Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 07
Erosive and cavitation wear

Welcome to lecture 5 of our Corrosion and Environmental Degradation and Surface Engineering course. In this lecture, we're delving into Erosive and Cavitation Wear. In our previous sessions, we touched upon adhesive wear, highlighting how it occurs due to material transfer and surface damage caused by intermolecular forces. Essentially, reducing the chemical activity of the surface is key here. Moving on to abrasive wear, we explored how hard particles or asperities can remove material from a surface. In this lecture, we're focusing on erosive or cavitation wear, where material is removed from a solid surface due to the impact of solid particles or fluid. This means that even a liquid can erode a solid surface.

We'll emphasize the significance of velocity in this lecture. In erosive or cavitation wear, particle velocity, along with size, plays a crucial role. A larger particle size, for instance, can result in more severe wear due to increased impact.

The only question that arises is: do we really need to study erosive wear and cavitation wear? In my view, it is crucial to comprehend these types of wear phenomena. Understanding the science behind erosive wear and cavitation wear enables us to utilize this knowledge for the betterment of society. By leveraging this understanding, we can develop superior products for society. We'll delve into a couple of examples in this lecture. So, let's begin with erosive wear.

In erosive wear, we also take into account the grit, much like we do in abrasive wear. Here, we note that this grit will be transported by the liquid or gas, possessing a certain velocity. What exactly is this velocity? Well, it needs to exceed 10m/s. In abrasive wear, we also factor in the grit, albeit as an asperity or particle.

Well, in this case, the velocity exceeds 10m/s. Another crucial aspect is the 5μm particle size. If the particle size is less than 5μm, it will not cause severe erosive wear; in fact, we might even neglect erosive wear altogether. You might say that particles smaller than 5μm won't have an impact, but remember, even a 50μm-sized particle wouldn't be detectable by eyes as a separate entity. Our vision is limited; we can typically see particles ranging from 38μm to 50μm, and for some, even distinguishing a 60μm particle is challenging. So, considering this limitation, the idea of discussing particles as small as 5μm seems impractical since they are practically indistinguishable. Moving on from particle size, we then consider velocity and impingement angles. For instance, if the impingement angle, let's call it α, is small, say 5 degrees, what happens? Similarly, what changes occur at 30 degrees and 60 degrees? These scenarios are what we'll delve into next.

The speed needs to exceed 10m/s, and it can even reach up to 100m/s. We're well aware that both solids and liquids can effectively remove layers of material when the velocity increases significantly. This aligns with what we've learned in abrasive wear. Next, we'll explore how grit size, speed, impingement angle, and even the hardness of the material being removed from a surface come into play. Overall, the erosive wear mechanism is influenced by the particle's angle of attack and the speed at which it impacts. It will be affected by size, and here's another new factor: the surface. It could be solid or liquid, depending on the case. Why are we studying these phenomena? Because they're incredibly common in almost all mechanical systems. Any systems with relative movement are bound to encounter dust particles, and a particularly severe case is seen in gas turbine blades, often failing due to particle impingement or erosion. Another common occurrence is with slurries, where high-hardness particles, along with impingement angles, can lead to pump failures, impeller damage, and housing deterioration.

So, we're looking at the housing and the impeller, where we can clearly observe erosive wear. Sometimes, there's a question: is it purely erosive, or is corrosion also a factor? There's often a combination, known as corrosive-assisted erosive wear. Naturally, particles may carry water droplets, which can also contribute to corrosion along with erosive wear.

Once more, this is a long-term process. It won't occur in a day, a few days, or even within a month; it's a prolonged phenomenon. Continuous monitoring is necessary to devise the right solution. When discussing iron as the material, rust is a potential concern. For other materials, corrosion is something to consider.

So, corrosion and rust will also play an important role in this type of erosive mechanism. Now, let's delve into a bit more detail. You must have observed mountains with water-carved passages. This phenomenon, known as water erosion, is very common in nature. Water finds a way, eroding rocks and various other materials, which we can also harness for beneficial purposes.

Similarly, we often encounter sand dunes that form and change shape due to erosive phenomena. These are common occurrences. Another important point to note is that when studying rock wear, hardness doesn't play a significant role. What's more crucial is high toughness. If toughness is adequate, surpassing the minimum requirement, erosive wear can be prevented or halted.

But if we solely focus on hardness, the problem arises because the harder material tends to become brittle. This brittleness leads to reduced resistance against erosive wear. Consequently, the material may break into multiple parts, creating tunnels and grooves, leading to increased failure rates. In essence, erosive wear shares similarities with abrasive wear. Just like when we initially discussed abrasive wear, similar phenomena occur in erosive wear. So, once again, we're essentially talking about a form of abrasion. However, erosive wear is categorized differently because, instead of focusing on load as we do in abrasive or adhesive wear, we now consider velocity or kinetic energy as key factors in the wear process.

In this scenario, the load indirectly manifests as energy, with the energy of the particles playing a more significant role. This is why we emphasize velocity, knowing that kinetic energy is proportional to velocity squared (V^2). In the case of liquids, this may be represented as V^5. Consequently, fluid erosion can be more destructive compared to solid erosion, which we're examining in this lecture. Another crucial point here is that if the energy or kinetic energy is low, toughness becomes paramount. Rubber, being elastic in nature, can even absorb more energy.

Rubber can sometimes outperform even tough materials like ceramics. So, in situations like these, we can opt for rubber instead of ceramics or other sturdy materials. This is an important consideration. When dealing with particles with lower kinetic energy than a certain threshold, rubber becomes crucial in resisting erosive wear. However, if the energy exceeds this threshold, the rubber may tear apart, leading to faster wear. Hence, to effectively apply our scientific knowledge, it's essential to understand the threshold limit—how much energy rubber can truly absorb. Each type of rubber will have its own unique threshold limits.

So, it's important to approach part design from this perspective. Often, we simply use a rubber coating, sometimes just a few millimeters thick. This can greatly enhance the overall system design. Additionally, as I mentioned earlier, erosive wear caused by liquid particles can result in severe failure. When these particles come at high velocity and flow, the failures can be quite brutal. This is exemplified in water jet cutting machines, well-known for their ability to cause brittle failure. However, this method can also yield precise machining, allowing us to create high-quality products using water jet machining.

So, brutal failure occurs due to liquid particles, and as I mentioned earlier, the wear rate in this case is much more sensitive—it follows a power of V^5, making it far more sensitive compared to the velocity required for solid erosion, which follows V^2. This comparison between V^5 for fluid erosion and V^2 for solid erosion is crucial. When discussing these phenomena, a big question arises: are they detrimental or beneficial? Can they lead to significant failures, or can we harness this knowledge to develop better products? One excellent example is aircraft. We know that aircraft must navigate through clouds, which contain numerous particles, including water droplets, and the relative velocity is high as the airplane moves from below the cloud to above it at high speeds. This phenomenon, known as fuselage erosion, is a significant concern in the aviation industry. Flying through clouds causes wear on the aeroplane fuselage, leading to numerous micro-cracks on its surface, which are then subjected to erosion from liquid particles. Fuselage erosion refers to the gradual loss of material from the aircraft's fuselage surface; it's not an immediate occurrence but rather a gradual process influenced by various weather conditions such as high-velocity winds, rain, sand particles, and other foreign objects. This is why ensuring the structural integrity of aircraft and prolonging their lifespan becomes a concern. To address this erosion, design changes often involve applying corrosion-resistant and erosion-resistant coatings. These coatings effectively mitigate erosion damage and extend the aircraft's lifespan.

So, here we mention corrosion again because water presence can lead to corrosion. These phenomena can occur sequentially or simultaneously, depending on various factors like wear and environmental conditions. To prevent such failures, routine, non-destructive checks are essential; we can't rely on destructive checks or scale down aircraft models. Instead, we must continuously monitor the surface using NDT tests to detect any small cracks, which could potentially lead to brittle failure. Regular NDT testing helps identify early signs of erosion, allowing us to anticipate significant failures and replace the affected components in time.

So, it's crucial to take immediate action or consider changing the coating or reconditioning when necessary. This understanding is vital. Given the high costs associated with the aviation industry, avoiding damage is imperative. Even small failures can lead to significant expenses, so we must have mechanisms in place to prevent them. Now, let's consider a positive aspect: while fuel can be harmful to aircraft, can we find something beneficial from a water standpoint? We know that water, when flown at high velocities, can yield positive results. In the upcoming slide, we'll discuss the water-assisted tunneling method.

It's a relatively new method that researchers are exploring, and if successful, it could bring about significant changes. So, what exactly is tunneling? We've seen numerous tunnels in various regions, and having more of them usually signifies a higher level of development. Smaller roads or pathways often result in faster development. Overall, there are several machines used for tunneling methods, but two common ones are drilling and blasting, and the Tunnel Boring Machine (TBM). TBMs are quite expensive and are typically only suitable for tunnel lengths exceeding 2 kilometers.

If the tunnel we need to construct is only 800 meters, 600 meters, or perhaps 1 kilometer, 1.5 kilometers long, using a Tunnel Boring Machine (TBM) would be too costly. In such cases, the more widely utilized method is drilling and blasting. This involves drilling holes into the rock or desired tunnel location, followed by grouting and placing explosive charges in the holes before initiating the blasting process.

As we proceed with the blasting, numerous particles will be generated, affecting the environment. Therefore, ventilation is necessary to clean the environment, enabling people to work safely. Additionally, mucking is required to remove all debris from the site, either to a distant location or to a designated landfill area. Once this is completed, rock support is essential, typically involving concreting or reinforcement to stabilize the tunnel. This process continues continuously, and typically, people can advance at a rate of 3 meters per day in this scenario.

The conventional tunneling method progresses at a rate of about 3 meters per day, which is both expensive and environmentally polluting. In contrast, with the Tunnel Boring Machine (TBM), everything operates robotically. A large cutter head cuts through the rock and collects the debris, which is then transferred back to the conveyor system. Another conveyor system brings rings from the backside to support the tunnel's surface appropriately. While the TBM is efficient, it's also costlier particularly for shorter tunnel lengths, especially those less than 2 kilometers.

In many developing countries, small tunnels exceeding 2 kilometers are hardly needed. So, what's the real solution? In such situations, we can explore alternative methods. One such method involves using water jet cutting to create tunnels. We're aware that water can penetrate even strong clouds due to its ability to cause brittle fracture. This occurs because the high velocity of the water creates a crushing zone, initiating fractures. However, these fractures can be controlled if the water jet is used properly. While the water jet may operate at high pressure, it can provide an effective overall solution.

Using a water jet provides a better solution compared to blasting because blasting can cause very deep stress fractures. Even if a tunnel is successfully constructed and concretized today, it may fail after 3 or 5 years due to these deep cracks. However, with water jet cutting, this risk is minimized. Mechanical rock cutting methods can be replaced by water jet cutting due to its effectiveness. So, the proposed solution involves using a water jet to create tunnels. For example, at the tunnel entrance and exit (marked as 1 and 2), a water jet can be used to cut through the required rectangular shape or any other needed shape. Then, these parts can be sliced into sections, such as 1 meter or 10 millimeters thick, depending on the requirements, and the complete slab can be removed.

Using water jet cutting results in less pollution because the rock remains intact and can still be utilized for development purposes. This means less pollution and more development, with the process also being faster since we don't have to remove muck; only stones need to be cut into the appropriate shape and directly delivered to the required location. Overall, this method benefits us by allowing rocks to be made into tiles and transferred directly to the desired places. Additionally, water is readily available in many areas, and even if it's scarce, water recycling technologies can be employed. Therefore, water-assisted tunneling can be highly beneficial because water, when activated at high pressure and flow rates, acts as an effective cutting tool.

To cut through rock using a water jet, the pressure needs to slightly exceed the threshold pressure. Ideally, the pressure should be about 20 to 25% higher than the erosion resistance of the rock, which may vary depending on the type of rock. This ensures that there's enough pressure to overcome resistance without causing excessive cracking. However, if the operating pressure exceeds about 1.2 to 1.25 times the erosion resistance, there's a risk of the rock cracking and forming micro cracks, making it easier to remove grains. Apart from pressure, the flow rate also plays a crucial role, and controlling it effectively can ensure a good depth of cut.

Now, with higher flow rates, we can achieve greater depth of cut, allowing for customized designs accordingly. Additionally, the loose particles produced during cutting can be repurposed as abrasive particles, thereby enhancing the wear rate. Although abrasive wear may initially seem detrimental, it can actually be utilized to increase the wear rate, which is crucial for tunnel construction. Moreover, by reutilizing abrasive particles, we can enhance the cutting material's effectiveness. Furthermore, since we're not using blasting methods, there won't be any demolition debris, making the process more environmentally friendly, cost-effective, efficient, and ultimately a win-win situation for us.

Sometimes, people utilize a diamond wire setup to cut the back slice of the tunnel because while water can pass through the front side, it may face obstacles at the back. In such cases, the diamond wire cutting method can be combined with water jet cutting to provide an effective solution. For those interested in learning more about this topic, visiting the website can provide additional insights, as ongoing research is continuously improving this technology. In the future, we may witness fully proven technologies for manufacturing tunnels using erosive wear mechanisms. As for determining erosive resistance and material durability against erosion, various tests and setups are available. One such setup involves using a compressor to propel gas or air, allowing the system to simulate erosive conditions and assess material resistance.

If we use water, we can control the velocity through a pump mechanism. Additionally, we can easily regulate the number of particles and their flow rate. Another factor to consider is the impingement angle, which can be adjusted by changing the sample's position, allowing for angles such as 10°, 20°, 30°, 40°, or 50°. This setup enables us to experiment with various particle numbers, sizes, airflow rates, and angles. For instance, experiments with alumina particles, typically 50 μm in size, can be conducted, although particle sizes can vary from 10 μm to 100 μm, depending on availability or industry standards. To conduct these experiments, we typically use an air compressor, but if a liquid carrier fluid is preferred, a pump can be utilized instead, allowing for the use of process fluid in the experiments.

Another important consideration is maintenance, especially given the potential for rusting and corrosion in the presence of water. If we aim for a clean environment and wish to eliminate all particles, including airborne ones, air demineralization may be necessary. This ensures consistent and repeatable results, preventing variations caused by changing humidity levels throughout the day. Initially, we need to rely on calibrated data, such as using a pressure of 0.15 bar and a flow rate of 12 grams per minute, with a velocity of 60 meters per second, based on ASTM standards. These standards provide guidelines for setting the pressure and determining the required flow rate, which can vary depending on specific ASTM requirements.

Another aspect to consider is the preparation of the test specimen. This specimen is mounted in a holder, and then the flow is directed onto it using a nozzle. Experiments can be conducted at various angles, such as 10°, 15°, 30°, 45°, 60°, 75°, and 90°, depending on the setup. Through these experiments, we can determine the material's resistance to the environment, particles, flow rate, or process fluid, thus calculating the erosion rate and wear coefficient. This allows us to rank different materials relative to each other. For instance, if we have 10 materials, we can assess which ones perform best or worst based on the conducted experiments. However, it's essential to repeat each test 2 to 3 times to ensure accuracy.

In a single set of experiments, we cannot immediately rely on the results obtained. It's necessary to conduct multiple experiments under the same conditions to ensure repeatability and to minimize noise, thereby obtaining more accurate results. Now, let's proceed to the next slide where I'll show you some results. In this case, as mentioned earlier, we used alumina particles with a size of around 50μm. The impingement angles ranged from 10° to 90°. We observed significant erosion at 10°, which is referred to as cutting wear.

At 75°, the spread is much narrower. We conducted experiments at two different positions, but in this case, there's only one position, right? So, you can see that the spread is wider here, narrower in the second case, and much narrower at 90°. This indicates that as the impingement angle increases from 10° to 90°, the erosion area becomes smaller compared to the area at 10°. Another important observation is that deeper penetration creates craters, as seen here, whereas shallow penetration may lead to crack formation or slight erosion. Depending on the particle size and material, especially if it's brittle, crack formation and accelerated erosion may occur at a higher rate.

So, particularly at 90°, brittle materials are not suitable, while at 30°, even ductile materials are not ideal. Depending on the angle, for instance, if $\alpha = 30°$, avoid using ductile materials as the wear rate would be very high. Similarly, if $\alpha = 90°$, avoid brittle materials. There are various curves, as we'll demonstrate in the next slide, that help us understand the impingement angle and select the appropriate material accordingly. Now, here, I'm showing it slightly differently. This is a discharge nozzle. At angles like 30° or 10°, you can see a cutting action, with detached material from the surface. Here, we can test not only the material but also different coatings. That's why we can discuss five different coatings to see which one performs better.

So it's not just the parent material; coatings can also be tested using this equipment. In this case, temperature is also a crucial parameter. We know that material behavior changes at high temperatures, so conducting experiments at the operating temperature is advisable. Here, we can see the depth of penetration of the particle, which is much higher compared to here. The spread is also wider. As mentioned earlier, the maximum wear in a ductile mode occurs at $\alpha = 30°$. Different ductile materials may have different angles, such as 25° or 35°, but roughly, we use 30° for ductile materials and 90° for brittle ones. However, slight changes may occur due to variations in microstructure. We can even simulate this erosive wear failure to better understand it. Here, it's noted that the maximum impact energy imparted to the ductile mode occurs at 30°.

That means whatever energy comes with the particles is transferred to the coating or substrate material being tested. The amount of energy actually transferred to the material is crucial. At 30°, the maximum energy is imparted to the surface, whether it's the coating or the parent material. Some energy may be lost with the particles, but the maximum energy in the case of ductile materials is absorbed at 30°, which is why we observe the highest wear rate at that angle. However, in the case of erosive wear in a brittle mode, the angle is 90°. This means that the maximum energy imparted to brittle material occurs at 90°.

So, if we conduct experiments at a 90° angle, we'll observe crater formation or deeper penetration compared to ductile materials or lower angles in this scenario. These two factors are important to consider when discussing erosive wear, as illustrated in this slide. Here, at a low angle of 30°, we observe shallower depths, whereas at 90°, we see much deeper penetration and crater formation. Many cuts occur in a narrow domain at lower angles, while at higher angles, there's more ploughing or plastic deformation, along with the presence of microcracks or micro-cutting. Thus, we can conclude that cutting wear prevails at low impact angles, and in this case, hardness may also play a role.

However, at larger angles, fatigue wear becomes prevalent, and in such cases, materials need to be tougher. So, the term "tough material" is more appropriate here, and using a tougher material at a 90° angle or larger will yield better results compared to a harder material. Now, let's discuss another mechanism called cavitation wear. Similar to erosive wear, cavitation wear also exhibits several similarities. In this scenario, particles are formed in a liquid state rather than a solid state. It's noteworthy that liquid can break down into numerous streamers or particles, which is a concern.

In this scenario, every fluid typically contains some amount of gas, usually around 0.1% to 0.2% under normal conditions, which isn't usually a cause for concern as the gas remains compressed. However, there are instances where bubbles are subjected to intense pressure, particularly in convergent-divergent domains. This schematic illustration depicts a pressurized fluid-air environment with a gas bubble. When this bubble comes into contact with a surface, it experiences extreme pressure from all angles, leading to its eventual bursting. Upon bursting, the bubble releases wave energy and disintegrates into numerous streamers and particles, which effectively creates an impact on the surface, resulting in the removal of debris in the form of fractures.

So, what I'm saying is that fracture formation doesn't happen in just one cycle; it usually takes multiple fluid impact cycles to occur. Cavitation is a slow process that begins gradually with pit formations, which then expand over time to cover a significant portion of the surface. These pits, although not immediately fatal, indicate a weakening of the material strength. When numerous pits are observed, it's a sign that the material needs replacement, as its strength has significantly decreased. Cavitation doesn't lead to spontaneous failure but will eventually cause failure. It occurs due to the formation of bubbles in low-pressure areas, which may grow and merge together over time.

So, there are individual bubbles here, there's another one here, and a third one here; they merge together to form larger bubbles. If these bubbles collapse in a fluid environment, it generates shock waves that can cause crack formation. When a bubble bursts on a surface, it creates pits. Both pit and crack formations are possible when bubbles burst. This collapsing process, which generates shock waves, can damage surfaces directly by forming pits or subsurface cracks. This phenomenon is prevalent in various machinery operating in fluids. It's particularly harmful to propeller water turbines and ships.

However, researchers have also explored ways to effectively utilize cavitation. We'll discuss this in future lectures. To summarize the previous slide, cavitation occurs when there's a buildup of negative pressure on the downstream faces of submerged objects in liquid flow. Bubbles of dissolved gases and vapor form in various liquids. For instance, in hydrodynamic bearings, we observed vapor formation when the pressure drops below the vapor pressure, leading to the formation of gas bubbles. When these bubbles collapse in areas of negative pressure, they may either dissipate harmlessly or directly impact the surface.

So wear occurs due to the repeated collapse of bubbles, hammering the surface with impact. Even hard surfaces can be damaged by this process. As mentioned earlier, toughness is crucial here. While hard surfaces can resist to some extent, they cannot completely absorb the energy, leading to surface cracks. If these surface cracks accumulate, they can form larger pits. When bubbles collapse either in the fluid or on the surface, material wear occurs, leading to localized cracks. The wear isn't confined to a specific location; it spreads continuously due to the unpredictable nature of bubble bursts. Cavitation wear is detrimental to propellers, water turbines, and various machinery.

Now, let's delve into some equations. We've discussed velocity in previous lectures, and now we'll examine its role in cavitation erosion. There are several stages to cavitation erosion. Initially, the erosion rate is gradual, with slow mass removal. This marks the slow phase. Then, there's acceleration, followed by a steady state where the wear rate stabilizes. At this point, material degradation has already occurred significantly, necessitating replacement.

So, what we're illustrating here is that the pit formation won't be localized; it'll spread continuously, leading to more failures over time. Initially, the rate of pit formation will be lower, possibly due to surface hardening. However, as the area affected increases, the material weakens continuously, eventually leading to the possibility of large crack formation or fracture.

Now, how do we predict this? Particularly, the erosion rate depends on the flow rate, which determines the extent of cavitation erosion on the surface. The mass flow rate, expressed in terms of density and volume, remains constant over time. So, it boils down to the rate of change of volume with time, expressed as dv/dt.

So, once again, we can represent this in a form where we focus solely on the initial phase. If the erosion rate is high initially, then we might need to replace the components. We've explored the cavitation erosion equation, but we also have the erosive wear equation to consider. We need to figure out how to develop a quantification or equation that will be useful to us.

In the erosive wear equation, Hutchings proposed an initial model. We know that erosive wear depends largely on kinetic energy, and we need some material constant or operational constant to quantify how much material will be removed from a surface. In this equation, they considered the density of the material (ρ) and velocity (U).

Here, U can be considered as the velocity, which we've denoted as V. So, in this case, U equals V, representing the initial particle velocity, not the final velocity.

However, he also considered the surface hardness and gave it importance. Now, in this case, we don't consider surface hardness as a very important factor. Instead, we know that we need to focus on kinetic energy. So, toughness matters more; it plays a bigger role. The erosion wear rate equation was initially formulated considering these factors but was later modified. In this modified form, the wear constant, denoted as K_1, remains the same, while velocity is changed to V^N, where N generally remains greater than 2; it's not limited to just 2.

For metals, we keep it lower because for ductile materials, it's less than 2.5, while for brittle materials, it's higher than 2.5. We typically state it ranges from 2.5 to 3; for metals, it's 2 to 2.5, but it's always greater than 2. Another factor to consider is the angle of impingement, denoted as α. They also consider hardness, although I mentioned that we don't necessarily need to focus on hardness. Instead, it might be better to introduce another constant, K_1/H. By altering the material hardness, we can reduce the wear rate, but it's preferable to use a new constant, K_1/H, rather than solely considering hardness because we're uncertain about its sensitivity. If the hardness is too high, it could lead to brittle failure, potentially resulting in a higher wear rate.

So, it's better to redefine K_1/H as another constant instead of considering it separately. Now, concerning $f(\alpha)$, it can be a function depending on the impingement angle. If the angle is near the surface, less than 30^0 or 40^0, instead of considering it individually, they use a summation method. This summation accounts for both cutting wear and deformation wear. Cutting wear occurs at lower α angles, while deformation wear occurs at higher α angles. This is why there's a cosα term; when α is lower, cosα dominates. Conversely, when α is closer to 90^0, $\sin^2\alpha$ dominates, indicating deformation predominance. Essentially, if α approaches 90^0, deformation dominates, whereas at angles near 0^0, 5^0, 10^0, or 15^0, cutting wear prevails. Different relations have been proposed for deformation mechanisms, such as the extrusion mechanism or the low cyclophotic mechanism, all of which are related to deformation.

Some suggest delamination occurs when bombarding at 90^0 due to the possibility of the complete coating coming off, resulting in delamination and potentially crater formation or deep plastic deformation. Conversely, if the angle is less, work hardening may occur. Various researchers have proposed different mechanisms depending on the environmental conditions. For our lecture, we'll focus on deformation, whether it's delamination, low cyclophotic behavior, or plastic deformation. We won't solely consider f_d as a function. Now, f is the main function determining the outcome, while α and the trigonometric functions provide horizontal and vertical components. By differentiating and equating to zero, we can find the optimum angle or the angle that maximizes deformation or wear rate. As mentioned earlier, for ductile materials, the peak wear rate occurs at around 30^0, while for brittle materials, it's closer to 90^0.

So, this can be obtained by using differential equations, and the final equation, which is more popular, states that the wear volume is proportional to a constant, known as the wear constant. As I mentioned, it represents the wear coefficient and signifies the probability of material removal, which is shown as the probability of wear particle formation. The parameter α is given as follows: $(V) = (particle\_velocity)^n$ where "n" can range from 2 to 2.5 for metals and from 2.5 to 3 for ceramics. The last parameter, M represents the particle size. If the particle size is doubled, the wear rate may increase by a factor of 8. Doubling the particle size can significantly impact the wear rate.

So, this is a quantification of erosive wear, and in the last slide, we discussed some sort of quantification of cavitation erosion or cavitation wear. These are two common terms in erosion, which generally occur with cavitation. Sometimes people refer to it as erosive cavitation or cavitation erosion, using these terminologies more popularly.

Now, I'm going to show you a couple of failures that we have experienced in our own lab with hydrodynamic bearings. These bearings are used for IC engine cases, which can be petrol engines or diesel engines, and we have observed that cavitation dominates in these kinds of bearings. Here is the bearing used for the IC engine case, and we have observed cavitation wear in this bearing.

The question arises: how does cavitation occur in a hydrodynamic bearing? We conducted experiments to investigate this by using a transparent bearing and supplying liquid to it. In the convergent domain, particularly, wear did not occur. Even on the suction side, we did not observe wear. However, in several other places, including the delivery side where the volume is much higher, some liquid leaks out. In the divergent zone, there isn't enough liquid to sustain the negative pressure, leading to the generation of negative pressure.

That's why these streamers form inside. So, within the fluid or lubricant, gas bubbles form, connecting to one another. We've developed several equations and have published papers demonstrating how these streamers form. Sometimes, multiple gas bubbles join together to create a larger one. If this system experiences high or reciprocating loads, the gas bubbles interact, experiencing changes in pressure. This fluctuation can lead to the bursting of gas bubbles, causing cavitation wear. This aspect is crucial; we've discussed erosive wear and cavitation wear, often using cavitation erosion interchangeably with cavitation wear.

In some literature, wear and erosion are considered separate phenomena, but in our class, we see wear as the broader domain, with erosion being a part of it. In our next lecture, the sixth one, we'll delve into fatigue wear and melting wear or diffusion wear. Thank you for your attention.