any hydrogen exposure, this HC1 is a hydrogen exposure, and the condition is something like, you know, they did an experiment in an autoclave for almost 160 hours using the hydrogen gas, and that would have a have a high pressure of 120 mega Pascal and a temperature of around 200^0C. So, this is a high pressure and maybe a moderate temperature condition. While this was HC1 and then HC2, what they wanted to do was go ahead with electron backscattering diffraction. So, they wanted to do a polishing, and then they did a polishing, and that took almost 10 hours, which means that this surface was exposed to the environment for 10 hours. They assumed that quite possibly hydrogen, which was encapsulated inside the surface, would escape, but that did not happen.

Therefore, we do not observe significant differences between the B and C failures and the E and F failures, which are essentially identical. While you can see in the case of the original without any hydrogen exposure, failures are more like ductile failures; this is a 100 μm and this is a 50 μm precipitation, but we find it is more like a ductile failure. And here you can see the many, many crevices, or maybe say there is some sort of discontinuity, and then, depending on the scale, you can find that there are a number of chances, or if the corrosion media is another corrosion media, it will really cause major damage. The same situation occurs in E and F, just as it does in B and C. Therefore, because hydrogen is difficult to remove, it tends to remain on a surface, leading to major failures. This is why we suggest that blistering will not significantly contribute to failures.

Once hydrogen embrittlement occurs, it deepens cracks, exacerbating brittle failure. If additional corrosion media is introduced, it intensifies the failure process. This summarizes the discussion on hydrogen embrittlement. Moving towards the conclusion of this lecture, let's explore another example from a 2022 publication by zoo ETL. This study investigated the combined effects of mechanical, thermal, radiation, and chemical mechanisms, focusing on the tidal zone—ranging from high tidal (HTL) to medium tidal (MTL) to low tidal (LTL) conditions—over three months. They examined corrosion, hydrogen embrittlement, hydrogen permeation, and mechanical stress-induced cracking on AISI 4135 steel surfaces.

In all cases—HTL, MTL, and LTL—they observed corrosion products on the surface, with persistent pitting even after removing the polyester surface layer. Pitting corrosion was evident across all samples, with varying pit diameters: 190 µm for HTL, 106 µm for MTL, and 102 µm for LTL. While MTL and LTL did not significantly differ, HTL exhibited notably larger pit diameters. Additionally, pit depths exceeded diameters: 212 µm for HTL, 147 µm for MTL, and a depth was also observed in LTL. This suggests mechanical action causing pitting corrosion and hydrogen embrittlement.

The failure mechanism analysis revealed ductile failure with shear lips and dimples in the fracture, indicative of hydrogen embrittlement in MTL and LTL. Conversely, in HTL, numerous cracks, including secondary ones in depth, were observed, suggesting a cleavage-type hydrogen embrittlement. This underscores the presence of hydrogen embrittlement in MTL and LTL conditions.

LTL exhibits essentially the same behavior as those with no exposure to the tidal domain. However, in certain cases, they discovered a secondary crack, which was also present in MTL. However, the failure is not significantly different from the normal case. However, in the STL case, there are significant differences. They explicitly mention the presence of a marine domain, hydrogen embrittlement, and the potential for a brittle failure. Therefore, we need to consider alternative materials to prevent this type of failure. We need to consider materials that can effectively prevent this type of failure. However, materials designed for low and medium tidal cases do not fail, nor do they significantly alter the fracture. Also, more or less this kind of ductile material may be somewhat present in a few places where secondary cracks are present, but not significant cracks are available there.

So, this is important to consider. Now, with this, I say thank you for attending this lecture.