Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 05
Abrasive wear mechanism

Hello and welcome to Lecture 4, Wear Mechanisms. We will be focusing on abrasive wear mechanisms. The primary mechanism we'll be discussing is abrasion. To begin, let's recap what we covered in our previous lecture on adhesive wear. As I mentioned, in this lecture, our focus shifts to abrasive wear. In my perspective, abrasive wear emerges as a more dominant and extensively applied wear mechanism.

Adhesive wear can lead to the abrasive wear, and we know that environmental dust particle may get involved in wear mechanism. So, that is why the abrasive wear is more common compared to any other wear mechanisms. As I previously stated, before delving into abrasive wear, let's recap what we discussed regarding adhesive wear. We highlighted that adhesive wear predominantly affects metallic surfaces due to the potential exchange of electrons, resulting in the formation of strong bonds.

When metal comes into contact with a reactive non-metal, for example oxygen, fluorine or even PTFE, it tends to undergo abrasive wear or potentially forms strong bonds. Additionally, we mentioned that high hardness levels can mitigate adhesive wear. Why is this the case? High hardness prevents easy deflection or deformation, thereby inhibiting metal asperities from coming into close proximity. Electronic transmission necessitates a specific distance between atoms, typically one to two atomic distances, which becomes unattainable due to the lack of deformation. Hence, hardness indirectly influences adhesive wear significantly.

Another point I mentioned concerns the interaction between metals and non-metals. If the non-metal is reactive, it behaves akin to a metal, forming strong bonds and leading to adhesive wear. There's a possibility that adhesive wear may eventually evolve into abrasive wear, a topic we'll delve into further. Additionally, I noted that adhesive wear results in the formation of debris, which serves as the medium for abrasive wear.

Another point we discussed concerns increasing the complexity of the structure to minimize adhesive wear. I provided an example comparing steel to iron, highlighting steel's superior performance in certain contexts. Additionally, we introduced the concept of the wear coefficient, which is linked to the probability and severity of adhesive wear. A higher value indicates greater chances of adhesive wear, while a lower value is preferable for product durability. Therefore, selecting appropriate materials, increasing hardness, and aligning operating parameters with requirements are essential for minimizing wear.

We also addressed the transition from adhesive wear to abrasive wear in that lecture. Abrasive wear can be categorized into two types: two-body abrasion and three-body abrasion. The former occurs when surface asperities interact directly, while the latter involves the presence of hard particles or asperities from the environment. Furthermore, abrasive wear varies depending on the ductility or brittleness of the metal and the shape of the particles, leading to four subdivisions.

The first subdivision is micro-cutting, akin to a cutting tool, where soft material is chipped off. If the hardness of the surfaces is similar, micro cutting of the soft surface becomes challenging. In cases where the opposing surface incorporates debris or asperities of higher hardness, abrasion of the softer surface occurs. The extent of abrasion depends on which surface is softer, potentially resulting in abrasion of the soft surface. If the surface is soft, abrasion of this surface will occur due to relative motion between the surfaces, with the major role played by the sharpness of the asperity. Sharp particles or hard asperities cause micro-cutting, resulting in the removal of material as wear debris. Consequently, material is removed from the surface.

Another mechanism in abrasive wear is micro-fracture, which occurs predominantly in brittle materials at the micro-scale. Sliding of brittle materials can generate micro-cracks below the surface and within the asperities themselves. Repeated sliding actions cause these micro-cracks to propagate and connect, eventually leading to surface fracture in a fragmented manner. Initially, tiny cracks form below the surface, eventually leading to surface fracture or the formation of micro-sized pits due to the merging of small cracks.These two subdivisions of abrasive wear, micro-cutting and micro-fracture, are common. Micro-cutting predominates in ductile materials, while micro-fracture occurs in brittle materials.

Two more subdivisions exist: micro-fatigue and grain removal. Micro-fatigue occurs in ductile materials, where sharp particles or asperities are typically blunt, preventing the formation of grooves on the soft surface. Conversely, in brittle materials like ceramics, grain removal occurs due to weak grain boundaries, causing entire grains to be removed as wear debris.

This scenario describes what happens when a ductile material is abraded by a blunt particle or asperity: cutting becomes unlikely as the particle cannot act as a cutting tool, as seen with sharp particles. In the case of a sharp particle, cutting occurs due to its shape. However, with a blunt particle at the bottom, material removal is hindered. Continuous motion, such as reciprocating or cyclic loading and unloading, exacerbates the situation. Even if there's no reverse motion and only one-directional movement, the particles and asperities in contact tend to push the material, creating built-up edges. Subsequent cycles of loading and unloading result in the formation and detachment of multiple edges. This process, occurring due to the interaction of numerous asperities, leads to micro-fatigue abrasive wear in ductile materials.

For this type of wear, three factors are essential: the ductile nature of the material, the bluntness of the particles or asperities, and the presence of loading causing sliding or cyclic stress.

Moving on to grain removal, materials like ceramics often have weaker grain boundaries. In this case, when debris attempts to remove material, it directly targets the grains. This action can lead to the complete removal of entire grains, hence the term "grain removal."

These are the four primary subdivisions of abrasive wear. To summarize, during micro-fatigue abrasive wear, the ductile material remains essentially intact for numerous cycles, ranging from 10^5 to 10^7, depending on various conditions. Eventually, however, it transforms into wear debris, acting as abrasive particles.

Another noteworthy aspect of understanding wear mechanisms is the similarity between abrasive wear and two related mechanisms: erosion wear and cavitation wear. We'll delve into these topics in our next lecture. The similarity arises from the interaction of particles with a surface and the presence of velocity. In erosion wear, particles exhibit high velocity and impinge at various angles, termed the angle of attack, resulting in erosive wear. However, the particles ejected during erosion wear resemble those in abrasive wear, highlighting numerous similarities between the two.

Similarly, in cavitation wear, instead of solid particles, liquid particles are involved. Due to negative pressure, these particles impact soft surfaces. The collapse of liquid bubbles under compression generates high-pressure impacts, removing material from the surface, thus termed cavitation wear. However, these topics—erosive wear and cavitation wear—will be discussed in detail in the subsequent lecture, emphasizing their similarities with abrasive wear.

To summarize the content covered in the previous slides, we distinguish between sharp-edged and spherical-shaped asperities. The mechanism of abrasion differs based on this distinction. Spherical asperities are more likely to cause micro-fatigue in ductile materials, while sharp-edged or conical asperities induce micro-cutting. However, in practice, a mixture of rounded and conical asperities is often observed, leading to a combination of mechanisms in abrasive wear, particularly in ductile materials.

When discussing brittle materials, instead of fatigue, a micro-fracture mechanism is at play. Micro-cracks develop beneath the surface, merging to form larger cracks, resulting in pit formation and particle expulsion. This phenomenon is characteristic of brittle materials. Additionally, brittle materials may exhibit weak grains, leading to the entire grain being dislodged from the parent material. Hence, there are four mechanisms of abrasive wear, as previously mentioned.

Furthermore, there are notable similarities between abrasive wear, erosive wear, and cavitation wear. The main difference lies in the kinetic energy of the particles involved. In erosive wear, particles impact the material with various velocities, potentially causing different mechanisms of wear for ductile and brittle materials, which we will discuss in the next lecture.

In cavitation wear, the formation and bursting of bubbles due to negative pressure result in high-pressure fluid impacting and damaging the surface, akin to abrasive wear mechanisms.

Now, transitioning to the discussion on two-body and three-body abrasion, we'll explore their respective mechanisms. In two-body abrasion, only two surfaces are considered, each with asperities. These asperities, such as conical ones, act as cutting tools, with the asperities of the harder surface interacting with the softer surface.

What does this mean? Let's assume that material 2 is harder. Initially, let's assume there's no relative motion between material 1 and material 2. However, under load, asperities will embed into the soft surface. Now, if we introduce relative motion, these embedded asperities, being part of material 2 or surface 2, will start to move. This movement can lead to groove formation and possibly the building of edges.

This mechanism is referred to as two-body abrasion. Here, the normal load causes harder asperities to penetrate weaker surfaces, resulting in plastic deformation, as shown in the diagram. Additionally, when velocity is introduced, a combination of micro-fatigue and micro-cutting removal occurs. Micro-fatigue involves building at the front, while micro-cutting involves groove formation, particularly in ductile materials. Conversely, in brittle materials, although the mechanisms are similar, the outcomes differ, resulting in micro-fracture or grain removal from softer surfaces.

To recap, in ductile materials, we consider micro-fatigue and micro-cutting, while in brittle materials, we consider micro-fracture or grain removal. Regardless of the material type, wear debris generation occurs, leading to a three-body abrasion scenario eventually. Initially, we discussed two-body abrasion, but eventually, these wear particles act as a third body. As discussed in a previous lecture, adhesive wear can lead to three-body abrasion.

Now, let's consider a few examples. We often observe two-body abrasion in manufacturing processes, industrial equipment, and automotive parts. This mechanism is prevalent across various machines and is a dominant failure mechanism among wear mechanisms.

For instance, when using emery paper, almost everyone has experienced the removal of material from a surface. This is a form of two-body abrasion, where the asperities on the emery paper interact with a soft surface, causing material removal and deposition onto the paper's grid. The degree of abrasion depends on factors like speed, pressure, hardness, surface roughness, and the presence of lubricants or contaminants. Lubricants can help reduce abrasion, although they come with their own considerations, including cost and related parameters. In summary, controlling speed, pressure, hardness, surface roughness, and the presence of lubricants or contaminants is crucial in reducing abrasion wear when other options are limited.

These are important aspects I'm illustrating here, comparing the hardness of the hardest and softest surfaces. When the hardness of surface one and surface two are nearly identical, resulting in a ratio close to one, it implies a comparable level of hardness. However, due to the inherent limitations in hardness measurements, there's a possibility of a ±20% variation. This variation is typically observed in experimental data, with results falling within this range. Consequently, when conducting numerous experiments, the data points often fall within this bracket. Moreover, when maintaining a ratio of one between the two surfaces, we observe a minimized wear rate, as depicted in the graph.

Another consideration arises when the ratio is notably high, where hardness of one surface may dominate. For example, if H_{s1} is ten times that of H_{s2}, the wear rate naturally increase rapidly, potentially by nearly 1000 times. Consequently, a tenfold increase in hardness could result in a wear rate increase of 500 to 1000 times. Thus, it's imperative to maintain balance in this ratio and ensure that the hardness of both the surfaces remains similar, especially in instances of two-body abrasion. Hence, we emphasize that hardness plays a significant role in two-body abrasion, and the relative hardness ratio (H_{s1}/H_{s2}) should ideally be close to 1, avoiding significant deviations. However, if a single material is preferred, it's recommended that material 2 be designated as the sacrificial element.

So, if we introduce a sacrificial element in this case, we can opt for a material with lower hardness. This means that the material will be more affordable, allowing us to replace it as needed. This is often the case with certain bearings, especially those with long stainless-steel shafts. These shafts tend to be costly and challenging to replace or reassemble in terms of difficulty. Hence, bearings are frequently used as sacrificial elements, as they maintain a lower hardness. In a previous lecture, we discussed an example where the surface hardness of steel shafts was high, while the bearing surface was intentionally kept lower. So, to ensure the shaft stays intact, it's crucial that the hardness H_{S1} is no more than 1.2 times greater than H_{S2}, which would result in minimal wear on surface 1. If this ratio exceeds 1.2 or is close to it, we might notice scratches on both surfaces. Therefore, it's important to determine if the material being used will act as a sacrificial element. If neither material is sacrificial and both are expensive, we should aim for a ratio close to 1. Additionally, lubrication might be necessary to reduce wear to a minimum. Now, consider another scenario where brittle materials are used. Here, we need to pay attention to their phase structure. In this case, the grains are shown to be uniform and fine. So, even if debris or asperities come into contact with the brittle material, they may chip away a small amount of material, but won't cause significant damage by removing large chunks.

In this scenario, the material removal rate will be lower. When dealing with a heterogeneous surface, where grains vary in size, such as grain 1, grain 2, and grain 3, we observe a higher grain size. Consequently, we might notice different types of wear patterns, like individual grains being removed or the formation of larger and longer pits. Therefore, it's advisable to avoid a heterogeneous phase structure when it comes to two-body abrasion or abrasion in general.

So, it's crucial to eliminate heterogeneous phase faces and choose homogeneous ones instead. We emphasize the importance of keeping the grain size as small as possible, as illustrated by this curve. When the grain size is less than 1 micron (1μm), the wear rate decreases. Conversely, if the grain size increases, for instance, by 12 times, failures can surge by 70 to 100 times. Therefore, it's imperative to maintain a low grain size, ideally as minimal as possible. This information is essential to consider as we attempt to quantify abrasive wear and two-body abrasive wear, having already quantified adhesive wear.

So, this is where Rabinowicz introduced an equation that we're going to discuss in detail. His assumption was to consider a conical cavity or asperity, as shown here, with an angle α. The total asperity angle becomes 2α. When under load, the hard asperity penetrates the soft surface to a depth x, as illustrated. We assume the cone angle to be 2α overall, as depicted. What Rabinowicz assumed is that during motion, this conical asperity indents the soft surface and can travel either to the right or left, depending on the requirement.

Another consideration is that, similar to adhesive wear, we assume plastic deformation and the complete removal of material as wear debris. Consequently, we derive a single wear coefficient that represents the probability of material removal as wear debris. These assumptions align closely with those made in adhesive wear quantification. Additionally, Rabinowicz introduced the concept of an "nth asperity," where multiple asperities are considered, unlike adhesive wear, where we typically focus on the ith asperity. Each asperity of the nth order experiences a load, denoted as W_n, equivalent to the hardness of the soft material multiplied to contact area. The soft material, characterized by its hardness H, is assumed to have a specific area of penetration, as illustrated by the diameter of the cone being 2a. If we denote the radius as "a," the area is πa^2, as depicted here, which is crucial for our analysis.

So, the average contact area turns out to be 0.5 x πa^2. When we multiply this by the hardness, we get the load sustained by the nth asperity. However, as we're aware, the value of "a" is not directly known to us, similar to how we dealt with adhesive wear. Instead, a^2 is expressed in terms of the load on W_n divided by 0.5Hπ, following a similar approach. Another aspect we consider, just like in adhesive wear, is the volume swept by the asperity penetrating the soft surface. As it moves, it naturally sweeps material, and this volume is calculated by multiplying the radius by the depth of penetration and the sliding distance. Additionally, we employ the triangular geometry to represent this scenario, where parameters like α, x, and "a" are given values.

So, the value of "x" remains the same. I can express "x" in terms of "a" and α, as mentioned here: a / tanα. This means "a" is already here, divided by tan alpha. We can replace a^2 with this equation, bringing in a and substituting a^2 with $W_n/0.5H\pi$. This gives us the volume swept by the nth asperity, assuming 100% material removal from the surface. These assumptions align closely with those already studied in adhesive wear. If we want to evaluate the total wear, it will be the sum of wear caused by individual asperities. In this case, we assume n equals 1, but it could range from another value, perhaps up to a last one denoted by capital N, or we might consider M.

However, to keep things simple, we assume "i" varies from 1 to N, representing the range of asperities. This W_1 denotes the load, assuming all asperities have a similar angle. We maintain this angle consistently throughout, considering it as a probability and counting it separately. The total applied load is the sum of the loads imposed by each asperity on the soft surface, including sliding distance and a geometry-dependent factor. This factor varies based on the tanα, determined by the geometry. It's essential to note that this factor can be considered a wear coefficient in this context, similar to how we discussed wear resistance in adhesive wear. The principles we learn in adhesive wear can be extended to abrasive wear as well. In both cases, total wear from a surface is proportional to the normal load and depends inversely on hardness while being proportional to sliding distance. Additionally, microstructure, specifically the asperity angle (α), plays a crucial role.

If we calculate the value of K in terms of α, we can assume different angles: 10°, 20°, 30°, all the way up to 80°. This represents a spectrum from sharp to flat, eventually approaching round. A round surface typically experiences minimal cutting and is more resistant to wear over many cycles. For instance, with an angle of 80° and an overall angle of 160°, the wear coefficient is only 0.11. Conversely, in a hypothetical case with an angle of 10°, we won't see sharp peaks, as they would break immediately or shift to angles like 40° or 45°, resulting in a wear coefficient less than 1. This example illustrates how the wear coefficient changes dramatically, approximately 360 times, as the angle α varies from 10° to 80°. It's crucial to consider these factors when designing surfaces to minimize abrasive wear, including the necessary hardness and normal load. Next, we'll transition to three-body abrasion from two-body abrasion, noting the similarities between the equations developed for each and those for adhesive wear.

Now, when it comes to three-body abrasion, the third body essentially refers to a foreign particle generated during the mechanism, whether it's due to adhesive or abrasive action. Unlike two-body abrasion, which involves just two surfaces, three-body abrasion introduces this additional particle as a third body. Despite initial concerns about which type of abrasion is more harmful, research indicates that three-body abrasion is actually less damaging than two-body abrasion. The reason behind this lies in the fact that the third body, being a particle, can engage in a rolling action rather than just sliding. This rolling action reduces direct contact with the surfaces, minimizing wear. It's noted that the ratio of sliding to rolling is approximately 0.2, further supporting the idea that three-body abrasion is less severe than two-body abrasion. Additionally, two-body abrasion may eventually transition into three-body abrasion over time. For instance, if the wear coefficient for two-body abrasion ranges from 5×10^{-3} to 50×10^{-3}, in three-body abrasion under similar conditions, this coefficient might be around 1/10 of that. However, it's essential to conduct experiments to validate these findings, as these numbers provide qualitative rather than quantitative comparisons.

So, we should utilize this data to begin selecting materials and determining the necessary hardness and surface softness profile. Following this, conducting numerous experiments will help us arrive at the right solution. In this context, three-body abrasion is also mentioned, as seen in adhesive wear where oxide or worn-out particles can serve as the third body. This oxide's hardness depends on whether it's composed of hard or soft materials. For instance, in fretting fatigue wear, some iron oxides act as solid lubricants, while others become hard and contribute to three-body abrasion. We'll delve deeper into this topic when discussing fretting fatigue wear. It's worth noting that the abrasion may occur due to hard oxides, but there's also the possibility of soft oxides. To minimize damage, increasing clearance—larger than the particle size—and filtration can be effective measures. Maintaining clearance greater than the particle size, as illustrated, prevents damage to the surfaces.

However, we often can't control particle size growth. Initially, it might be 1µm, but continuous sliding can increase it to 3µm, 5µm, 10µm, or even larger if particles adhere due to high surface energy. To minimize damage from three-body abrasion, we must consider particle size and clearance. If clearance exceeds particle size, damage is reduced. Filtration is also crucial: as particles are generated, filtering them out helps. One way to achieve this is by texturing the surface to create spaces where particles can be trapped as they roll.

Therefore, there's a chance the particle won't reach the next surface. This is where surface texture comes into play, as mentioned earlier. By designing the surface with specific features, we can minimize wear. For instance, in earth-moving equipment, such mechanisms are crucial for reducing wear, emphasizing the importance of maintenance. Similarly, in slurry pumps, three-body abrasion is common, and particle size may fluctuate continuously.

When it comes to rock drilling, numerous particles are generated, potentially leading to drill failures. Similarly, in crushers or pneumatic transportation systems, transferring powder between locations can create high-impact situations, damaging pipes, or equipment. Even in powder metallurgy, dies with high hardness can gradually wear out due to particle removal, eventually leading to failure. Given the significant costs associated with maintaining such equipment, it's crucial to address these three-body abrasion issues. Additionally, failures due to two-body abrasion can eventually escalate into three-body abrasion scenarios. Hence, a comprehensive understanding of three-body abrasion and conducting practical experiments are essential for mitigating such failures.

Now, let's delve into the characteristics of particles themselves. Whether particles are round or sharp can significantly impact their abrasive nature. For instance, a particle with a round shape may be less abrasive than a sharp-edged one, even if both are of the same size, such as 50µm. Considering this, determining the roundness factor of particles becomes important for assessing their abrasive potential. Initially, abrasive particles may appear sharp, with a low roundness factor.

With continuous usage, it's likely that the roundness of particles will increase. This indicates a gradual chipping away at the edges, gradually smoothing them out. As this process continues, the roundness factor improves. When the roundness approaches a perfect circular shape, the roundness factor reaches 1. Thus, the range of roundness can vary from 0.1 to 1. A roundness factor of 1 indicates optimal roundness, signifying that the particle is safer compared to a sharp-edged particle, which tends to cause more damage.

The shape of particles significantly influences the type of wear experienced. It's not just about hardness, area of contact, or sliding speed; particle shape also plays a crucial role in determining the wear mechanism observed. For instance, particles with sharp edges, as depicted here, tend to cut faster, accelerating wear. However, operating machinery at lower speeds initially can help trim down these sharp edges over time. Many manufacturers recommend starting machines at lower speeds to allow hard asperities to round off gradually during operation. Subsequently, after the initial maintenance, the machine can be operated at full speed. This principle is commonly applied in automobiles. Abrasive particles can vary in shape, ranging from angular, which are sharper, to circular forms.

However, I also mentioned the flaky particles, which are mostly generated by adhesive wear. These particles come in the form of flakes or kind of plate-like shapes, a thickness that is almost negligible. They keep getting adjusted as per the situation without offering much resistance or causing extensive scratching. So, sometimes they are better compared to foreign particles. Let us consider silica dust particles, which have hardness of 1100 VHN, significantly higher and harder compared to the steel surface itself.

So, when these kinds of particles are present in the environment, we naturally need to think how to adjust and develop the right resistance. That is why in a previous slide, I mentioned examples like earth-moving equipment, slurry pump, and rock drilling. In these cases, all the particle hardness is very high, and we need to consider regular maintenance of those equipments. This is what has been mentioned.

Now, let's summarize what we've covered in the last few slides. Abrasive wear is largely influenced by grid characteristics, surface hardness, and material ductile parameters. Resistance to wear isn't solely a material property; it depends on the situation, and different materials may behave differently in various situations. Additionally, there's a possibility of encountering many different grid particles, not just sharp or round ones, but rather a mixture of particles. This results in wear tracks with multiple grid sizes showing impressions.

Therefore, the overall wear predicted using the Rabinowicz equation may not be as high as expected. This is because initially sharp particles tend to blunt over time, reducing the wear rate. Additionally, micro-cutting may transform into micro-fatigue, allowing materials to sustain numerous cycles, such as 10^6 or 10^7 cycles. Lastly, we've mentioned the importance of considering the hardness of the material in relation to the particle hardness.

In this case, when comparing the surface asperities, we establish a ratio of 0.8 to 1.2. I emphasize that if the surface hardness ratio is 1.2 or higher, the surface will remain intact. Similarly, if the particle hardness impinging on the surface is less than 1.2 times the surface hardness, it won't cause significant damage. Therefore, it's crucial to note that adhesive wear often generates particles that are softer.

I also provided an example involving iron oxide, which we'll discuss into further in a case of fretting fatigue wear. Iron oxide can vary in hardness, with some types being softer and others harder. This distinction is often reflected in colors, such as red, blue, and black oxides. We'll explore these variations in fretting fatigue wear. However, I also noted that maintaining the same hardness can be crucial. For instance, if both surface 1 and surface 2 have identical hardness, there may still be some scratching on both surfaces. Conversely, if the surface hardness exceeds 1.2, scratches are unlikely to occur.

Additionally, I mentioned silica or sand particles as an extreme abrasive material due to their high hardness, exceeding 1100 VHN. It's challenging to prevent these abrasive particles from coming into contact with surfaces and causing damage, so we need to consider strategies for prevention.

So, that's why we need to develop new technology, known as coating technology. This involves applying a surface coating, typically ranging from 50μm to 200μm in thickness, to maintain surface integrity. By creating a surface that's harder while keeping the core tougher, we can effectively address issues related to abrasive wear. We'll explore this concept further when we discuss coatings in more detail.

Now, let's consider a few more examples of three-body abrasion. I've often observed this phenomenon in automobiles, particularly in internal combustion engines, where efficiency loss occurs. Why does efficiency decrease? Well, because we often find scratches on main bearings due to particles present in the lubricating oil. Similarly, scratches can also appear on piston liners despite the presence of lubricants. These scratches can lead to variations in film thickness, causing insufficient support for the piston and potential misalignment. Moreover, larger debris or foreign particles can cause even more severe abrasion.

So, when the piston cylinder liner fails or the bearings fail in an IC engine, it leads to a loss of efficiency. Often, in older vehicles, they struggle to climb slopes due to excess clearance created during wearing processes. People suggest using textured surfaces to address this issue. For instance, smoothing out the top surfaces to eliminate peaks and asperities leaves only valleys. These valleys are effective in retaining particles, leading to what we call ultra mild wear. Removing these particles helps maintain the surface condition. This surface texture is crucial for performance. Additionally, if particles keep entering the oil, it degrades its quality and properties.

So, we need to change the oil regularly, or we can say that one good solution for all of this is regular maintenance. However, if we can incorporate all these concepts, we can come up with a very effective solution that addresses every situation. Let's consider another example that we covered in the initial lectures: brake pad wear. We showed that the original pad looks like this, and after wear, it looks like this. These pads are used in the disc or rotor, which is connected to a wheel hub. A car typically has four wheels, meaning a total of eight pads and four pairs of pads. Now, why does abrasive wear occur with these brake pads? We say abrasive wear is one of the most common causes of brake pad failure. Why? The reason is that dust and dirt come from the surface. I mentioned that dirt itself has a hardness of 1100 VHN, which is very high. Although some debris may not be harmful, dust and other particles can be harmful to this type of brake pad. They get into the brake pad and disc, and we know very well that when there is pressure from outside to apply the disc to stop using the brake pad, if particles get in between, they will be highly stressed. When particles are highly stressed and have high hardness, it causes a problem. One issue is that because of such particles coming between the pad and disc, there will be irregular control over the braking itself. We will not have full control over the brake. Another issue is that the disc will get worn out. So, it's not only about the wear of the brake pad, but there is also a possibility of wear occurring on the disc in this situation.

So, how do we address this kind of situation and prevent it? We suggest avoiding aggressive driving in dusty or unclean environments. Once we're aware of this, we can consider solutions. Continuously driving in such conditions can seriously damage the disc and brake pad. To mitigate this, we can either adjust the hardness of the disc and pad to withstand such conditions or opt for regular maintenance, perhaps changing the brake pad-disc arrangement every 3 or 4 months. Another option is cleaning. For instance, after driving in a dirty environment for about half an hour, cleaning the components thoroughly can remove particles, ensuring they're ready for the next service or ride.

Now, I'm attempting to compare abrasive wear and adhesive wear. You can observe adhesive wear on the surface, which appears smoother, while abrasive wear shows more irregularities. Soft surfaces tend to exhibit more irregularities, especially when subjected to abrasive wear, due to the variable sizes of wear particles getting dislodged from softer surfaces. In adhesive wear, such high variation in particle sizes is not usually found. You might notice some particles that appear flat like adhesive wear, but they are actually due to cutting, such as particles labeled as numbers 1, 2, and 3, coming from abrasive wear, showing significant variations. We often wonder how to distinguish between wear types after analysis.

Mostly, adhesive wear results in flat-like shapes on relatively softer surfaces, with shorter cuts, while in abrasive wear, the aspect ratio is different, leading to longer cuts. So, what's the key difference in wear debris between adhesive wear and abrasive wear? It lies in their size, shape, and hardness. Debris from adhesive wear typically has different sizes, shapes, and hardness compared to abrasive wear. In adhesive wear, the debris tends to be more plate-like, with a more or less rectangular shape, with not much variation.

Hardness of wear particles, emerging from softer surfaces, tends to be higher compared to the parent material in many cases. In adhesive wear, smaller flakes are present, often with a rectangular shape, and the debris is softer. However, in abrasive wear, the aspect ratio is larger, with dimensions ranging from 1 to 10, and the length is notably longer due to cutting. As a result, the shapes of the debris, such as those labeled 1, 2, 3, 4, and 5, are irregular, and they are generally harder compared to debris from adhesive wear. These are the main differences between abrasive wear and adhesive wear.

Let me share an experiment conducted in my lab to illustrate this further. In the setup, depicted with numerous annotations and arrows, we utilized a motor, a dynamometer, and loaded it to achieve the required speed and load. Additionally, we used two metal surfaces, labeled surface 1 and surface 2, to conduct the experiment.

Surfaces 1 and 2 were located in the gearbox, although they are not clearly depicted in the larger zoomed-in view. In this setup, the two surfaces come into contact, and after conducting numerous experiments, we observed particles in various shapes, resembling abrasive wear. We use the term "abrasive wear" here because we aimed to maintain a lubricated condition. When there is lubrication, adhesive wear is generally avoided or minimized. Therefore, there is a higher likelihood of occurrence of abrasive wear particles. For surface 1 and surface 2, we employed one gear with a number of teeth (T) 53 and another gear known as a pinion with a number of teeth (T) 27.

The harness was maintained at approximately 30, and this consistency helped reduce wear. The applied rotational torque was around 10 Newton per meter, and the rotational speed, measured in RPM, was set at 1200. This setup operated for approximately 200 hours, during which various types of particles were observed, including cutting particles, fatigue particles, and irregular particles. In the abrasive wear mechanism, we typically find flat particles and chunks that may result from adhesive wear. These particles, continuously moving between the two surfaces, can contribute to abrasive wear and potentially lead to changes in surface appearance.

Another example to debunk the myth that spherical particles do not cause abrasion involves an experiment similar to the one previously mentioned with the disc. Instead of traditional brake pads, we used a smart liquid known as MR liquid, short for magnetorheological liquid, to apply the brake.

So, what exactly is a magnetorheological liquid? It consists of iron particles, typically pure iron with a purity of over 99%. When magnetized, these particles align themselves, maintaining their shape even when subjected to relative velocity. Once the magnetic field is turned off, they return to their original shape. This unique behavior earns them the label "smart liquid." In this setup, the coefficient of friction ranges from 0.03 to 0.6, allowing for significant changes in friction within fractions of a second. One advantage is its environmental friendliness; unlike traditional brake pads, which release particles into the environment, the use of this green brake system prevents such pollution.

In our experiment, we created this green brake system enclosed within a setup, with the fluid containing a high concentration of iron particles, typically ranging from 80 to 90% by weight, with a particle size of 20 microns. The microstructure resembles a starry sky due to the multitude of particles. Through testing, we observed minimal wear on the disc, eliminating the need for brake pads exposed to the environment, hence the term "green brake." However, we did notice wear on the disc, evidenced by wear circles, with wear increasing towards the outer edges. This wear displayed characteristics similar to abrasive wear, with irregular fractions, deep scratches, and pit formations on the disc surface.

So, even spherical particles can cause damage, as demonstrated here in the case of abrasive wear. When subjected to sliding conditions, such as during braking when rotational speed is almost halted, spherical particles can still cause wear. In the close-up image, you can observe the brake disc embedded with particles, showing that even spherical particles, after undergoing plastic deformation, can become embedded in the disc. This shifts the abrasion from three-body to two-body, a significant change from initial assumptions.

Friction coefficients vary significantly in this scenario, and other parameters must be appropriately designed. Increasing the hardness of the disc brakes significantly compared to the particles proved effective in mitigating wear.

In conclusion, abrasive wear particles typically high loads get welded to the sliding surface. It can be said that material transfer between surface and particles occurs. In other words, abrasive wear under high load condition can lead to adhesive wear by transfer material from one surface (material 2) to another (material 1), as depicted here.

When it comes to abrasive wear, we categorize it into two types: two-body abrasion and three-body abrasion. In two-body abrasion, the wear coefficient is generally higher compared to three-body abrasion. This is because in three-body abrasion, there is a possibility of rolling, and the particles involved may not necessarily be in the same shape. Additionally, since the particles are not confined to either surface 1 or surface 2, they can roll and slide, with approximately 80% of the kinetic energy being consumed in rolling motion.

In contrast, when surface asperities are hard and most of the energy is consumed in abrading the other surface, abrasion tends to be higher in two-body abrasion compared to three-body abrasion. In our next lecture, we will delve into erosive and cavitation wear, covering wear mechanisms in lecture 5. Thank you.