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

Lecture – 08
Fatigue, Fretting, Melting and Diffusive wear mechanisms

Welcome to Lecture 6 of the course on Corrosion, Environmental Degradation, and Surface Engineering. The topic of this lecture is Fatigue, Fretting, Melting, and Diffusive Wear Mechanisms of Surface Degradation. The diffusive wear mechanism will be introduced in this lecture. However, we will cover this topic in detail in Lecture 11.

So, you might wonder how so many topics are being covered in this lecture. If you remember, in Lecture 1, we presented a slide about the material degradation mechanisms, or surface degradation mechanisms. And we say in mechanical action, we will be covering the wear and we will be covering the fracture. So, we are trying to complete this topic wear in in the present lecture.

We will be covering fatigue wear, melting, and diffusive wear in this lecture. As I mentioned, the diffusive wear model will just be introduced here, and we will explore it in detail in Lecture 11.In the seventh lecture, we will cover fracture mechanisms related to mechanical failure. In Lecture 8, we will discuss how heat and radiation cause surface degradation. Lectures 9 and 10 will focus on surface degradation due to chemical actions. In Lecture 11, we will explore the correlation between various mechanisms, explaining why the diffusive wear mechanism is often associated with other mechanisms.

We will cover the diffusive wear mechanism in detail in Lecture 11. Now, let's start with fatigue. As I mentioned, we will discuss fatigue, fretting, melting, and diffusive wear in this lecture. The reason for covering all four topics in one lecture is to provide a comprehensive overview of wear mechanisms. Another important point is that these mechanisms often coexist or interact with each other. For instance, fatigue can contribute to fretting corrosion, and sometimes fatigue can lead to melting, with adhesion and diffusion mechanisms being connected.

The wear coefficient in nearly all mechanisms will be much less than 10^{-7}. This indicates that, directly or indirectly, fatigue phenomena will occur in these wear mechanisms. Therefore, it is essential to cover all four topics in one lecture.

Now, what is fatigue? I assume everyone has some knowledge of fatigue. Fatigue occurs as a result of cyclic or repeated loading.

In this type of mechanism, every material will experience alternating or varying stresses and strains. Eventually, this kind of loading will cause crack formation and propagation. If the cracks become numerous and large, the product will ultimately fail.

Thus, in the overall mechanism, the initial fatigue crack often serves as a starting point not only in fatigue but also in fatigue wear. It can also be a starting point in melting wear.When discussing fretting, we refer to it as a form of abrasion. There is a connection because particles will form and remain in a localized area, causing additional wear. This is why three-body abrasion is closely related to fretting. Fretting occurs when there is oscillatory motion, leading to dynamic loading in one way or another.

However, the difference between fatigue and fretting lies in the scale of movement; fretting involves very small amplitudes, often on the order of 1 µm. So, that's a special case of fatigue. You might wonder how such small movements can cause significant failure—we will cover that in detail. Localized surface degradation from fretting may include material loss. The material will be lost but remain in the area, and if you open a connection, you will find a lot of debris. This can cause pitting and the accumulation of wear debris in one location, which requires a lot of energy to compress. These phenomena are all interconnected with fatigue loading in one way or another.

So, that's why many people refer to fatigue wear or fretting wear. You can find information on these topics through a Google search, as they are frequently discussed and described. Now, what are the important aspects? Stress concentration is crucial as it causes fatigue wear. As I mentioned, fatigue wear and fretting wear are related, with loading being oscillatory or dynamic. This results in fluctuations in load, torque, or speed during oscillatory motion, leading to fatigue wear.

One especial case of fatigue wear is severe wear, often referred to as melting wear. In previous lectures, we focused on ultra-mild wear, emphasizing that products should be designed to experience ultra-mild wear modes. However, melting wear represents severe wear, which requires careful consideration. Additionally, melting wear doesn't necessarily occur immediately; it may take many cycles to develop.

We need to continuously monitor and predict this type of wear well in advance. When considering melting wear, temperature becomes a critical factor. If the working temperature or the temperature at the contact point exceeds the melting point, localized melting will naturally occur. This means the metal or solid will convert to liquid.

Why does this kind of temperature occur? It can be due to environmental conditions or high-temperature conditions directly from the environment.

Another factor is frictional heat. When the coefficient of friction is high and the body cannot dissipate the heat effectively, insufficient cooling leads to temperature accumulation. Over time, this accumulated heat can reach the melting point of the material or surfaces. When melting occurs, hot surfaces are unable to dissipate the heat, resulting in volume loss and microstructural changes. This means that the original design intent will fail completely, as material properties and behavior will change. Therefore, we must avoid this type of wear by designing products and selecting materials in a way that prevents melting wear from occurring.

We need to place significant emphasis on this issue. Regarding diffusive wear, we have already discussed this mechanism in the context of adhesive wear. In adhesive wear, metals are more chemically active and can transfer electrons from one metal to another, or even from metal to a reactive non-metal. This is a critical aspect. However, in the case of diffusive wear, an additional factor comes into play: high temperature.

Diffusive wear does not occur at low temperatures; it is a slow process that does not happen instantaneously like adhesive wear. In this case, temperature is crucial. High temperatures can contribute to diffusive wear, especially if combined with melting wear, insufficient energy dissipation, lack of cooling agents, or inadequate lubrication. This type of wear is common in tool wear mechanisms, where the tool loses material to the chips, which are eventually discarded. While this material loss doesn't serve a purpose, it leads to tool wear that we need to prevent.

As mentioned earlier, we are covering all four topics in one lecture because these phenomena are interconnected and influence each other. Their interdependence means that they affect one another. For instance, inadequate heat dissipation can cause cracks, leading to fatigue. Once a crack is initiated, fatigue will aggravate it, and if the temperature continues to rise, melting may also occur. Fatigue can lead to localized melting, as wear particles generated during the fatigue process can increase abrasion, especially if there is no effective heat dissipation mechanism. This localized heating can result in localized melting. Additionally, fatigue is related to frictional heating.

It appears that these wear mechanisms are interconnected. Melting, for example, is directly or indirectly related to frictional heat. An increase in frictional heating can lead to melting. When material weakens, stress or load increases significantly, generating more particles and enhancing frictional heating, thereby linking the mechanisms.

Regarding diffusive wear, an increase in frictional heat will raise the temperature, which in turn accelerates diffusive wear. This temperature rise can result from inadequate heat dissipation. Consequently, melting wear and diffusive wear can occur simultaneously. Additionally, fatigue can gradually weaken the component, generate particles, and increase the coefficient of friction, further intertwining these wear mechanisms.

These mechanisms are interconnected, which is why we're covering them together. Now, let's delve into fatigue wear. It's a prevalent type of wear, and if the wear coefficient is less than 10^{-7}, it indicates involvement of all wear mechanisms in fatigue wear. This makes it a crucial mechanism. We understand that particles will be removed from the surface with a certain probability, represented by the wear coefficient. A wear coefficient less than 0.7 suggests that wear will occur only after the cycle has repeated at least 10^7 times, indirectly linking it to fatigue.

Fatigue wear occurs due to periodic loading and unloading, with stress transitioning from positive to negative, or positive to 0, or negative to 0. This failure is attributed to multiple reversals of contact stress, indicated by a wear coefficient less than 10^{-7} or a failure probability of once in 10 million cycles. Repetitive stress, significantly lower than the material's ultimate or endurance strength, plays a crucial role. Additionally, crack or rupture formation on the material's surface is another important point to note.

This phenomenon is localized, potentially resulting from high heat, fatigue, repeated loading, or particle entrapment leading to abrasion. Whenever a small rupture initiates on the surface due to fatigue, it gradually expands in size and depth under cyclic loading, ultimately causing material failure or surface degradation. Sometimes, cracks form a few micrometers below the surface, even up to 100 μm, where high shear stress exists. The reasons for high shear stress will be covered in the upcoming slides. Additionally, if the crack is perpendicular to the load direction or the maximal tensile stress, its opening will occur much faster, leading to faster failure.

So, depending on the location and orientation of the crack, various factors come into play. These facts are already established in relation to fatigue wear phenomena, and I'm simply reiterating them. Now, another important point to consider is whether fatigue wear is related to the Archard equation. I mentioned the constant or in this case, the wear coefficient. We assert that fatigue wear results in permanent deformation, potentially leading to plastic deformation and crack formation, which then grows, and forms wear debris. The Archard equation can represent this wear debris generation, even in cases of dry lubrication. Many authors have proposed additional mechanisms or equations, but the Archard equation stands out for its simplicity and adaptability to various mechanisms. However, an essential parameter, the wear coefficient, remains unknown, necessitating numerous experiments to determine it. Once known, we can develop mathematical models to predict fatigue wear well in advance.

Fatigue wear commonly occurs in rolling bearings and gears, where the rolling elements experience rotational motion and power transmission. Frictional dry contacts occur in cams and followers. In all cases of wear, contact stress is notably high, indicating that wherever there is high contact stress and tangential motion, fatigue wear is likely to occur.

In almost every case, surfaces exhibit some form of asperity. Asperities can bend, tear, or form cracks when subjected to relative sliding, leading to localized fatigue. This localized fatigue occurs in nearly all cases, underscoring its importance. Fatigue plays a significant role in abrasive and adhesive wear mechanisms due to the presence of asperities. Asperities experience continuous loading and unloading, resembling a fatigue phenomenon, which links abrasive and adhesive wear to fatigue. Fatigue wear can be divided into two categories: fatigue wear during rolling and fatigue wear during sliding, depending on the slide-to-roll ratio.

When discussing fatigue wear during rolling, we assume perfect rolling, where a majority of the energy is devoted to rolling action.

In the figure I presented, you can observe numerous pits, indicating a high density of pit formations. The presence of multiple pits suggests that the formation of a single pit does not lead to fatigue failure. Instead, there is a continuous occurrence of pit formations. However, it's important to note that the progression of pit formation can be significantly faster. For instance, while it may take X amount of time to form one pit, it's possible for ten pits to form within a shorter time frame. This accelerated progression is evident in the outer ring of a roller bearing, which I analyzed approximately 20 years ago. Despite experiencing surface fatigue, this bearing did not exhibit uncommon failure; in fact, it endured over 40,000 hours of operation.

So, this bearing has operated for more than 40,000 hours. Such fatigue-related failures are common after prolonged operation. After 40,000 hours, we can either inspect the bearing or simply replace it. If inspection reveals that the bearing is in good condition, we can recondition or reuse it, albeit with slightly increased maintenance. It's worth noting that this particular bearing cost around 35 lakh rupees. Therefore, it's crucial to understand the distinction between normal fatigue wear and sudden fatigue wear, which can lead to fractures, a topic we will cover in the next lecture. If you require a perfect and reliable bearing, understanding these mechanisms is essential.

Rolling bearings necessitate a smooth and undamaged contacting surface to function reliably. However, when the bearing surface contains numerous pits, it becomes unreliable. Pitted rolling surfaces induce severe vibrations due to their irregularity, rendering the bearing unable to sustain loads effectively. If left unchecked, these vibrations can escalate, potentially leading to fracture.

For a bearing to operate reliably, it must endure the designed number of cycles before exhibiting a noticeable number of pits that are discernible to the naked eye. It's worth noting that pits smaller than 50 μm are invisible to the naked eye, underscoring the importance of thorough examination.

So, if there are numerous pits on the surface that are not visible to the naked eye, we can still continue to operate the bearing. Now, the question arises: how and why do these pits emerge on the surface of the outer ring of a rolling element bearing, particularly on the inner surface of the outer ring? The process begins with the application of a normal load, which induces high stress at the contact point. In this case, the stress level exceeds 2 gigapascals. Under such intense contact stress, plastic deformation occurs. However, this plastic deformation is minimal and hardly noticeable, significantly smaller than the overall dimensions of the bearing.

So, it's not really a significant concern at this stage, as we're discussing per cycle. However, as the number of cycles increases, the deformation will gradually escalate. Continuous plastic deformation may lead to the initiation of cracks. These cracks can occur due to material defects or exceptionally high coefficients of friction, resulting in visible surface cracks. Alternatively, in cases where the material is flawless, and the coefficient of friction is well-controlled, subsurface crack formation or nucleation may occur just beneath the surface.

As I mentioned earlier, dynamic or fatigue loading on a surface initiate what we refer to as stage B. In this stage, the number of cracks may start with just one and gradually increase in density, with successive cracks appearing. In the third crack, for instance, the crack may expand due to factors such as alignment with tensile stress or perpendicular orientation to stress. This expansion occurs as a result of stress reversal and the crack extending towards the surface over time. If the coefficient of friction increases during this process, traction forces may contribute to crack propagation. Eventually, the crack may extend to the surface, releasing wear debris. These wear debris particles can be as small as 10 μm or even smaller, making them invisible to the naked eye. Given the size of the bearing, using a scanning electron microscope or other microscopy techniques immediately to detect such failures is not feasible.

So, we need to rely on a time scale or the number of cycles the component has executed, and then we need to inspect accordingly. For instance, if the operating life is 40,000 hours, we may conduct inspections after every 1000 hours or during routine maintenance intervals to check for the formation of cracks or pits on the surface. These are crucial aspects of fatigue wear that can ultimately lead to component failure, so continuous observation is necessary. Now, let's shift our focus to fatigue wear during sliding. In the previous slide, we emphasized fatigue wear during rolling, but now we will place more emphasis on sliding.

We always prefer rolling motion over sliding motion because, in sliding, the coefficient of friction tends to increase. In rolling, however, the coefficient of friction can either increase or decrease, and the system can sustain very high contact stress. In the diagram, we illustrate sliding motion where the top layer is heavily deformed, obscuring the grain orientation as it moves parallel to the sliding direction. This layer can be deformed to a thickness of up to 100 μm or 0.1 mm. This deformation is influenced by friction, affecting the thickness (t). When the coefficient of friction approaches unity (almost 1), the thickness is significantly impacted. While some may doubt coefficients of friction exceeding 1, we've observed values much higher than this.

So, if the coefficient of friction is on the higher side, even around 0.9, 0.8, or possibly 1, there's a chance that the entire layer, denoted as 't', will deform in the direction of sliding. This is why we're studying fatigue wear during sliding. We've divided the surface into sections, labeled as divisions 1, 2, and 3. In division 2, we observe the location of the cells, describing it as moderately deformed due to surface stresses, which can lead to void and nucleus formation.

The figure illustrates how sliding induces surface stresses, especially under extreme conditions where the coefficient of friction approaches 1. Under these conditions, the dark layer will deform significantly in the direction of sliding. However, if there is less friction or lubrication is provided, the deformation and thickness reduction will be minimized, resulting in less impact from sliding.

Overall, providing good lubrication can minimize fatigue wear during sliding, reducing the coefficient of friction to even less than 0.1. This is crucial because high stress and sliding with a high coefficient of friction can lead to maximum shear stress at the surface, causing the grain structure to collapse and dislocate. This dislocation may lead to void and crack formation.

In division 2, where cracks may form, there's a possibility of void formation and crack manipulation. As for the third layer, composed of materials with inclusions, fatigue may not pose significant problems.

However, if there are inclusions or if we use certain alloys with additives such as high thermal conductivity or nano-particles, it may increase the likelihood of fatigue wear or the initiation of cracks. This is a common occurrence in engineering materials, as many contain inclusions or defects that lead to void formation during plastic deformation under loading and unloading. In such cases, the presence of cracks, discontinuities, or foreign elements, including inclusions, can act as nucleation sites. This may cause the material to behave in a brittle manner, potentially leading to the detachment of a whole chunk.

Therefore, it's preferable to use materials free from inclusions, especially in applications involving fatigue wear and sliding. An excellent example is pure copper, which, despite having a high coefficient of friction, exhibits low wear due to its minimal inclusion content. It's important to note that a high coefficient of friction doesn't necessarily correlate with a high wear rate, nor does a low coefficient of friction guarantee a low wear rate. In different scenarios, a higher coefficient of friction may actually result in less wear, while a lower coefficient of friction might lead to higher wear rates.

So, they are interconnected, and we will also cover those aspects. As we discussed in previous slides, different materials tend to generate dislocation cells, and this tendency varies from material to material. The reason for this is often attributed to stacking fault energy. For example, metals like iron, copper, and aluminum produce dislocation cells due to their high stacking fault energies. These cells are typically thin, elongated in the direction of sliding at the interface, and may function similarly to flight tiles.

If the flight tiles exhibit a certain behavior, they may indicate a higher likelihood of dislocation, increasing the chances of fatigue wear. However, as seen in the example of pure copper with inclusions or laser treatment, it demonstrates better wear resistance. Nevertheless, if the stacking fault energy is high, this resistance may not be as pronounced. Additionally, the location where void formation and crack nucleation are prone to occur, particularly in high-energy cells, can lead to increased voids.

This correlation between energy levels and wear behavior applies to adhesive wear as well. Similarly, in fatigue wear, the presence of high-energy cells increases the likelihood of void and crack formation, leading to wear. Moreover, such wear may not be confined to the surface but can also occur below due to pre-existing distorted cells. Fractures related to fatigue typically initiate at weak spots, such as grains with exceptionally high energy, from where they propagate and eventually manifest on the surface, causing significant fatigue failure.

Sometimes, secondary cracks can be observed at deeper levels, but continuous plastic deformation or loading and unloading can lead to further crack formation. Eventually, these cracks converge, moving towards the surface and resulting in surface failure or degradation.

Fatigue is a well-studied phenomenon, and minimizing surface energy can reduce the occurrence of cracks. However, if discontinuities are present, such as surface dislocations or voids, fatigue may occur more frequently. For example, let's consider fatigue during sliding and examine its mechanism. This scenario often occurs in gears, where rolling is predominant but sliding can still occur on the gear surface.

In this demonstration, I'm illustrating the reciprocating motion between surface 1 and surface 2. Assuming there's a crack on the surface, let's explore its behavior.
Now, if I magnify this surface, we can observe surface initiation already present. With continuous reciprocation, there's a possibility that the crack will propagate in a similar manner. As the crack propagates, it may lead to the detachment of a complete chunk, posing a significant risk, especially for sliding gears. Due to the sliding motion, the crack tends to orient itself in the direction of sliding, resulting in the removal of a chunk from the surface and the generation of debris, which is problematic.

This emphasizes the importance of minimizing inclusions and artifacts, as their presence increases the likelihood of crack initiation and propagation, ultimately leading to failure. Therefore, surface-initiated cracks expand during unlubricated conditions, highlighting the need for effective lubrication to mitigate fatigue-related issues.

If sufficient lubricant is applied, the coefficient of friction will decrease significantly. This reduction prevents the dislocation of the top surface, which would otherwise occur parallel to the sliding direction. Consequently, the growth of cracks is inhibited, and the initial crack size may remain unchanged over many cycles.

In the case of unlubricated sliding, wear particle formation is likely, whereas under lubricated conditions, this occurrence is minimized. The wear coefficient under lubricated conditions is considerably lower than that under unlubricated conditions. Therefore, considering the wear coefficient, the application of lubricant is essential for achieving a low wear rate.

Lubrication can take various forms, such as oxides, solid lubricants, or coatings that act as lubricants. By incorporating suitable lubrication methods, surface design can be optimized to enhance service life and longevity.

This is an example I wanted to mention about pure copper, typically containing 99.96% purity. Even common copper alloys may contain some inclusions. In an experiment conducted by one of the authors, pure copper slid against steel, exhibiting a wear rate ten times lower than any other material. When compared to other materials, sliding them against steel results in a much higher wear rate than pure copper.

However, the coefficient of friction is on the higher side, meaning that for steel and pure copper, the coefficient of friction will be very high. Despite this, the wear rate will be low. This illustrates a scenario of high coefficient of friction but low wear rate. So, it's important to note that this is not about velocity, but rather about wear rate.

Another example is carbide-rich steel, which exhibits a low coefficient of friction but results in a high wear rate due to numerous inclusions. These elements are added to enhance the hardness of the steel. Consequently, while the coefficient of friction can be reduced, the material still experiences a high wear rate.

In summary, there is a possibility of having a pair with a low coefficient of friction but a high wear rate. Again, it's important to emphasize that "V" here does not represent velocity but rather wear rate.

Now that we've grasped the wear mechanisms, we can engineer products and surfaces to significantly extend their lifespan, ultimately yielding better overall results. Having covered fatigue wear, let's summarize it in combination with other factors, such as fatigue wear in the context of sliding.

When the coefficient of friction is high, the location of maximum shear stress gradually shifts upwards. For instance, if we compare the scenarios where $\mu_1 > \mu_2$, with μ_1 representing the unlubricated condition and μ_2 the lubricated condition, we observe that under the unlubricated condition, the maximum shear stress location shifts upwards, possibly even to a higher level.

Conversely, under lubricated conditions or other circumstances, shear stress may occur below the surface. It's crucial to note that the contact stress is exceptionally high in fatigue scenarios. This understanding allows us to devise strategies to mitigate wear and optimize performance.
So, it experiences both compressive stress and tangential motion resulting in tensile stress. When the coefficient of friction is lower, the maximum shear stress occurs just beneath the contact surface, typically around 100 μm to 200 μm deep—not as shallow as 0.1 μm. At this depth, the contact stresses are exceedingly high at the interface.

Under conditions of repeated rolling and sliding contact, the fatigue wear mechanism involves the propagation of subsurface cracks. Even if surface cracks exist, their propagation is secondary to that of subsurface cracks. These subsurface cracks may originate due to sliding and repeated loading, or they may stem from pre-existing inclusions or voids. Eventually, these cracks propagate and manifest on the surface as wear debris particles. This phenomenon is frequently observed in gear systems.

Pure rolling occurs solely on the pitch line. Above and below the pitch line, sliding occurs, resulting in very high contact stress. This combination of sliding and rolling places immense strain on the top surface layer of the gear tooth. Consequently, this top surface is subjected to exceedingly high strain, rendering it vulnerable to cracking. The formation of cracks under such extreme strain leads to the generation of wear particles.

In real-world gear wear observed in the laboratory, we often encounter pitting wear. This manifests as numerous pits on the surface, sometimes with wear particles embedded within them.

The wear particles generated under high contact stress become embedded in the material. Once embedded, these particles indirectly contribute to increased surface roughness, leading to abrasive wear. Consequently, fatigue can result in abrasive wear or severe wear in such situations. The applied stress, number of cycles, material characteristics, and environmental factors all play significant roles. Moisture presence, for instance, can facilitate surface corrosion. When the oxide layer is removed from the surface due to high friction, the exposed surface reacts with water to form another oxide layer, resulting in corrosion. This corrosion may be more pronounced compared to normal oxide wear. Thus, environmental conditions are crucial, and all these parameters collectively influence surface failure or fatigue.

So, these factors are crucial: stress level, number of cycles, material properties (whether it's brittle or ductile), environmental elements, and whether they are chemically active, leading to corrosion-assisted wear. Now, let's delve into the second topic: fretting wear. Coined around 1927, fretting wear is a silent killer. Unlike pitting wear, which shows visible signs during regular maintenance, fretting wear often occurs in interference fits, which are not typically accessed during routine maintenance, posing a major problem. Fretting wear involves motion within a range of 1 to 300 μm, characterized by high-frequency oscillations and vibration exposure.

You can assume that in an interference fit pair, after traveling 1000 kilometers in a truck, it may have undergone many cycles of low-amplitude, high-frequency vibrations, potentially leading to pit formation or other failures. Since interference fits are not frequently checked, and often remain unopened, detecting such issues can be challenging. Imagine loading an item in one location and finding fretting wear already occurring after 1000 or 10,000 kilometers in another location. This illustrates the potential for silent material failure, known as fretting wear. This type of wear occurs when two surfaces repeatedly move in relation to each other at high frequency but with very small amplitudes, typically ranging from 1 to 300 micrometers. The repetitive motion can gradually remove surface material, resulting in localized surface wear and degradation.

However, particles or debris trapped between surfaces prevent them from fully contacting each other, making it difficult for us, or the operator, to expose or observe them. This obstruction occurs because the particles become lodged between the surfaces, hindering their separation and visibility. Consequently, unless there's a joint failure, we may not detect these particles unless we utilize non-destructive testing methods. This phenomenon is common in mechanical assemblies, such as press fit rivet and bolt joints. Even though bolt joints can be opened, upon inspection, one often finds debris present—typically black or brown residue, even in aluminum joints. This accumulation of debris highlights the prevalence of fatigue wear, a phenomenon exacerbated by the subtle relative movements between supposedly stationary joints. Despite these movements being imperceptible to the naked eye, they contribute to fatigue wear, manifesting themselves as small pits that culminate in premature joint failure.

Fretting contributes to fatigue failure, and conversely, fatigue conditions exacerbate fretting wear, establishing a relationship between the two phenomena. Even within a minute amplitude of around one micron, where sliding motion is unintended, attempts to alleviate the issue with lubrication prove futile—an indication of the significant challenge posed by fretting wear. Focusing on fretting, when two surfaces are in contact, pressure distribution reveals maximal pressure at the center. However, due to vibration and incidental motion, tangential motion occurs, resulting in minimal stress at the center and maximal stress at the joint periphery. This pattern typifies scenarios where compressive stress peaks coincide with minimal tangential stress, fostering high tangential motion in areas with reduced compressive stress or nearly zero compressive stress. Such dynamics illustrate the behavior within a contact, where the connected surfaces undergo elastic deformation, experiencing a gradient of load from its zenith at the contact center to zero at the periphery.

So, this is what we call contact stress or contact pressure. As demonstrated earlier, this contact pressure is shown to be maximum at the center and diminishes to zero at the edges. These being the edges and this the center. It's noted that stress is at its peak at the contact center and diminishes gradually towards the edges.

If we consider the possibility of frictional energy loss due to this contact and the ensuing vibration, it's natural that energy supplied to the joint must dissipate and redistribute elsewhere. This redistribution is what we refer to as friction, and the resulting motion may occur in the axial direction or other directions. In such a scenario, we might assume a uniform tensile stress. However, as demonstrated, this is not the case; stress distribution is non-uniform, with maxima occurring at the periphery and minima at the center, presenting a unique characteristic of this situation.

However, we cannot assume anything; this is a real situation we have discussed. In this scenario, we can determine the local coefficient of friction. When the compressive stress is at its maximum at the center and tensile stress is at its minimum at the same location, naturally, the coefficient of friction approaches zero at the center. Conversely, moving towards the outer region where tensile stress peaks and compressive stress is minimal, the coefficient of friction is exceptionally high. It could even exceed 1. However, as stated, the friction coefficient increases from its highest point, which occurs at the contact periphery. Some sources suggest that the coefficient of friction could theoretically approach infinity because there's no possibility of wear debris escaping from that area.

However, rather than suggesting any vale of coefficient of friction, we anticipate a scenario where slip occurs. Slip arises when the tangential stress surpasses the frictional stress. In essence, slip formation is contingent upon the relationship between the applied load, frictional stress, and tangential stress. If the applied load escalates to a point where tangential stress exceeds frictional stress, slip will ensue; otherwise, slip will not occur. In summary, within this contact region, there exists a combination of tensile stress, frictional energy, and compressive stress, all of which interact predominantly within this specific area. Generally, wear is less prevalent or even absent at the center of this region. Instead, it predominantly manifests in the peripheral domain, where wear particles attempt to escape but often remain intact due to the high tangential stress compared to the center.

That's why the possibility of relative sliding exists, and if such sliding occurs, wear is inevitable. Continuing with fretting, we note that it predominantly occurs in interference fits, as demonstrated here with a rivet joint. In a rivet joint, multiple contact interfaces exist, providing numerous locations susceptible to fretting wear. It's nearly impossible to entirely prevent microscopic motion, as even in assemblies like riveted ones, vibrations from the external environment are bound to induce such motion. This phenomenon is similarly observed in nut and bolt connections; upon disassembly, debris, often varying in color, is commonly found between the mating surfaces.

Similarly, if contact occurs solely on a cylindrical surface, wear will be concentrated in this region, with maximum wear typically observed at the edges compared to the center, as illustrated in the preceding slide. Furthermore, reiterating our earlier point, although it's impractical to entirely prevent such wear, minor wear over several cycles usually doesn't raise significant concerns. However, it's crucial to acknowledge that despite its subtle nature, continuous wear occurs, albeit often unnoticed. Ultimately, upon disassembly of the connection or nut and bolt assembly, evidence of wear, such as wear scars and debris, becomes apparent.

And then, as the debris is removed from the surface, clearance increases. This increase in clearance leads to a greater amplitude. So, if initially it was 1 μm, the next time it may reach 5 μm, then 50 μm, and eventually 100 μm. This progression ultimately culminates in complete failure, which is the consequence of fretting wear. However, it's important to note that wear continues unabated due to motion. Now, regarding why wear debris isn't visible, it's because the debris becomes trapped within the sliding interface due to the limited sliding amplitude relative to the size of the sliding contact. This sliding contact area acts as a barrier, preventing the generated debris from escaping, as they remain confined within this enclosed space.

And then, only when you open it up, a significant number of debris will be released from this space. On the damaged surface, a layer of worn debris gradually accumulates over time because these particles are unable to escape, leading to continuous buildup. Initially, there may be only a few particles, but over time, even these particles can act as abrasive materials, exacerbating failure. The rate of wear depends on the formation of new debris and the susceptibility of these particles to further increase in wear rate. Therefore, the eventual outcome will depend on whether the new debris acts as a lubricant; if so, it's possible that the wear rate will decrease significantly. Although wear will persist, the presence of new debris might introduce a mechanism to slow down the process, potentially counteracting any tendencies towards accelerated wear.

So, what we're asserting is that fretting wear accelerates mechanical fatigue by inducing surface cracks, primarily manifesting as surface cracks rather than subsurface ones. These cracks tend to develop around wear scars, propagating gradually until eventual failure occurs. In the subsequent slide, we aim to illustrate the progression of fretting wear. Initially, there's a "stick" phase where the riveted joint maintains its connection, yet wear still occurs, represented by values in the range of $10^{-16}, 10^{-15}, 10^{-14}$.

So, we divide fretting wear into four phases: phase 1, phase 2, phase 3, and phase 4. Even with good construction and design, load variation and thermal expansion can't be completely eliminated—they persist. Fretting wear progresses through these phases, starting with the stick phase. In this phase, joint surfaces remain in close contact with almost zero relative movement due to the joint's purpose. However, the forceful connection of the surfaces induces high compressive loads, leading to surface deformation and the possibility of micro-crack formation due to the extreme contact stresses.

Moving to the second stage, a mix of sticking and slipping occurs. Here, additional external loads exacerbate the situation, causing micron-sized cracks due to the intense compressive force. Subsequent vibration or changes in load conditions initiate slight movement of the joint surfaces during this mixed stick-slip phase.

Even though there's movement, there's also an incredibly high contact pressure or stress, keeping the surfaces nearly stationary and not visibly shifting. For instance, the movement might be within the range of 1 to t_1 micrometers initially, then progressing to something like 10 to 12 micrometers, which remains imperceptible to us—this characterizes stage 2 or phase 2. Transitioning to the gross slip phase, where micron-sized movements become noticeable, the motion becomes repetitive, dynamic, and cyclic in nature. This noticeable movement is termed gross sliding motion because the previously tight or intact condition has loosened considerably, allowing for relative motion to commence. If external stresses or vibrations continue to increase, the surfaces will slide against each other, leading to the formation of wear debris.

It's possible that debris and worn-out material might have formed in this area, but it's hard to see any visible wear now. There's a chance that wear is emerging from the joint itself. Another factor could be an oxide layer that may have provided lubrication before, but now it's likely ruptured. This debris and oxide layer might act as abrasives, possibly causing further damage to the joint surface. This explains why the wear rate has increased from almost negligible (wear coefficient ~10^{-15} to 10^{-14}). After this, the reciprocating sliding motion contributes to fatigue, causing damage. So, in the fourth phase, the joint surface has moved significantly, resulting in severe damage or material failure.

Now, this process has created several surfaces that will trigger other mechanisms, ultimately leading to joint failure. What happens as a result of this four-stage process? Well, the wear debris generated is very tiny, maybe initially around 0.01 to 0.1 micrometers, which is at the nanometer level. This could potentially cause the joint to loosen, increasing vibrations and accelerating wear. Let's take a look at patches A and B. In patch A, you can see pit formation caused by the joint, which is at a level of about 20 micrometers. This means these pits could be around 100 micrometers in total. So, what used to be a joint of 100 micrometers is now showing these pits due to the open connection.

In this particular case, you can observe an increase in surface roughness. Now, this roughness has become quite severe, making it almost unusable for regular purposes. Additionally, there's an increase in micro pits, contributing to the rough surface. All of this leads to a decrease in fatigue strength, ultimately resulting in fretting failure. So, how can we identify fretting wear? Often, the mating surfaces change or lose their coloration.

Now, we've noticed aluminum oxide appearing black, while for iron oxide, we've identified three different forms. Ferrous oxide isn't commonly found, but there's a soft black magnetite oxide that serves as a solid lubricant, making it preferable. However, in dry conditions, we typically see Fe_3O_4. If moisture is present, rust and corrosion occur, leading to wear debris that are harder and more abrasive than the previous black magnetite oxide, causing more severe damage.

So, it's possible that fretting wear can lead to abrasive wear, especially if there are hard particles and oxide particles like iron oxide (Fe_2O_3). We've also noticed that materials like titanium or certain solids are highly susceptible to fatigue damage, so it's best not to use them in these joint connections. It's important to study this further because many bridge failures have been linked to fretting wear in the initial stages, followed by other wear mechanisms taking over. This type of wear can cause significant damage, often without much warning, so regular maintenance or surface reconditioning is crucial. To reduce fatigue fretting wear, minimizing moisture and applying lubricants can help. Moving on to another type of wear, melting wear is quite rare because it requires extremely high temperatures. However, we've observed cases, such as during four-ball tests, where melting wear occurs on the surface due to high temperatures. This results in cracks forming, and when subjected to sliding conditions, these cracks can generate wear debris or even cause fragments to break off.

So, what we're seeing here is the result of a ball failure in a four-ball tester. This tester is used in tribology to apply extreme stress and determine if a lubricant is effective. In this example, the extreme pressure leads to frictional heat buildup. Without proper lubrication, this can cause metals to melt or soften, resulting in material flow. Consequently, wear debris accumulates in ruptured forms, as seen here with numerous cracks. Further testing under sliding conditions or high speeds can lead to even more wear debris being released from the surface. This localized heat generation, combined with heavy loads and high-speed sliding, damages the surface significantly. If this heat isn't dissipated quickly, it can lead to temperatures surpassing the material's melting point, forming a molten layer known as melting wear. If this layer isn't removed immediately, it solidifies, causing irregular surface and that further increases the wear rate.

And eventually, it will emerge in the form of droplets and may have an irregular mixed form as well. However, another important point to note is that whenever melting occurs, atmospheric oxygen is typically present. If atmospheric oxygen interacts with the molten layer, it may form an oxide layer, which can significantly alter the material's characteristics and behavior. Whether this oxide formation is beneficial or detrimental depends on the material and the type of oxide formed. To illustrate melting wear, we can imagine a surface under high load conditions leaving some red material on another surface. If the layer is thicker, perhaps a few microns, there may be crack formation within this layer during solidification.

So, in this case, we can say that the increase in frictional temperature is directly related to how quickly we move the materials. The temperature rise depends on the velocity of the material, the faster the relative velocity, the higher the frictional temperature. There's a mathematical relationship stating that the temperature depends on the square root of the sliding velocity. It also depends on the coefficient of friction; higher coefficients of friction lead to higher temperature rises, while lower coefficients result in lower temperature rises.

And with very high sliding speeds, the temperature rise will be higher side, the temperature rise will be lesser with lower sliding speeds. So, these are some basic facts about melting wear. As I mentioned, it depends on localized heat. We don't have energy spread across the entire surface; it's just localized heating where a molten layer forms and then solidifies immediately.

It won't spread across the entire surface. Frictional heating and the heavy load create a molten layer between two surfaces. What we're saying is that the molten layer in melting wear is caused by heat. It's only a few micrometers thick; it's not the entire material flowing onto the other surface. It's just a localized phenomenon where melting occurs, followed by solidification, and the solidified layers turn into wear debris.

But eventually, it emerges from the surface. That's why there's material loss, resulting in wear. So, when the molten layer interacts with atmospheric oxygen, an oxide layer forms. This oxide layer may affect subsequent wear and friction characteristics. Depending on its behavior, it could be either helpful or harmful. Now, let me introduce a concept that has been popular in literature for almost three decades: the wear map. What's a wear map? Generally, wear maps are created for commonly used materials, and several authors have developed such maps for various materials.

I am merely demonstrating a steel substance, and after that, they will utilise a pin on disc setup to determine if this is the kind of map that they are looking for. There is also the fact that they are demonstrating the ultra-mild wear domain correctly. In addition, the vertical line represents a normalised pressure, while the normalised velocity is represented by this form. Both values have been supplied in this form. As a result of this, we can observe that the rate of wear is continuously growing as the pressure continues to accumulate. When the sliding speed increases, the amount of wear that occurs likewise increases.

On the other hand, there is a domain that is extremely moderate, and if you can function in this domain, then you will have the finest arguments. If you are unable to work within this domain, then either the load is on the upper side, and it is reasonable to assume that there will be some kind of wear that is dominated by plastic. On the other hand, following that, there will be some kind of oxidation wear, and when we go to the higher speed side, there will be oxidation wear. In this instance, we are using the phrase moderate, but in this instance, we are using the word severe. As the speed increases, we are indicating that the material will undergo severe oxidation wear. The melting wear that is brought in by this location is what we are referring about here.

And melting region itself is a severe wear phenomenon. Melting region, also known as melting wear, is a phenomenon that occurs when there is severe wear. And then, if you do not take the necessary action, it will eventually be seizure. The seizure is quite high, which implies that we are attempting to supply a relative motion between two surfaces, and the surfaces are not going to move on their own because the energy is being converted to heat. In addition, the heat is continuing to cause an increasing number of failures. Because of this, we ought to steer clear of this kind of phenomenon, and we ought to steer clear of melting wear as well. After that, we ought to select the appropriate material, and we ought to try to arrive at the ultra-weak zone. It will supply a good number and the good high to the academic staff or students who can go through it and select the material again. This sort of wear maps are popular and available in literature for the various materials. It will also provide a nice high.

We can get suitable material from this kind of map, but we cannot rely completely on that. We need to test those material pairs again in a real situation, or, we may say, in a similar situation, we need to perform again the way they have tested the pin on the disc machine. We can do a pin on a disc machine, we can do on a four-ball tester, we can do on some other tribometer, but we need to confirm. Reason being that from one zone to another, the wear-causing coefficients will keep changing. It may be 10 times; it may be more than that also.

So everywhere, the situation will be somewhat different, the operating conditions will be different, and the environmental conditions will be different. So, we can provide some sort of hint from existing literature. So finally, we need to perform experiments to get the right results. So, what are the critical points about this wear? We say it highlights critical wear mechanisms. Why is it that we are using what? Because here we are able to control, which means all operators are able to control pressure and velocity, and in this case, pressure and velocity are both things we are able to control. And then what we say is that in this case, there are field boundaries; these are some sort of boundaries that have been shown here, and then we are able to really calculate those things.

Let's consider a scenario where mild oxidation wear occurs on one side, and severe oxidation wear occurs on the other. By applying wear equations to these different types of wear, we can determine the boundaries between them. There will be some variations, but we can still establish these boundaries.

For example, if we have wear equations for severe oxidation wear and melting wear, we can equate them and attempt to solve the boundary. Similarly, if we have wear equations for melting wear and seizure, we can solve that boundary as well. These processes are relatively straightforward, but relying solely on complete wear equations can be challenging.

That's why you'll notice thicker lines instead of just thin ones. There will be variations, so we won't always get the exact same results. Another thing to look at are the contours, like 10^{-11}, 10^{-10}, 10^{-09}, 10^{-08}, which represent the wear rate. It's important to note that this isn't velocity, but rather the rate of wear. What's interesting here is that this provides a sum of all types of wear mechanisms—abrasive wear, adhesive wear, fatigue wear, fretting wear—resulting in the final wear constant. This means that all wear equations should ultimately yield similar results, with variations mainly in the wear coefficient. So, we aim to structure equations in a way that allows for changes in wear coefficients to provide accurate results.

Now, another point arises regarding oxidation. Sometimes, we mention the formation of oxides occurring under sliding deformation, and then this oxidation layer also gets removed, exposing the nascent surface or the virgin surface. Again, it will have a chance to oxidize. Therefore, oxidation formation and removal are continuous phenomena. That's why we say that three elements govern the thickness of the oxide layer: rupture time, which indicates how much time is required to rupture the oxide layer; reoxidation time, indicating how much time is needed to reoxidize that layer; and finally, the formation rate. If there is a balance among these factors, the oxide layer will likely remain intact. However, if there is no balance, the oxide layer may either grow or be completely removed.

So, these are the situations we need to address, and this comprehensive information stems from a wear map. What we have gathered from wear maps, or similar graphical representations, is the ability to detect the wear behavior of materials under specific conditions. This means we can assess how a particular material will behave under various conditions. These maps assist us in understanding and identifying wear mechanisms, as well as determining the optimal operating conditions to minimize and reduce wear. By observing patterns and identifying key operating situations, we can pinpoint where wear is most severe.

If we want to avoid severe wear, we need to identify the critical factors that should not happen at all in even the worst-to-worst situations. So those factor patterns can be spotted using the wear maps. Wear maps can assist in the selection of appropriate materials because if we have 15 or 20 maps and we are connecting, then we are almost in a similar situation as to which material is going to get better results. Again, only for one condition may not be the right thing, but we need to see what the fluctuation the fluctuation will be in the wear condition or operating conditions and then choose a material based on that. We are seeing that the wear map can assist in the selection of appropriate material.

Optimization of the design parameters is also possible in this map, as is the development of a method to elevate. If we are thinking about the lubricant, if we are thinking about the coating, it will allow us to think in the right direction and give the right direction or suggestion to go for the innovation or invention. So in short, we can say map acts in the design of wear-resistant components and systems. So they are very important; they are very useful. Now I am just showing one step ahead of that in the wear map. We introduce a concept called a seizure, and then what we say the severe wear to seizure is important. Why we are using the word seizure is because earlier we were talking about wear debris in a micron, but you can see here that this is very big wear debris that is coming out.

Even if the scratches or lines are shallow, their depth can reach up to 127 µm. Some are even deeper, indicating a much higher depth. I've also provided two examples illustrating complete seizure, where the high temperature causes the balls to melt and become adhesive, bonding with the inner ring. Separating them becomes a challenging task, as they do not easily come apart. Therefore, manual separation of these rollers is necessary. This is why we emphasize that components such as roller bearings' inner rings and rollers generally do not separate on their own after seizure. To separate them, significant force is required, and upon separation, they are rendered completely unusable and cannot be reused.

You can attempt reconditioning, but it will require time and cannot be reassembled in the same manner. It's important to understand that you cannot operate it after disassembly, refitting, and operation. The reason is that there is already significant wear, almost 50 to 100 µm, causing the rollers to wear out. If you use it, the clearance will increase. In rolling element bearings, we typically find very low clearance, perhaps in the range of 10 to 50 µm. With over 50 µm of surface already removed, the overall clearance will exceed 100 µm. This substantial clearance difference, from the initial clearance to over 100 µm, will result in significant vibration, low stiffness, and considerable noise. As a result, the bearing becomes entirely unusable and cannot be employed further.

So, this is why we mention that the material is lost from the surface of the roller bearing and cannot be used anymore. This severe wear, as we've been illustrating, occurs when the load increases, causing a sudden change from moderate wear to abrupt wear rate increases several times over. While the wear rate may initially be ultra-mild, then mild, then moderate, and finally severe, this increase is not linear; there is a significant change each time, such as from ultra-mild to mild or from mild to moderate.

As the load increases, it distorts the surface to the extent that oxide formation does not occur, and when the oxide layer fails completely, it reveals fresh metal. If this fresh metal doesn't have enough time to rebuild the oxide layer, it may lead to additional wear and eventual failure. Here, melting causes this additional wear, highlighting how wear mechanisms are interconnected. Therefore, we need to be mindful of how various wear mechanisms work together, aiming to minimize the wear coefficient to achieve better results.

So, what we've gathered about seizure is that it's when two parts bind or stick together, rendering them unusable and unable to be reassembled. Some may suggest reconditioning is possible, but it requires careful conditions. When two solid surfaces slide against each other, they lose mechanical energy due to friction. This energy needs to be dissipated, or it will increase the temperature, leading to melting wear and potentially resulting in seizure. Therefore, to avoid melting wear or seizure, we need materials with high thermal conductivity to dissipate heat effectively. If heat dissipation isn't immediate, we should consider reducing friction with lubricants or coatings to manage temperature rise within limits.

If these steps don't work, we should consider regular maintenance. Sometimes, despite our efforts, failures like melting wear or seizure still happen. Then, we should check if there's any misalignment in the assembly. Even a tiny misalignment of 0.1 degree can raise the temperature by 5 degrees, or even up to 180 degrees in some cases. Misalignments often cause more problems than other issues.

So, we need to consider all 5 criteria if you want durable, reliable results from a component. Now let me provide some quantification of the melting wear. Here, we have been repeatedly discussing temperature; it can be a flash temperature or a bulk temperature, and melting point occurs when the bulk temperature reaches the melting point. Even though we say "instantaneous," there is a possibility of instantaneous melting. However, the melting wear is more dominant when the bulk temperature exceeds the melting temperature. Here, we are attempting to illustrate a pin and disc arrangement, where the pin and disc have a certain geometry that come into contact. There is a tangential speed on this, generating heat at the interface, resulting in a temperature rise, which we refer to as the bulk temperature.

So we can equate how much friction energy has been generated and how the heat is getting dissipated. We compare friction energy with the heat flux and the rearrange equation, we can find out the bulk temperature T_b in terms of the environment temperature, atmospheric temperature, or temperature sink. With that, some sort of fraction of the energy—not-necessary 100% friction energy—is going only to the temperature increase.

If there are other mechanisms involved where only a fraction of the heat is transferred, denoted by α which is not necessarily equal to 1 but can be 0.8 or 0.9. There's friction force, applied load, tangential speed, and surface area, all of which are equated here. The conductivity coefficient, related to the thermal conductivity of the surface, is represented as well. α represents a fraction of the heat flow that contributes to the temperature rise. However, in my opinion, flash temperature is more critical because it typically results in a higher temperature compared to bulk temperature. If we manage to control the flash temperature, the bulk temperature will likely be kept in check. We also need to consider the level of surface roughness (asperities) and the corresponding temperature rise. If the temperature rise at the asperity level is significant, it can lead to problems like seizure or melting, indicating that most issues start at the asperity level. Therefore, controlling the earlier stages can lead to better results overall.

Now, just to highlight this, I will take an example of a gear pair. What we covered in the previous slide is the rate of heat generation per unit area, which involves the coefficient of friction, relative sliding, and contact stress. Gear pairs generally experience contact stresses, and the σ_d distribution can be found using the Hertzian formulas. These formulas are related to Hertzian contact relations and are empirical. We won't go in-depth because solving the complete thermal and elastic equations would take much longer.

Instead, I will introduce a well-known empirical formula to the class. This is the flash temperature (T_f), which depends on the coefficient of friction, relative velocity, normal load, effective Young's modulus, effective radius of curvature, and face width (depth of the gear). In this formula, β_1 and β_2 represent the coefficient of thermal conductivity. Different authors have various terminologies, and I am using Bartz's terms. Bartz has a famous book on gears, and I have taken this formula from his book. The coefficient of thermal contact (beta) can be given as thermal conductivity (λ), specific heat (C), and density (ρ).

If the beta value for any material is lower, the temperature will be higher; if the beta value is higher, the temperature will be lower. Therefore, we should choose a material with a high beta value during material selection. The effective Young's modulus and effective radius of curvature are also given in this relation.

Here, we are using W_n. We know that for a gear, W_n can be calculated from the applied torque (T). If we know the pitch radius, we can find W_t. W_t can be given in terms of the normal load on the gear pair: $W_t = W_n * \cos(\varphi)$, where φ is the pressure angle. The radial force (W_r) can be given as $W_n * \sin(\varphi)$.

Once we calculate these, we can substitute all these values into the relation to find the flash temperature. We require some data, and Bartz has provided a slightly modified formula. This formula considers the relative speed of the pinion and the gear, the β conductance, the applied load (W_n), the face width of the gear, the module, the number of teeth, the effective Young's modulus, and the factor F_z given by the author. As the number of teeth increases, the stress level decreases. If the stress decreases, the coefficient will also decrease.

That means, if the coefficient is 0.813 with 17 teeth, increasing the number of teeth to 100 will reduce it to 0.124, a sixfold reduction. If the temperature for 17 teeth is around 100, increasing the number of teeth to 100 could reduce the flash temperature to only 16°C or 17°C. Therefore, design changes are possible and should be considered.

In this context, the author has compared two gear material pairs: nylon-nylon and nylon-steel. They selected gears with 17 teeth, a module of 3, a face width of 30 mm, an angular speed of 150 radians per second, and a power transmission of around 850 watts.

This is the same formula highlighted in the previous slide, and the coefficient of thermal contact, beta, is given here. They provided a beta value for nylon versus nylon, which is 0.417×10^6, and for nylon versus steel, which is significantly higher—almost 400 times more. However, the coefficient of friction in both cases is the same. Many people emphasize the importance of the coefficient of friction, and here it has been kept constant.

Additionally, the Young's modulus is almost double in the case of nylon versus steel. When calculating T_f for nylon versus nylon, it turns out to be 161°C. Under the same operating conditions, if one material is nylon and the other is steel, T_f is 9.5°C. I'll show you some calculations and the simple program written to find the tangential force, normal force, and flash temperature, given the pitch radius and the torque.

For the nylon versus nylon case, the beta value was 0.417×10^6 (417,000), and for the steel versus nylon case, the Young's modulus for nylon is roughly half that of nylon versus steel. These two parameters were changed, and we found that T_f for nylon versus nylon is 160.75°C, almost 161°C, while for steel versus nylon, it is 9.2°C. This significant difference shows how changing the material pair can lead to better results.

It's crucial to perform experimental tests to validate these calculations. This is just an introductory part, and we are emphasizing that experimental validation is necessary to get reliable results.

In the next lecture, we will cover surface fracture and surface degradation. We have covered wear and surface degradation in the first six lectures, and we will move to lecture 7 on fracture and surface degradation. Additionally, we will discuss abrasion and the diffusive area, which we briefly mentioned, in one of the upcoming lectures.
Thank you.