Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 04
Adhesive wear mechanism

Welcome to the third lecture of the course on Corrosion, Environmental Degradation, and Surface Engineering. In this lecture, we will discuss wear mechanisms. We have already learned that wear-related material surface degradation can lead to the failure of the top layer. Over time, this process weakens the material, leading to product failure. Therefore, we need to take appropriate care. Wear occurs when two surfaces rub against each other and are subjected to mechanical load.

This causes the surface to lose material, and in the worst case, it will break, or the product will break. In our previous lecture, we discussed a few mechanisms related to mechanical wear. We mentioned adhesive wear, abrasive wear, fatigue wear, erosive wear, fretting wear, melting, and diffusive wear. While we named these types of wear, we need to delve into more detail.

So, in the current lecture, we will focus on adhesive wear. In its extreme form, adhesive wear between two metals can result in a cold junction, binding the two surfaces together and completely halting relative motion, leading to seizure, or weakening the integrity of the system. Therefore, it's crucial to understand the wear mechanism. Let's begin with adhesive wear, which is particularly common in metals, indicating its predominant usage in metal applications.

Naturally, what's the reason behind this? In our previous lecture, we discussed that all contacts occur only at the asperity level, meaning these contact points are much smaller than the apparent area. This results in extreme stress, as the actual area of contact is typically only 1% to 2%, or 5%, which is much less, compared to the apparent area. Additionally, when metals undergo plastic deformation and come very close to each other, with a separation of less than 1 atomic diameter, electron transmission occurs. This means that electrons can transfer from a green-colored metal to a blue-colored metal, or vice versa.

What problem arises in this situation? There's a possibility of electron interchange or transmission, leading to potential micro welding. If we apply force or tangential force to move the green metal relative to the softer blue metal, there's a chance that some of the blue metal may transfer to the green one, initiating the wear process or adhesive wear, which could eventually lead to severe wear. Understanding this is crucial. Another important aspect is the cleanliness of the metals. Using clean metals can pose more challenges, especially if the material is manufactured and immediately put into use.

What's the problem here? The issue lies in having a very clean metal, as it increases the likelihood of instantaneous or spontaneous electron transmission, regardless of time or temperature conditions. This phenomenon is why we refer to these micro welds as cold welds. This entire process can be termed as forming a stronger junction. Why is it considered a stronger junction? Because when we attempt to move one metal against another, shearing doesn't occur easily, resulting in difficulty in movement and extreme wear. This confirms that shearing isn't straightforward, indicating a stronger junction. Therefore, what's required is to create a somewhat weaker interface or induce weaker shear strength or shear stress at the interface.

How is this possible? Let's consider metal 1 and metal 2 with asperities and possibly some plastic deformation. This necessitates moving metal 1 relative to metal 2. There's a chance of a junction forming here, but it's a weaker interface, allowing metal 1 to glide easily on metal 2. So, what's needed? We need a weaker interface to avoid adhesive wear, where shearing between the metals occurs at the interface itself, resulting in mild wear. Conversely, with one strong material and one weak material, the interface won't be weaker, leading to more metal transfer compared to even softer metal-pair. Hence, it's crucial to select metal pairs or situations that only allow mild or ultra-mild wear.

Now, let's discuss slightly deeper into adhesive wear. What we're emphasizing is the need to quantify adhesive wear in engineering. We truly need to establish parameters that are more sensitive and understand how to adjust and optimize them effectively. Essentially, what we're suggesting is that to model adhesive wear, we must consider certain assumptions. One such assumption involves the plastic deformation of the asperities. This implies that all the asperities coming into contact will deform plastically, and the real area of contact can be represented by the formula $A = W/H$, where W is the applied load on the surfaces and H is the hardness of the weaker or softer material. We will only consider the hardness of the softer material, as typically one of the surfaces, either metal 1 or metal 2, will have lesser hardness. However, it's important to note that this assumption may not be entirely true, as many asperities may undergo elastic-plastic deformation as well.

Suppose there are 1000 asperities between the metals at interface. The possibility is that maybe 900 undergo elastic deformation, while only 100 undergo plastic deformation. Thus, it becomes a hybridization of both plastic and elastic deformation. However, we cannot quantify this solely using a counting factor like a probability factor; that will be discussed in the next few slides. One advantageous aspect of this is how we can create a weaker interface. As mentioned in the previous slide, we need to emphasize the importance of a weaker interface.

A weaker interface can be achieved through the presence of a surface film, which is what we refer to as surface engineering. With a surface film, there's a reduced possibility of electron transmission and, consequently, less metal transfer and wear. This occurs because when a metal is finished or ready for use as a product, it may encounter environmental pollutants or agents like oxygen, fluoride, or water on its surface. This leads to the formation of a contaminated layer, which is typically porous and weaker at the interface, resulting in lower shear strength. Another benefit is that only a small fraction, typically less than 50%, of the material is lost, and the material removal from the parent material is minimized. Therefore, it's a mutually beneficial situation. Environmentally, this natural process helps reduce interfacial strain when metals come into contact with each other. This highlights an important aspect: Are we ready to model adhesive wear, or do we need further knowledge for modeling purposes? If more knowledge is needed, then naturally, we must formulate hypotheses.

What's the hypothesis? Here, we suggest that when two metals come into contact—metal one and metal two—asperity contact occurs because metal needs mechanical support. Thus, there will be contact at the asperities. What happens at these asperities? There's a possibility of deformation, either plastic or elastic, and if there's relative motion, the protective oxide surface layer, known as the contaminated layer, may be removed. This could potentially generate loose particles. So, the question arises: Are these loose particles beneficial or harmful?

If the loose particles are soft in nature, they may act as solid lubricants. However, if they are hard, they could lead to abrasive wear, a topic we'll discuss in the next lecture. Therefore, once again, we need to consider the nature of the metal oxide or contaminated layer. This requires additional information. Another important point to note is that the stress levels will be very high.

Formation of the adhesive junction cannot be avoided in such conditions. Even with surface coatings or lubricants, adhesive junctions may form, although they can be easily sheared. However, the formation of adhesive junctions is inevitable. This is illustrated in point "b." These junctions can fail or grow. Initially, there's formation of the junction, and when metal one moves relative to metal two, this junction may need to be fractured or broken. This is termed as junction failure. If the interface isn't weaker, then the softer material (assuming metal two is softer) may experience deposition of particles or transfer of material from metal two to metal one.

That means metal one is going to carry metal two in the form of a lump or projection system, as already shown in the previous slide. Metal transfer occurs due to electronic transmission and cold weld junctions, highlighting the need for such hypotheses. If this process continues, material transfer, even secondary, is possible from metal one to metal two due to work hardening, resulting in surface deposits. This continuous movement, over cycles ranging from 10^3 to 10^4, leads to accumulation. The continuous increase in particle transfer and accumulation eventually results in the formation of large lumps. When these lumps exceed the size of asperities, they come under stress and may fracture from the surface, as shown in the fractured surface or removed particle. This failure of junction by pulling out large lumps can create loose particles, potentially transitioning adhesive wear into abrasive wear. However, detailed study of this transition will be reserved for future lectures; today's focus remains solely on adhesive wear.

The question arises: Do we require more knowledge, or are we ready to model adhesive wear? In my opinion, before seeking further knowledge, let's review our current understanding of adhesive wear. We recognize that adhesive wear stems from mechanical activity, gradually removing discrete particles from surfaces, with metal-to-metal interaction leading to electron and material transfer. Additionally, even the smoothest surfaces are subject to microscale distortion upon contact, resulting in smaller contact areas and higher local pressure and stress.

And under these high stresses, what happens is that the surfaces come into contact and form a cold junction. This cold junction formation can only be avoided with some sort of coating, contaminated layer, or lubricant. In the absence of such protective measures, cold junction formation occurs. When this happens mistakenly, we need to break the junction to enable relative motion between the two surfaces. There's a possibility that once one junction is broken, there's a chance of another forming, and this process continues. Unless the metal or material selection results in a weaker interface, adhesive wear persists, leading to more material transfer between surfaces. Eventually, this transferred material becomes loose wear particles, leading to abrasive wear.

Therefore, it's crucial for us to review and consider this aspect. Now, we can begin to think about establishing some sort of relationship, which was proposed long ago by Archard. This relationship is known as the Archard wear equation. It's important to note that this equation is qualitative in nature and doesn't provide quantitative results due to certain assumptions, many of which are probabilistic. For the time being, we can consider it qualitative and focus on understanding the parameters involved in adhesive wear. To achieve this, we need to formulate equations and establish relationships to arrive at a final equation.

What we started earlier is the concept that the real area of contact can be determined by the normal load applied over the surfaces and the hardness of the softer material. Additionally, in this scenario, when two particles or surfaces come into contact, they meet at asperities. The number of asperities can vary greatly—whether it's 100, 1000, or 10,000—as we need to make assumptions to formulate the equation. Therefore, in the present case, we are assuming a certain number of asperities, acknowledging that this number may continuously vary due to the presence of both high and low peaks, with the possibility of continuous variation.

Initially, we assumed instantaneous contact at asperities, along with plastic deformation occurring at some of them. However, there's also a possibility of elastic deformation at other points. Now, considering the real area of contact denoted by A, it's the summation of the contact areas at each asperity, given the total number of asperities, N. This means we need to consider the summation of the contact area at each individual asperity.

This concept forms the basis of the Archard equation. Archard assumed that when semicircular or hemispherical asperities come into contact, there's an overlap between them, as illustrated. This overlap represents perfect matching, but as the surfaces depart from each other, they deviate from this perfect match.

So, this process continues continuously, and we can say that because in this case, the radius is "a," then the maximum area will be πa^2. If we multiply this by the hardness, it will give us the amount of load carried by each asperity, or we can say that each asperity, with an area of πa^2, will carry a load of δW. Similarly, we can consider the wear that will occur, resulting in the loss of volume from the surfaces. Assuming that 100% of the asperity has been damaged or transferred from one metal to the other metal, the volume can be given by $2\pi a^3/3$, with a probability or multiplication constant involved. This constant can be expressed as a percentage of 100%. Therefore, in this relationship, if I assume that the area and the distance traveled with 2a in the situation because the overlap is 2a, then per unit sliding distance, the volume divided by the per unit sliding distance, can be represented in this form, and the load can be given in this form as well.

Now we can integrate or sum up the volume per unit sliding distance and determine the overall weight carried by the asperities. The important aspect here is that we need to eliminate N, which is unknown to us, and A, which is also unknown. In this case, we can calculate the total load in terms of πa^2 and the range from 1 to N. Similarly, we can determine $\pi a^2/3$, which is related to the volume. Now, if we express the volume in this manner and substitute πa^2 from this side, we will obtain an equation resembling the following: Volume per unit sliding distance equals a $(k_2 W)/(3 k_1 H)$.

These are the important parameters: the applied load, the hardness, and certain constants. If we denote the total sliding distance as L, we can determine the overall volume worn out from a surface, which can be represented by a coefficient that is proportionate to W, proportionate to the sliding distance, and inversely proportionate to hardness.

Initially, our assumption was that if we increase the area of contact, as indicated by the first equation A=W/H, we can reduce stress on the asperities. This implies that to minimize wear volume, we need to maximize hardness.

However, there are two different expressions here: one suggesting minimizing hardness, and the other suggesting maximizing it. To determine which approach is correct, experiments need to be conducted to yield accurate results. Nonetheless, according to Archard, wear volume is directly proportional to sliding distance (L), directly proportional to applied load (W), and inversely proportional to the hardness of the softer material. The constant k_1 is dimensionless and represents the probability of removing a wear particle, which may be considered an index of severity.

What does that mean? When k_1 equals 1, every junction involved in a mechanical interaction will result in a wear fragment. This implies that 100% of the junctions coming into contact will contribute to wear. However, if k_1 equals 0.1, only 10% or one-tenth of the friction junctions produce wear fragments. Similarly, if k_1 equals 10^{-7}, it indicates that only one failure occurs out of every 10 million junctions.

So, what we aim for is the lowest possible value of k_1. If we can engineer such junctions, it would greatly benefit overall product design and surface engineering. Our focus lies in minimizing k_1. Now, let's delve into the nanoscale. While the macro scale presents smooth surfaces and the micro scale exhibits roughness, what occurs at the nanoscale? Understanding this is crucial due to the impact of local stress and relative motion on junction failure. We strive for easier passage and weaker junctions to facilitate smoother relative motion and minimize power loss.

Moving forward, can we accurately measure adhesive force between surfaces? Yes, through techniques like atomic force microscopy. Additionally, real area of contact can be inferred using microscopy or profilometry, providing quantitative insights beyond qualitative measures like the Archard equation.

Now, considering adhesive wear, critical factors include surface roughness, where minimizing or intentionally designing roughness can yield better results. Chemical composition also matters, as the surface energy of metals influences performance. Operating conditions further affect k_1 values, as demonstrated by varying RPMs. Each scenario may require a tailored k_1 value.

Considering the nanoscale, understanding adhesive wear is crucial for developing new materials. This holds true for surface engineering, where coatings—whether soft or hard—play a significant role in minimizing wear and prolonging machine lifespan. Overall, minimizing surface energy during material development is advisable, given its initial high energy state.

The favorable aspect here is the environment's immediate reaction with surface energy. If free electrons are present, oxidation occurs, leading to the formation of a contamination layer. Fortunately, in the case of iron oxide, there are three types of oxides. In some instances, up to 40% of the volume may consist of iron, with 60% being other contaminants. Alternatively, it may be 42% or 48%. Therefore, the quantity of iron involved in oxide formation is relatively low.

Initially, this results in a weaker surface, creating a weaker interface, which is essential. Additionally, the transferred or lost material is minimal, which is crucial. The formation of an oxide layer on the surface or rendering the surface chemically inactive would be advantageous.

To illustrate experimental procedures at the micro or nano scale, we typically use a pin, cylindrical piece, or sphere placed on a substrate with oxide formation. By bringing these objects into contact and initiating relative motion—whether unidirectional, reciprocating, or under applied flexing loads—we can conduct various experiments. Electronic transmission occurs on clean surfaces, where electrons may transfer between surfaces.

For example, indium, a soft material, can form a layer on steel when in contact. Similarly, carbon materials transfer layers when brought into contact with steel. This demonstrates layer transfer. Upon contact with a steel ball, rupture may occur, leading to the removal of the oxide layer, or complete removal may take place. The same applies to the cylindrical piece, where layer transfer can occur upon contact with a pin.

So, what are the key points? We can conduct experiments with both a pin and a ball. By adjusting the relative speed, we can potentially remove the oxide layer entirely or partially. In such a scenario, asperities may form upon breakage, generating debris, which can have varying effects depending on the hardness of the surfaces. This will be further discussed in the next lecture on abrasive wear. Now, let's revisit what we learned about the nanoscale. We observe that when metals form, there's a possibility of the top surface developing an oxide layer due to atmospheric gases reacting with it, leading to contamination. This highlights the importance of controlling the environment to facilitate oxide layer formation, which can be achieved using fluids or gases, with known additives capable of forming such layers on surfaces.

Looking at it from an atomic perspective, we see an orange-colored layer on the top surface, a black layer in the middle, and possibly a red-colored layer on the side. The electrons on the top surface may have higher energy levels than those on the bottom, potentially interacting with other surfaces. For example, if we consider a sphere contacting a surface, atoms may transfer from the more reactive surface to the less reactive one, indicating the significance of understanding and minimizing wear rates in product development. Taking a closer look, we recognize the importance of addressing severe wear by selecting materials with comparable hardness to mitigate adhesive wear issues.

If there's a softer material involved, a transfer layer forms. If this layer weakens the interface, it's beneficial. However, if it strengthens the interface compared to either metal 2 or metal 1, it's harmful. This was demonstrated in experiments, such as the four-ball test, where high loads and lack of lubrication led to significant plastic deformation resembling a scissor-like action. This severe wear results in the breaking of numerous junctions and the generation of multiple fragments from the surface. To avoid such wear, we consider factors like hardness and the ability to alter phases, such as comparing iron with steel.

When iron has fewer phases than steel due to compositional differences, steel is less prone to severe adhesive wear compared to iron. Therefore, using less pure metals is preferable, or else employing a lubricant layer becomes necessary. The presence of a lubricant almost eliminates adhesive wear. If using a lubricant isn't feasible, creating an oxide layer using oxidizing agents is another option. The effectiveness of these measures varies depending on the specific situation. In some cases, oxidation is crucial, while in others, lubrication or hardness plays a key role.

So, we need to consider that perspective. Now, to elaborate on everything we've studied, as I mentioned, the Archard equation provides a qualitative ranking of materials, allowing for comparisons. To illustrate this, let's find the best material for a dry journal bearing, even though journal bearings are typically liquid or gas lubricated. For this purpose, we perform experiments on the pin-on-disc machine. Why do we need experiments on this machine? Because the constant k_1 for one material may vary under different conditions. Therefore, we need to conduct experiments since the Archard equation only provides qualitative, not quantitative, results. The Archard equation offers parameters that must be considered and optimized using experimental techniques.

While we could conduct more detailed analyses, for quick results, we can directly use the pin-on-disc machine. In this case, the disc material is AISI 1040 steel, meaning the shaft or journal material is already chosen. Our task is to select the bearing material from options A, B, C, D, or E. Each material undergoes testing under specific conditions: 30 rpm disc speed, 100 Newton load, and 350-minute duration, resulting in a wear score of 9.7 mm. In another scenario with the same rpm but doubled load and reduced duration, the wear score is 8.81 mm. This doesn't imply one material is better than the other; rather, we must input all parameters into the Archard equation for comparison.

Moving to the third scenario, where rpm and load are doubled but duration is reduced, the wear score also doubles, indicating potential thermal issues. For material B, two tests were conducted at 30 rpm and 160 rpm with the same load and duration.

We observe that at higher speeds, there is a wear score of 15.27 mm, whereas at 30 rpm, it is 12.63 mm. Materials C, D, and E also undergo testing, and the observation is that the minimum wear score diameter is 8.81 mm, while the maximum is 20.83 mm. However, this does not indicate the material's quality; rather, it provides data for comparison using the Archard equation. The wear score is represented by the scars on the pin, and its maximum value cannot exceed 2R. By knowing the wear score value and the pin's radius, we can calculate the wear volume.

Different wear scores occur due to varying conditions, leading to potential changes in k_1 values. We demonstrate this in a three-dimensional model and illustrate the wear track's depth, commonly measured as the wear score. The choice of bearing material depends on the best-performing pin material. When applying a normal load, contact between surfaces must be ensured, with proper alignment and no misalignment between the disc and pin. The pin-on-disc tribometer is a widely used experimental setup for such studies.

The Archard equation, derived earlier, correlates wear with normal load, sliding distance, and hardness. By substituting known values, we can determine the k_1 value. Results indicate that material B consistently performs best, with k_1 values of 0.021 and 0.022, showing statistical variation. Other materials can be considered if B is unavailable.

The key takeaways include recognizing adhesive wear as inevitable and preferring non-metal to metal contact. Additionally, dissimilar materials or maximum hardness should be chosen to prolong service life. Routine maintenance is crucial to prevent adhesive wear from escalating into severe wear, which can be exacerbated by fluctuating loads and speeds. Ultimately, minimizing adhesive wear, using weaker interfaces, and considering maintenance strategies are vital for equipment longevity. The next lecture will delve into abrasive and erosive wear mechanisms.