Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 06
Wear Phenomena Defined by Dimensionless Parameter

Welcome to Lecture 4A. This is an extension of the third and fourth lectures, and the topic of this lecture is wear phenomena defined by dimensionless parameters. We have covered two significant wear mechanisms, which are adhesion and abrasion, in the last two lectures. And we understood that adhesion occurs when two surfaces come into close contact and experience bonding forces. This causes the removal or transfer of material from one surface to another, ultimately leading to the generation of wear debris and material loss. You know that adhesive wear is more common in metal-to-metal contacts.

Abrasive wear occurs when hard particles or asperities from one surface come into closer contact with a softer surface. These asperities flow through the material, cutting the softer surface and leading to the generation of wear debris and material loss. Many factors affect abrasive wear, such as the size, shape, and concentration of abrasive particles, the applied stress, the relative motion, and the sliding-to-rolling ratio present. Adhesion and abrasion can happen independently or simultaneously in real-world situations. For example, if an abrasive particle has a stronger bonding force towards the material, it can also cause adhesive wear.

And once adhesive wear occurs, it can lead to the formation of wear debris, which in turn can cause abrasive wear. So, this kind of wear mechanism can also occur simultaneously. As you may recall, we covered adhesive wear and abrasive wear earlier. Now, I'd like to highlight a few features or diagrams that we have already discussed. In adhesive wear, the bonding force between the two surfaces is crucial. This bonding force leads to the formation of a plastic zone or what we refer to as micro-welding. When relative motion is applied to one of the surfaces, there is a possibility that material will transfer or detach from the softer surface and attach to the harder surface. This transfer or removal of material ultimately results in the formation of wear debris.

And Archard's equation was developed for adhesive wear. Archard's wear equation is essentially qualitative because it involves many variables. Even if we repeat the experiments under the same conditions - same load, sliding distance, and hardness - we might get different results. So, we introduce a statistical parameter known as the wear coefficient, denoted as K_1. This K_1 is inherently probabilistic; it varies and should always be less than 1, indicating the probability of wear and particle removal, but not exceeding 1. This is what we've learned about adhesive wear.

As for abrasive wear, it can involve either two asperity contacts or three-body abrasion. Rabinowicz's equation was derived for this type of wear in our lecture. In this case, we learned that wear volume can be calculated using this equation, where W represents the applied load, L is the sliding distance, and H is the hardness of the softer surface. Again, K is a probabilistic factor representing the probability of wear debris generation. We can relate both probabilities, K_1 and K, with a wear curve. We've discussed the bathtub curve, where rapid wear occurs in zones A to B and C to D. Meanwhile, wear in zone B to C remains relatively constant, gradually increasing. For consistent results, the constant K or K_1 should mostly relate to the BC zone. Otherwise, repeatability might be compromised.

The reason for this lies in the initial surface conditions, where surface asperities are sharp. Over time, during the running-in period, these asperities become less sharp, possibly forming a curvature at the bottom. Initially small angles α may increase, resulting in larger angles like 80, whereas initially they might have been 20°-40°. This adjustment affects the overall angle 2α, making it around 150° - 160°. This change in angles affects the interpretation of α, which might not be represented in degrees, as we learned in lectures 3 and 4.

And to reiterate, K represents a probability, and K_1 is a probability equal to 1 when every junction involved in the process of adhesion or abrasion results in wear debris, indicating 100% failure. For instance, if K or K_1 equals 0.1, it means that one-tenth of the junctions in contact will generate wear debris. Conversely, when K or K_1 equals 10^{-7}, only 1 wear fragment will be generated in 10 million contacts or repeated contacts. It's advisable for the wear factor to be 10^{-7} or even lower, as it ensures prolonged product life.

Sometimes, because this process closely resembles fatigue, we refer to it as a micro-fatigue process. We've learned that the wear coefficient plays a significant role, hence the numerical value assigned to it. Now, let's talk about dimensionless parameters. In reality, numerous parameters exist, making it impossible to quantify or consider them all. Hence, we need an alternative approach, which is where dimensionless parameters come in.

To illustrate, let's consider an example where we have a hard steel surface with an array of conical asperities. Each conical asperity has a different cone angle. Although Rabinowicz described this as a generation without single asperity, in reality, it involves multiple asperities, leading to variability. This variability is why we rely on probabilistic and statistical methods, necessitating multiple experiments to yield accurate results. Due to its statistical nature, one experiment may produce different results from another.

So, that's why we're using this example to grasp what's happening. We talk about an array of conical asperities, assuming an average cone angle of 120°. This is just a convenient assumption for theoretical purposes or to understand mechanics and make predictions, although it might not be completely accurate. It helps us grasp the concept and compare different materials. That's why dimensionless numbers are crucial; they allow us to compare materials, but they're not absolute. We can't definitively say one material is the best in all situations among a set of materials; it depends on the context.

In any experiment or result we obtain, having a solid understanding is key. Without it, we'd need to conduct countless experiments. With knowledge and understanding, we can reduce the number of experiments needed and achieve more conclusive results. So, in this case, let's assume an average cone angle of 120° and a given load of 15 Newtons, although we won't consider this load in our calculations. Rabinowicz's coefficient can be determined based on the cone angle, but in reality, we'd need additional parameters like sliding speed, volume changes, hardness, temperature, and vibration.

For simplicity in this example, let's calculate the wear coefficient and observe how it changes as the asperity angle or cone angle varies between 60 and 180°. This numerical exercise helps us understand the underlying mechanisms better.

To summarize the given data, we have a conical angle of 120°, so the half angle, represented as α, will be half of that, which is 60°. The applied load may not be necessary to consider because we have α available, and for abrasive wear, the coefficient is typically given by $k = 2 / (\pi \tan\alpha)$. So, if we're given α, we might not need to factor in the load. However, for the sake of the example provided, we'll consider the given data.

If we want to simulate or analyze this numerically, we'll need software. Fortunately, MathWorks has agreed to provide free access to MATLAB for all students, along with tutorials. This way, students can learn MATLAB, practice with exercises, and we can provide them with relevant exercises based on that.

For our initial exercise, we've written a simple MATLAB code. Given the provided data, we're given θ in this case because it's 120°. However, if we're asked to determine the angle when it varies from 60° to 180°, we'll need to perform additional calculations.

So, MATLAB provides quick and accurate results. We set θ to vary from 60° to 180° with an increment of 1°, making calculations smooth and efficient. Doing these calculations manually would be time-consuming and unnecessary. That's why we prefer using code, which gives us results in just a fraction of a second. The angle of the conical asperities, denoted by α, is crucial, and we calculate it as $\theta/2$. The applied load isn't necessary for these calculations.

Once we know α, we can easily find the value of K using the formula $2 / (\pi \tan\alpha)$. MATLAB already recognizes π, so there's no need to input its value manually. We convert α from degrees to radians for the calculation using the function deg2rad. This gives us the value of K quickly, as we increment from 61 to 180, step by step.

As we calculate, we notice that the wear coefficient decreases as the asperity angle increases. This means that as the cone angle gets larger, the aggressiveness of the asperities decreases. This is crucial information for us, showing that as the edges become more rounded, they're less likely to cause wear.

Around 60°, the wear coefficient might be 1 or even lower, indicating better performance. The absolute value for a 120° cone angle gives us a constant value of 0.368. This suggests that in reality, we should consider a multi-asperity model rather than a single one for accurate predictions. When comparing wear coefficients, lower values indicate better results, guiding our design decisions.

This equation is essential because, despite numerous equations in literature, none provide a complete and foolproof solution. That's why we rely on experimentation to fine-tune our understanding. Every experiment introduces different variables like lubricants, humidity, temperature, and rigidity, which affect the results.

So, conducting experiments is crucial, which is why we emphasize the use of non-dimensional numbers. For comparison purposes, we can and should utilize dimensionless wear coefficients. But how do we determine what's good or bad? Well, if the wear rate exceeds 0.001 or the wear coefficient is greater than 0.001, it's considered unacceptable, and we should discard those solutions.

On the other hand, if we consider micro-fatigue and find that the wear coefficient is less than 10^{-7}, then we know the system is functioning well. In that case, we can focus on further reducing the wear coefficient, aiming for values like 10^{-14} to 10^{-16}, entering the ultra-mild wear domain. It's important to remember that wear is inevitable when two surfaces come into contact. Our goal is to minimize it through engineering and scientific efforts.

To elaborate on what I've mentioned, we can conduct a comparative analysis of wear phenomena using dimensionless parameters. Stress is one such parameter, and you're likely familiar with another: the coefficient of friction. In reality, we need both the wear coefficient (K) and the coefficient of friction (μ) for a comprehensive understanding. Both are essential for achieving completeness in our analysis.

The coefficient of friction has been covered extensively in other courses, so I won't dwell on it here. Instead, I'll focus solely on the non-dimensional wear coefficient. This dimensionless matrix helps engineers and scientists analyze wear phenomena more effectively. It allows us to examine various factors such as load, sliding distance, material characteristics, thermal aspects, density, and porosity, and compare them in different ways.

Another crucial factor is the contact condition. Sometimes, a contamination layer can significantly reduce wear, while other times, it can increase it. Therefore, we need parameters like the dimensionless wear coefficient to make comparisons and draw conclusions.

There are many other parameters that can affect system performance. Changes in system rigidity can lead to variations in contact and vibration phenomena, altering friction coefficients. Test environments may also change, with factors like pollution, gases affecting wear and corrosion. In one complete lecture, we cannot explore the effects of the environment on wear phenomena and surface degradation.

Now, when it comes to wear phenomena, we understand that every wear process involves numerous variables. Even in adhesive wear, there are approximately 25 variables to consider if we delve into a micro model. However, many of these variables are difficult to measure, presenting a challenge in accurately accounting for them. Therefore, wear phenomena itself is inherently statistical, and the wear coefficient reflects this statistical nature. We rely on the wear coefficient for repeatable results, understanding that it's not an absolute value but rather a tool for comparison. It allows for qualitative comparisons among materials or lubricants, providing valuable insights through the use of non-dimensional numbers.

As mentioned earlier, the friction coefficient is another non-dimensional number you've likely encountered in previous courses. It's essentially the ratio of the frictional force to the normal force acting on surfaces. This coefficient plays a crucial role because it determines the level of interaction between surfaces. For instance, in metal-to-metal contact, a lower coefficient of friction significantly reduces frictional forces. Conversely, higher coefficients of friction can lead to energy loss and temperature rises, potentially altering material properties and causing variations in wear.

Therefore, the dimensionless nature of this parameter makes it critical in controlling wear phenomena. However, it's important to note that while the friction coefficient is a critical factor, there's no direct correlation between it and wear. A high coefficient of friction doesn't necessarily mean high wear, and vice versa. It varies depending on the specific circumstances.

Now, let's consider the wear coefficient. Like the friction coefficient, it's also dimensionless and indicates the rate of wear. A high wear coefficient suggests a significant rate of wear, which may necessitate design changes, material modifications, adjustments to temperature conditions, or the application of coatings or lubricants to mitigate wear effects.

So, that's what we control. It's also connected to sliding distance, which we've discussed in both adhesive and abrasive wear. Additionally, it depends on the normal load and material characteristics, especially hardness, although toughness is equally important. Toughness plays a significant role in wear volume. Sometimes, instead of the normal load, people consider contact pressure, which is deemed more realistic in certain situations. Others opt for compressive/contact stress. These choices depend on the specific wear mechanism being explained.

Sometimes we use a normal load, sometimes contact pressure, sometimes compressive stress, but when we conduct experiments, it's the dimensionless wear coefficient that makes the most sense to us. Now, why are we explaining so many things? It's because nothing is absolute. Let me give you an example from the literature, like in the ASM handbook. They mention the case of an auto engine camshaft, where they avoid complete hardening procedures. Why? Because such procedures can lead to cracking or a reduction in toughness, which increases the wear rate. So, while wear equations suggest that increasing hardness yields better results, going beyond a certain hardness compromises toughness, turning a material brittle instead of ductile.

Thus, we need an upper limit on hardness, and we find this out through experiments. If we notice that increasing hardness also increases the wear coefficient, something is amiss. It means other mechanisms are now playing a major role compared to the existing ones. Take another example: some brake materials wear out much faster at low speeds. Typically, increasing speed increases sliding distance and wear, but not always. Certain configurations and grain structures might make them wear more at low speeds. This highlights the importance of understanding different mechanisms.

Finding the wear coefficient provides valuable input for brainstorming solutions. It helps us realize when something isn't working as expected, prompting us to reconsider our assumptions and adapt accordingly. Another example: hardened steel wears out more quickly at high sliding speeds. This underscores the importance of not solely relying on literature. We need to conduct simulated testing, where we perform real experiments under specific conditions, such as load and rotational speed, to obtain accurate results.

Ultimately, wear behavior is influenced by numerous factors, including material properties, surface condition, lubrication, temperature, and contact geometry. More knowledge equips us better to find solutions. Some might feel overwhelmed by the numerous parameters, but simply conducting experiments isn't always enough. Understanding the system in-depth is crucial for reliable results.

Understanding comes from delving into the literature and creating setups that yield accurate results. That's what we're aiming for. Therefore, knowledge of the wear coefficient is crucial, especially for comparing and analyzing wear properly. The wear coefficient is vital for comparing different materials, lubricants, temperatures, and hardness levels. When comparing wear phenomena like adhesive and abrasive wear, expressing them in dimensionless form is helpful for evaluation and understanding their severity. I've listed four bullet points to summarize:

1. The wear coefficient helps quantify and compare the severity of abrasive and adhesive wear. In future lectures, we'll cover more types of wear mechanisms that can also be compared using wear coefficients.
2. Knowledge of the wear coefficient aids in selecting appropriate materials and coatings. It helps determine which materials or coatings will perform better based on their wear coefficients.
3. Similarly, when choosing lubricants or surface treatments, understanding the wear coefficient guides us in selecting the most suitable options.
4. Maintenance frequency can also be determined using the wear coefficient. Systems with very low wear rates, such as ultra-mild wear (around 10^{-19} or 10^{-20}), may not require frequent maintenance, if any at all.

Moreover, we also consider product reliability; if the wear coefficient is very low, product reliability will increase further. This will reduce downtime and result in cost savings, making it economically beneficial. Another advantage, as mentioned earlier, is that it provides a relative measure of severity and material loss impacts. These are just a few of the many benefits of the wear coefficient.

Let's consider a couple of examples related to the wear coefficient that often come to mind. The first question might be: How can experimental data from a pin-on-disc tribometer, which we will discuss in future lectures along with other types of tribometers, be utilized? Besides the pin-on-disc setup, another common setup is the 4-ball tester. With these setups, experimental data can be gathered to determine the wear coefficient. So, how can this data be used to compare the performance of lubricants or materials? It can serve for both material and lubricant comparisons. Even if the same material is used, different lubricants can be compared based on their performance under the same conditions.

Question 1: How can experimental data from pin-on-disc tribometers and 4-ball testers be used to compare the performance of lubricants or materials?

Using dimensional wear coefficients, we have a simple rule: the lower, the better. A very low coefficient value indicates better material or lubricant performance. Moreover, this approach can be standardized, allowing for qualitative or quantitative comparisons, depending on the precision of the experimental setup. Sophisticated equipment may enable quantitative comparisons at the nano or macro level, whereas at the macro level, qualitative comparisons are more common. This enables ranking of materials and evaluation of various lubricants based on their performance and efficiency.

Question 2: What is the significance of comparing wear results using wear coefficients?

When comparing wear results using wear coefficients, the influence of specific test settings is eliminated. This ensures a fair comparison across different materials, despite variations in test conditions. It standardizes comparisons across different test techniques or setups, removing biases introduced by specific testing methods. Otherwise, different test setups could yield conflicting results, leading to misleading interpretations based on test settings alone.

Now, if we're comparing the same materials and the same lubricant, we'd expect similar results. If there's some variation, it prompts us to think about why it's happening. Is it due to surface roughness? Or perhaps the test samples we've used are different? This leads to critical thinking, allowing us to delve into design philosophy and rectify any underlying issues. Another question arises: what are the benefits of using the wear coefficient to assess lubricant and material performance? To some extent, I've already explained this, but I'll elaborate here. The wear coefficient provides numerical values, which are essentially numbers, and for engineers, numbers are crucial.
In engineering, it provides you with numerical data, allowing for comparison. I'm using the term "quantitative comparison," but it's relative, not absolute. Don't rely solely on absolute values.

This means it's always present. In one setup, results are given. With four materials, five materials, ten materials, or even a hundred materials, we can compare them. However, changing the setup may yield slight differences in results. The ranking may remain the same, but absolute values could vary. Therefore, we opt for relative values and rankings to choose the best material or lubricant. From an evaluation standpoint, these rankings provide valuable insights. Often, they offer repeatability, despite being statistical.

So, we typically use a bar diagram or a bar chart, or maybe even provide a range, showing variations in the coefficient of friction or wear coefficient within a certain range. Due to their statistical nature, these results won't be exactly the same each time. There will be variations, but they'll be consistent within that range. This allows us to optimize surfaces; for instance, when selecting a coating, we opt for one that delivers optimal performance. Similarly, we choose lubricants based on their performance, aiming for optimization. Another advantage is that it provides a standardized method for comparing lubricants and materials.

In my opinion, the wear coefficient should be utilized. While you've already learned about the coefficient of friction, we'll eventually compare both. The wear coefficient is a relatively new concept compared to the well-known coefficient of friction, but it's gaining traction. In future discussions, we'll provide numerous examples of wear coefficient comparisons and demonstrate how to rank materials, coatings, and lubricants accordingly. Thank you for your attention.