Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 32
Surface Engineering

Hello and welcome to the twenty-ninth lecture of our course on corrosion, environmental degradation, and surface engineering. We've now reached the final phase of this course, and today's topic is surface engineering. This is a particularly fascinating subject because, as we've discussed throughout the course, most material failures occur at the surface. In fact, 70% to 80% of material damage happens at or begins from the surface.

This raises an important question: Can we actually engineer the surface to reduce degradation? Surface engineering is precisely about modifying and improving the surface to minimise damage—ideally to a negligible level. But before we dive into the details, let's first clarify what we mean by surface,' as different literature offers various definitions of this concept.

One literature indicates the top 2 to 10 atomic layers or molecular layers will be treated as a surface. That means a top 0.5 nanometre to 3 nanometre layer will be only treated as a surface; otherwise, it is not a surface. Second literature, which has a layer thickness less than 100 nanometres, should be treated as a surface.

Otherwise it is a bulk solid-trip state property; anything exceeding 100 nanometres is not a part of the surface. However, we will be thinking slightly differently, but before that, we want to really know how we engineer the surface. So, for that, we need to improve surface qualities. Now in surface quality again, we have a subclassification: what will be the chemical composition of the top surface, what will be the morphology of the surface, and what will be the structure: a SP 2 structure or a SP 3 structure? What kind of structure do we want to award or give to the surface? So, this is completely a novelty of this course that we need to think about engineering a surface, making the surface a kind of interface between the environment and the functionality, and then separate these two.

So, that degradation comes to almost negligible, and that is why this lecture is important, and the next three lectures will also be in the same tone. Now what we want to do here is improve the surface quality to achieve desirable functional qualities. What are the desirable functional qualities? Minimize the friction, minimize the wear, minimize the corrosion, minimize erosion; there should not be any damage to the surface. So, these can be functionalities also, and what about the performance enhancement? Whatever we are doing can really enhance. So, we need to have a lot of literature review studies and then think about how we continuously improve the performance.

Basically, we are already using some surfaces, but how do we improve that performance? There should be some sort of quantification measurement, and then we can think about enhancement. So, in short, surface engineering is basically the fabrication of surfaces, which can really provide a higher durability, higher wear resistance, higher corrosion protection, and better tribological characteristics. How do we do that? By modifying surfaces at the atomic level, molecular level, or microstructural level. So, if I am thinking about the surface layer as a 0.5 to 3 nanometre, naturally I have to think about the atomic layer or maybe at most the molecular layer.

However, when we think about 100 nanometres (0.1 microns), you can think about a microstructural level. This depends on the word, whether we are thinking about the microtribology, nanotechnology, or microtechnology kind of activities. So, what are the different approaches to surface engineering? We say there are three main approaches. Can we go ahead with the coating? A kind of other surface we coat on the surface or maybe the subsurface, which we really require, and the coating can be like, you know, 100 nanometres or maybe even a few microns, or can we think about the surface patterning? Can we really make it? Are we, can we really do a surface treatment? However, surface treatment is one of the most common in mechanical engineering.

We try to treat the surface so the desirable properties can be awarded to the surface itself. Now before starting this whole topic, first the key aspect of the surface is a surface roughness, and we know there is established a standard for that, which is ISO 4287, that defines all the parameters related to the surface roughness, and then we will try to connect this with a surface engineering in the present lecture. So what is the surface roughness? We say basically surface roughness is related to irregularities on the surface, and we know most of the damage on the surface happens because of the irregularities, and irregularities really look very awkward at the micron or nano level. You are able to see this complete surface, and there is a red colour line; there is a mean line in that. So this is a typical surface profile or surface profile.

So what we do in this case, we say surface roughness, refers to how far surfaces deviate from perfection. So if I am assuming the red colour is a perfect line, this is a surface line. How much deviation is happening from this surface that is the peak side and valley side also? So negative and positive both. So we say the term surface roughness refers to how far the surface deviates from perfection. So surface roughness naturally will comprise some sort of scratch.

So this roughness can come because of the scratches, because of the tool wear, maybe because the tool is not very sharp; it is a plant, right? So those kinds of things, or maybe the possibility of the pit formation at the nano- or micron-level, possibilities of the grooves, and so on. So there may be a number of faults and a number of defects, and we know very well that any defect on the surface will create some sort of initiation of the crack, or maybe stress concentration, and that stress concentration will lead to the corrosion or will enhance the corrosion rate, and that is not really acceptable from a sustainability point of view. We can now quantify and measure surface roughness through the use of a profilometer. It can be a contact type or a non-contact type also.

In this case, what we aim to do is determine the vertical displacement. If we consider the red line as the mean line, we measure the vertical displacement both in the negative and positive directions. Now, imagine we are using a stylus, perhaps a contact device with a diamond tip, moving across the surface. The goal is to move it in one direction while continuously measuring the vertical distance.

This process can be done in either 2D or 3D. However, we generally prefer a 3D profile because surface contact occurs in three dimensions, and a 2D profile cannot provide a comprehensive understanding of the surface. This is especially important when we are focussing on digitisation and data-driven approaches, as a 2D representation falls short of capturing the necessary details.

But from an understanding point of view, from a concept point of view, we may require a 2D also, and what we say is a rougher surface will have a larger deviation. So a larger deviation means rougher the surface, right? So these are some sort of thing, which already you may be knowing, and then, because of surface roughness in our first lecture itself, I say that the many times the nominal contact area reduced to 1 percent (1%) of the area. We do not really get a complete area, and that is why almost every aspect goes through the plastic deformation. Even in mechanical engineering, we assume the load is too low, and then it will be subjected to only elastic deformation.

In reality, our asperities go to the plastic deformation and cause some sort of modification in a roughness value. So this is one of the examples that have been given where there is; we have shown a stylus, and a stylus can travel, and maybe the stylus has started from this position; this line is the starting position, and then it is ending at the finishing position over here. So this is the initiation and the finishing position, and we are able to see that a stylus position. Now, depending on the radius of the stylus itself, we will decide what kind of surface roughness will come. If it is a pin point, it will be very sharp, and then we will find out the true surface roughness.

If it is not so, then quite possible it will have this as well as some sort of radius, and then that will affect the accuracy. So it depends on what we are really using and which kind of stylus we are using. That is why this profilometer can be very low-cost, like something like 2 lakh rupees, or it can be very costly, maybe like 2 crore rupees also. So there is a variation and then kind of accuracy and the 2D or maybe 3D. What kind of parameters do we require when we want to really compare, we want to really design something, and can it really give an interactive surface also? So in this case, what are the different things for which we are able to see one name here? Something is called evaluation length. So what is the evaluation length we will be considering in this lecture.

So when we think about the quantification of surface roughness, we have a number of methods, but we prefer to go hard with the digitisation, because in this case, what we do is pick up the points on line and then try to calculate the value. So this is the digitisation method, and this is what we say average surface roughness; whether we are choosing, we are taking the absolute value of average z point or average height, whether it is a negative side or positive side with respect to surface, but we are taking the absolute value. So we do not get a negative value, in this case, and then whatever the mean value comes out of this. However, one interesting point is that surfaces may have two kinds of things; one is what we are considering the roughness, and another one may be the weaviness also. However, we know that when we think about the microtechnology or nanotechnology, mostly waviness is acting because that is on a higher amplitude side; we concentrate only on surface roughness.

And here we have also shown the analogue approach, maybe the continuous approach, we are integrating.

$$R_q = \sqrt{\frac{1}{l}\int_0^l z^2\,(x)dx}$$

This brings us to the concept of evaluation length or sampling length. Here, we’ll primarily use the term 'sampling length.' We’ll also discuss the differences between sampling length and evaluation length.

If we express z(x) as a function of x, performing an integration makes sense. However, if not, we typically proceed with digitization, summing the values and then dividing by the number of data points.

There are two key roughness parameters: Rq, which represents the root mean square roughness, and R_a ,which represents the average surface roughness. In manufacturing, R_a is commonly used to define surface roughness across most processes. However, in surface engineering, we often prefer Rq because it gives a more accurate representation of surface characteristics needed for design purposes. This is why Rq is favored over R_a in surface engineering.

To clarify the difference between these two values, I have shown two figures. Figure 1 illustrates a bad bearing, and Figure 2 shows a good bearing. In both cases, the R_a value is the same—0.25. This could be in angstroms, microns, or nanometers. However, the R_q value is different: in the first case, it's 0.58, and in the second, it's 0.37. As we know, the roughness should be as low as possible, so the lower R_q value is preferable."

So that way this value is a good value, is a preferred value. Even though the Ra value is the same, I will choose this surface, and this surface has been designated as a good bearing surface. Then, being that it does not have sharp peaks, it has valleys, and these valleys can act as a dust pit. So they collect the debris there, and then they keep ultra mild wear—you know, ultra mild wear itself. Even the corrosive products that are coming out, maybe they get delaminated easily because of the brittleness; those particles can also come on the side in this kind of valley.

It will not interfere in a work, and that is what we want. That is why this surface is more important or preferable compared to this surface. . You can see here there are very high peaks, which have a very high stress concentration also. In fact, your area of contact will be low, and the stress will be very high.

While in this case, area of contact will be less or more, and then stress level will be lesser, and then again, as I mentioned in a previous figure, these act as valleys, and that will be useful. Even in both cases, the surface roughness is almost the same. In this case, it is the first case, and the second case is 2.5 microns. But here we are talking about the angstrom level, and here we are talking about the micron level. It can vary from an angstrom nanometer to the micron side. Now we also had the first slide; we mentioned something like an ISO standard that is a 4287, and that gives surface roughness parameters. And what are those surface roughness parameters? There is a long list, but we will just focus only on the 5 parameters, which are a R_a value, R_z value, Rq value, R_t value, and R_p value.

R_a value and R_q value were demonstrated, or maybe they are shown in a figurative manner in a previous slide. However, we are trying to repeat over here. We say it is an arithmetic mean roughness and average deviation of the surface roughness profile from a mean line. R_a is calculated as an arithmetic average of the absolute value. That is what we showed in a z value that the absolute sign of all the measured profile heights. Now an interesting point: this is done on the sampling lines.

Coming to the next one we say R_z, we take a 10 points and then 10 point roughness, and then this in this case also we take absolute value of the peak 2 valley. Now here the phi we take the highest peaks and phi we take the lowest valleys, and here we count something like an evaluation length, which is different than the sampling length. So R_z is done mostly on a bigger scale compared to the R_a value. So this is a basic difference, and R_z provides an indication of the height difference between the highest peak and lowest valley, then from the evaluated or within the evaluated section. So if somebody asks what will be the surface in the layer or may be the top layer, I will say better you go ahead with the Rz value.

If the Rz value is 20 μm, you treat the surface as having a 20 μm roughness, but it could be higher if the Rt value is on the higher side. These variations are possible, but I prefer to work with the Rz value when defining surface roughness in terms of dimension.

Now, let's discuss the R_q value. As mentioned earlier, R_q represents the root mean square of the surface profile height deviations from the mean line, measured over the sampling length. It provides an overall indication of surface roughness, and R_q will always be higher than R_a.

Moving on to R_t, which represents the total height of the surface roughness. This is the vertical distance from the highest peak to the lowest valley, measured within the evaluation length. For R_z, we select the five highest peaks and five lowest valleys. In contrast, R_t captures the highest peak and the deepest valley over the evaluation length.

In summary, we use R_a and R_q values for roughness over the sampling length, while R_z and R_t are measured over the evaluation length. Additionally, Rp, the maximum peak height within the evaluation length, is important in determining the surface roughness, especially when evaluating R_z or R_t.

From a surface analysis perspective, R_a and R_q are the primary roughness indicators when comparing surfaces. However, if these values are close, additional roughness parameters may be needed. In this discussion, we haven't covered kurtosis or skewness, which were explained in previous lectures. While these values aren't critical for a good surface, they become important when analyzing damaged or degraded surfaces.

Finally, all these parameters are generally measured in micrometers or nanometers, providing a quantitative assessment of surface roughness.

It is essential to understand these values clearly. Let’s first look at the evaluation length and sampling length. The process starts with the traversing length, followed by the evaluation length, and finally the sampling length. The sampling length is the smallest of the three, the evaluation length falls in the middle, and the traversing length is the largest.

Typically, five samples are required to calculate values like R_a and R_q. That’s why the evaluation length (L) is set to be 5 times the sampling length. The sampling length is the smallest, the evaluation length is 5 times that, and the traversing length (T_L) is 7 times the sampling length.

But why do we add two extra lengths? When the stylus moves onto the surface, there can be deviations due to edge loading, and similarly when it moves off the surface. These deviations can skew the results, so the first and last values are excluded. Profilometers account for this with built-in algorithms that ensure accurate measurement.

Here is an example of a surface roughness profile. If you observe the profilometer reading, you'll notice three key lengths: Lc, the sampling length, Lt, the traversing length, and Lm, the measuring or evaluation length. In this case, Lc is 2.5 mm, Lt is 7 times that, which equals 17.5 mm, and Lm is 5 times the sampling length, resulting in 12.5 mm.

For this surface, the roughness Ra is approximately 0.1 µm. As mentioned, the Rq value is always higher than Ra, typically around 50% more, which in this case is about 0.15 µm. The Rz value is around 1.1 µm, and the highest peak is approximately 0.4 µm.

The variation in Rz, which is 1.1 µm, indicates significant surface deviation, including valleys. This shows that the surface is not confined to just the top 3 nanometers, and the valleys are an integral part of the surface profile, which we need to consider carefully.

According to ISO 4287, the sampling length must be specified along with the average roughness value. This is important because changing the sampling length can alter the surface roughness measurement. The ISO standard provides guidelines, suggesting specific sampling lengths based on the roughness of the surface.

As the roughness increases, the sampling length should be adjusted accordingly, and if the roughness decreases, the sampling length must also be reduced. This process is iterative—it's not as simple as mounting a profilometer, taking a reading, and being done. Instead, we must adhere to standards to ensure consistent and accurate measurements.

Standardization is key to ensuring that surface roughness measurements are comparable across different labs. For instance, if one lab reports a roughness of 0.1 µm, and another reports 0.2 µm or 0.05 µm for the same surface, there's a lack of consistency. Following ISO standards helps maintain uniformity in measurements globally.

We picked up the one metal surface here. You can see on this side that this is the metal surface, and we mounted a profilometer on this. This is a profilometer with which we are able to show in this view, and this is a surface roughness profile. You can see a lot of looks like kind of a lot of noise on the surface, and in true sense, every surface has this kind of characteristic.

In addition to this, we aim to design the surface intentionally. This means we want to manage surface irregularities (or noise) and make them more useful, beneficial, and effective in preventing surface degradation. In this example, the Ra value is approximately 0.6 µm, and the Rq value is 0.76 µm, again showing that Rq is higher than Ra. The Rp value is around 1.85 µm, and the Rz value is 3.63 µm, which represents a significant difference.

These values can vary slightly depending on the type of profilometer being used. I have something small to demonstrate, a video where we see a stylus moving across the surface. It highlights how loading and unloading affect measurements, which we need to consider carefully.

Next, we'll dive into surface engineering—how we can modify and improve surface roughness to achieve better performance and control over these factors.

So, that we get a better surface or better feature, that is why we say the functional features, including wetting behaviour, where the surface will get wet easily, will absorb the moisture, or maybe they can keep the moisture for a longer time or improve the tribological surfaces, like a friction and wear surface or optical characteristics. All these are possible using the surface modification, or surface design, and sometimes we call a surface texturing. We texture the surface, and as seen in this slide, there is clear evidence of surface texturing. You can observe various projections on the surface. As mentioned in an earlier lecture, the surface texture can vary based on the movement of the tool—it can create horizontal, vertical, cross-patterned, or even diamond-shaped textures, depending on the direction of the tool's movement.

Each of these textures will affect the surface properties differently. Friction, wear characteristics, and even corrosion behavior will change based on the texture. By simply altering the orientation or movement of the tool, we can produce a surface that may either be harmful or highly beneficial, depending on the application.

So, why not study in a manner we get only benefits, not harm? That is why this topic is important. Now, this surface is also shown earlier; you can see here the multidimples in the surface, and we know the dimple has a kind of curvature on the surface, which concentration will not be significant here. In addition, they may have a number of dustbins or maybe some sort of pocket to keep a reservoir of the oils also. So, this type of surface is really important for a number of products. So, we can say the surface design is a process of manipulating surface structure to generate desirable surface parameters in order to reduce the surface failure due to wear, erosion, and corrosion.

If you are able to play with this, if you are able to do really like this naturally, we will get a desirable distance. Now, how do we do that? What are we talking about the manufacturing? Now, we're talking about something like micromanufacturing. Then we go on with micromanufacturing, and the laser texturing is one of the micromanufacturings in the process. Microelectric discharge machining is a micromanufacturing process.

CNC ultrasonic machining is a micro-manufacturing process. Alongside it, there are several other techniques such as chemical etching and electrochemical etching. While we won't cover every process in detail, we will highlight a few key ones to give an understanding of how surfaces can be altered to achieve desirable characteristics, resulting in better and more refined features.

As for the reason behind texturing, I believe we've already covered that sufficiently and there's no need to revisit it now.

You may be already very familiar, or texturing is essential. The texture is very important. However, in a tribology we have several examples. This can be from different streams. In this case, we have given examples of the piston rings and thrust bearings, and there are many examples. And in this case, basically the microdimples that we showed in the previous slide were also organised in some sort of structured manner and matrix manner or arisen manner.

They really reduce the friction; they reduce the wear and increase the surface life. So, sometime we were talking initially only 5000 hour cycle life. Now, we talk about the 50,000 or 15,000 life cycle also just by tuning the surface, and that is the beauty of the surface engineering. You see, surface in this texture serves the three key rules, particularly in a tribology and in the domain of lubrication.

It traps the debris. So, keep ultra-mild wear. It does not cause an increase in the wear rate because of the trapping of those particles between the interface or maybe at the interface between the surfaces. So, this acts like a pocket, and whatever the debris, it gets dumped there, and I use the word can act as a dustbin. And then this can act as a surface to keep a reserve of the lubricant even in between some pump fields; at least we know the lubricant is there. So, the product will survive for some more time, and then sometime because there are pockets and there is pressure generation, these pockets also work as microbearings. So, three main characteristics of this texture surface are that they act to capture or trap the debris to keep a lubricant reservoir, act as a lubricant reservoir, or maybe act as a microbearing also in the surface.

Now, what is the difference? Perhaps the mechanical machining techniques, such as milling, turning, and grinding, which utilize sandblasting, can also be used for surface finish operations and produce various patterns. No doubt, this mechanical machining process can develop the patterns, but on the larger scale, if we require a nanoscale or microscale, I will prefer not to go with this kind of mechanical machine; we really require macro machines; we do not go with mechanical machines. Now, there is one process in this case, chemical etching, which is why we do not go out of the mechanical micromachine, but chemical etching. Here in this case, we selectively remove the material by putting on some sort of mask and then treating the surface. So, in this process of selectively removing the material from a surface using chemical etching, remove the chemically surface from selected persons. Specific patterns and textures can be generated through processes that even alter the chemical composition of the surface. By changing the concentration of the etchant or its chemical composition, different surface characteristics can be achieved. The chemical composition of the surface itself can also be modified during this process.

This method is ideal for producing micro- and nanoscale textures with high precision and repeatability. However, when masking or selectively removing material, some surface deviations may occur. Therefore, even if the surface appears to be of high quality, additional post-processing may still be required to achieve the desired finish.

So, chemical etching may give very good surface precision, but we want better than we need to really do postprocessing in that. Now there is another thing that we also use; we see we first put in the layer, and then we are chemically selecting it and removing some portion of the layer. It can be a 25 percent (25%) removal portion; it can be 30 percent (30%); it can be 50 percent (50%) also. So, why do we really do that? Why not go ahead with additive manufacturing itself? Wherever we require a deposit, material you deposit. Why do you want to remove the surface? Why do you want to go with a more and more waste of materials? So, when we think about what we have considered, like a life cycle assessment, we know what is really the trash that is coming out of the surface, right?

From that point of view, I believe that additive manufacturing will be a better option. The question comes will that be acting accurately, precisely that is where we require more and more development, more and more innovation. So, this is the future; we kind of like a 3D printing may make in a manner so that surfaces really get a very good surface gets a top good layer within the nanometre, or the few micron level, and that 3D printing can do faster.

The reason is that when printing something as fine as 5 microns compared to 5 millimeters, additive manufacturing can achieve much better results, provided that the CNC machines used are of high quality and the system has strong stiffness. Additionally, it’s crucial that the material being deposited adheres firmly without delamination.

By ensuring strong adhesion, we can overcome many of the limitations of current additive manufacturing processes. I’m confident that this technology will play a significant role in the future of surface engineering and may eventually replace or enhance traditional methods.

In this case, we can create specific patterns on the surface texture, and additive manufacturing offers exceptional design flexibility. It allows for changes in materials, chemical composition, and temperature, enabling the creation of customized textures, even on complex surfaces. These are significant advantages, though we are still waiting for a fully reliable additive manufacturing technology, which will likely emerge in the future.

Now, let’s discuss two well-known manufacturing processes for producing complex texture patterns: laser-based techniques and electrochemical etching. While we’ve already touched on chemical etching, electrochemical etching uses a different approach. Laser ablation, on the other hand, removes material using a highly concentrated laser beam, precisely targeting the areas where material removal is needed.

By carefully adjusting the laser's intensity, a wide range of patterns, shapes, and depths can be achieved, making it ideal for creating nano- and microscale textures.

And then this can be utilized. The laser ablation process can be utilized for even metal, ceramic, and much plastic also. So, it is versatile; the same setup can be used for the many materials, and on top of that, it really provides very high accuracy. Of course, the cost of laser ablation is relatively high, but the overall cost may decrease if we use this machine for several hours daily. This cost may be something we can get back in a few years time. So, there are two surfaces. A very complex surface has been shown you, and as you can see here, this is the textured surface. In this case, we have made a number of pockets. Here we are trying to show some sort of very regular pattern, but many like that, there is a good number of arrays on this.

So, this has been shown as one of the textured surfaces. Now what are the different kinds of textures? There is a lot of literature available on that, and people have done it, and unfortunately, the same texture: one author will say it is good, the other author says it is bad. What is the difference? Some situations may benefit from it, while others may find it detrimental. we do not have a generalised pattern or generalised texture, which is the best for all the situations. They have a good situation, and then the pattern is good for some situation, but it may be bad for some other situation, and that is why we really require a thorough literature review to understand all those things. So, we have picked up these figures, which may be the next two or three slides also from this 2016 publication, and the name is the surface texture manufacturing techniques and tribological effects of the surface texturing on cutting tool performance.

Later we are talking about the cutting tool performance only, not the work piece. It is a basically cutting tool, and then here, in the first case, they have shown a segment; each segment is around 150 x 150. So, this texture surface, we say, is not able to reduce addition, particularly for the aluminium cutting. Reason being that whatever the aluminium chip, they clothe this kind of texture itself. So, there is no room as such available, and then this texture gets spoilt very fast, and it also increases because of the clogging of this texture, particularly with the chip, the friction coefficient increases significantly.

So, in this situation, we say 150 x 150 texture is not recommended, which is why we say it here. So, reducing the dimension may solve the problem, which is what the literature indicates. So, another one is now coming to the depth of 100 to 150 nanometres, spacing 700 nanometres.

In this case, we observe that the anti-adhesion properties of the sine wave texture, as shown in the sine wave pattern, are found to be lower compared to linear banded grooves. This suggests that the use of cutting fluid, which helps reduce adhesion, needs to be increased for the sine wave texture. However, the oil retention capability is slightly improved in this texture.

Reducing the dimension can increase the oil-retaining capabilities. However, it can also be subjective because we know oil will vary. Now, the cutting fluid: what kind of cutting fluid has been used, what are the really properties, or what are the properties of the cutting fluid? It may again work for some cases; it may not work for the other cases. Now, similar depth, similar spacing, there is another one saying instead of here we are talking about aluminium cutting.

We come to the steel cutting. We say because of the high contact forces, these textures with the dimension were found to be useless. So, for aluminium, it works well; for steel, it may not work well right. This is why a thorough literature review and deep understanding are crucial—what works in one situation may not be effective in another. However, knowing the different types of texture patterns and their behaviors is essential. If we lack this knowledge, it's important to conduct initial pilot studies to determine which pattern will offer the best solution.

In this context, surface textures can generally be classified into two categories: grooves and intermediate pits or dots.

So, these are the intermediate ones, and these are the grooves we can divide. Disconnected dimples, and that the way maybe we will show in the next slide. Disconnected dimple texture reduces the wear more efficiently than linear connected grooves. So, this groove will have a slightly higher wear rate compared to the disconnected texture, and then sometime because we are able to see this texture. If I embed solid lubricant in that, it will act very nicely. So, with friction, the coefficient of friction will come down significantly, even though the wear rate will be significantly down, because solid lubricant will be sticking to the opposite surface, and the wear rate will come drastically down. So, that is why we say the solid lubricant present in texture reduces the friction and addition by forming a dynamic firm on the contact surface.

So, we do some texturing and embed some sort of solid lubricant. The retainability of the solid lubricant in those grooves or not in the grooves, and then the texture will be better compared to the other surfaces or maybe otherwise utilising the solid lubricant as it is. So, for filling the channels with MOS, 2 solid lubricants improve the wear resistance, and it can be achieved. We say the connected texture like a grooves such as groove allows lubricant to flee because, as you can see here, if the lubricant is here, it will pass easily. So, it will get drained. If I have a just perpendicular to that, maybe there is another layer also on the surface; naturally, lubricant will get trapped; it will not be skipping.

So, that is why we say connected texture, and such as the grooves allow lubricant to flee tribological contact and decrease a kind of lubrication or then a hydrodynamic pressure generation, or will be less, and the vice versa for from the lubrication point of view and wear point of view. So, this kind of long groove may not be good if you go with the perpendicular grooves also, or maybe say the texture in a manner. So, that we get this kind of cross pattern that will really reduce the coefficient of friction in this manner. Now, as I mentioned, there are different kinds of textures: pit shape, dot shape, and banded grooves, where grooves we have already explained. Now here the different references also have given that their width and the depth dimensions are different, then again the behaviour will change.

Behaviour will not be he same. So, that is why this really required a good and then knowledge of a different kind of texture. So that we get better and better results. Now let us use a dot type here. Dot type reduces the friction and normal force compared to an untextured tool.

Yet compared with untextured, it is good, but it will be less effective than the pit type of texture. Now if this is a pit type, it is here we are able to trap the lubricant, while in this case spacing is more that we are not able to trap the lubricant. So a naturally dot shape for the lubrication purpose will not be as good as a pit shape. However, compared to the smooth surface compared to the vertical grooves, the naturally dot shape is very good. So, from that point, I will say if I put a vertical arrow, performance will improve significantly.

Of course, the cost will also increase in this manner only. Now let us take a couple of manufacturing processes. These are what the texturing process is. The first texturing process has been shown in a factor-second laser micromachining process in this situation. What we are really developing is some sort of laser beam focused on a surface, and then it can be a mask; it can be without a mask also. So it depends on what kind of surface we are developing and what kind of energy we are trying to give. So there are two processes in this case we are saying that are basically laser beam fabrication. Sometimes we use our laser texturing or laser surface texturing elasticity.

It utilises the laser pulse of the high energy to remove the material to ablate the material through rapid melting and vaporisation, which is the first process. Rapid melting and vaporisation occur immediately. So metal was there, and metal is not there; something immediately melts and vaporizes. And then, in this case, this is the first process. However, we say based on the interaction of the laser energy with the material, the laser ablation process can be divided into two processes: one is called a pyrolytic and the other is called the other is called a photoelectric as such.

In pyrolysis, that is what happens; rapid melting and vaporisation happen, and that is what immediately happens. So when it comes to the photoelectric process, what will happen? In this case, chemical energy, whatever is really required, will only be overcome. May be the only breaking of the bonds will be really required, and that is why this process is also called something like a cold ablation. We do not raise the temperature to some extent—to a significant extent; we are not really melting; we are just debonding the chemicals, and then we are removing the material from there. Now, as we know very well, lasers are very focused. So heat-affected zones also will not be very significant, which is very important because most of the mechanical manufacturing process heat-effect zones are significant, and that changes the property significantly, and that is why the laser texturing or laser processes are far better than those mechanical machines.

In this case, there is also a possibility that heat-affected zones could generate defects such as bursts. For this reason, it is necessary to perform additional processes like grinding, polishing, or lapping to remove these imperfections.

So super finish operation is really required after that. However, as I mentioned, if we are able to really develop in a future laser additive manufacturing may be with a even the very focus one that will turn out to be very far better compared to removing surface or material from a surface and again then we do for the polishing. Compared to that only add material which is very almost negligible in nanometer to micron level, so that laser based additive manufacturing may turn out to be very good success, a big success in the near future. So what we are saying here in this case to make it effective manner we can go ahead with the mask fabrication or non mask also.

However, the mask fabrication is mostly used but it has a drawbacks particularly as I say that we really required a polishing and all those things. Another one which is not a mask one then we really required individual feature to be removed. So that is why turn out to be the it is becomes a precise but it will be the time consuming , and that is where it has been when shown over here it is a femtosecond which is around 10^{-15}-seconds. The pulse is based on this and we do not really go ahead with high energy, high current and then we give precise manufacturing. We do not have too much burst if we are trying to remove only small material and that very high frequency with high frequency those are important.

Now most of the surfaces in these days are getting manufactured whether this kind of laser micro machining system. Here the most of the cutting instrument, bearings, pistons, cylinders, implants or biomedical plants, mechanical seal, magnetic storage devices are getting manufactured using the laser micro machining system. There is another manufacturing process that is I got a USM. What is the full form of USM is something like ultrasonic machining, and this also is connected with a CNC. So CNC has a machine and then we try to use ultrasonic machining on this machine itself , and what is really done here that the tool is really given ultrasonic motion, and then we impinge abrasive particles. So earlier we studied that abrasive particle would cause a wear and then we were very much worried that abrasive particle in atmosphere are really damaging the surface.

So we understand that science and use that science for the our good work. We say those process which we have understood can we really go with a good manufacturing; can we really go ahead with a good texturing this one and it has been shown here. So, first with the impinge them on this abrasive material, or particles and other end we connect collect those surfaces or then those particles, and possibility that we reuse those particles also. So, the CNC mounted ultrasonic machining process employs abrasive particles and vibrated tool that has been shown over here. This is a vibrated tool and then the abrasive particle has been shown over here.

The tool vibrates at the ultrasonic frequency and abrasive particles which directly will come and impinge on the brittle material. This is very good for the brittle materials is something like a ceramic, glass, silicone which are very hot and then they will break easily with the high impact and the impingement of the particles. We already have known that maybe the smaller whenever there is a abrasive materials, then we should impact the higher angle maybe 60 degree, 75 degree, 90 degree and it looks like this degree angle is also on a higher degree. Now this kind of process can be utilized for the number of shapes something like a circular shape, or rectangular shape or hemispherical shape, and then one dimension also can be, and then we have a significant range is something like a 50 micron to the few mm and depth also can go to the 1 to 10 mm. But there is a possibility because we are going with a very deep 10 mm there is a possibility the whole surface get fractured.

So we need to really look at what the sensitivity of the surface is towards this kind of manufacturing process. Indeed, the manufacturing process has the potential to produce either a texture or a complete breakdown of the piece. So that is why hard material may result in the microdrill failure, rendering this inappropriate for texturing using the CNC USM. And the CNC USM can be costly also with this because we are mounting everything on the CNC, and in addition, we are increasing the number of accessories. And then if we really want to go ahead for the better arrangement and because we are using 2, 3 tools for particle collection, impingement of particle, tools for motion, and maybe the workpiece portion also.

So we really required a multi-axis CNC machine, and preferably people use a 5-axis CNC machine. So overall, this turned out to be the costlier. The alternative is that we go out with a rotary ultrasonic machine. What is in there? It is a kind of CNC USM variant, and then here they incorporate the diamond gridding, and the diamond grinding itself is rotated, and then they also generate an ultrasonic motion. So mechanical, along with ultrasonic motion, may turn out to be slightly less costlier, and then it really provides a more suitable result and also remains cost-effective compared to the other techniques. Something like we are talking about EDM, we are talking about the laser technology.

So this rotary ultrasonic machining may turn out to be cost-effective and very effective as such from a performance point of view. In this series, we are going to discuss only the last process, which is ECM electrochemical machining, which is basically electrochemical cell, which we already studied in our corrosion-related topic. What we do in this situation is remove a material through anodic dissolution, and then we know the process will be done through electrolysis. Contour of the machine surface is determined based on the shape of the electrode. What kind of shape of the electrode we are using will decide what will be the texture and then the surface. And we also do if we use this electrolysis process or with the electrolyte, which has a very high resistance, then we can go ahead with a small because we are really required to give energy to remove the material.

If the resistance is high and the sensitivity of the resistance (R^2) is on the higher side, we can apply a smaller current to achieve a better surface finish. In some cases, an electrolyte jet can be used as a micro-tool for localized electrochemical dissolution, which is often more effective than conventional methods without the jet.

Another advantage is that research has shown that ECM (Electrochemical Machining) can be integrated with a Scanning Tunneling Microscope (STM), enabling ultra-finishing operations. This combination allows for material removal at the atomic level, achieving ultra-precision. As a result, ECM stands out compared to other texturing techniques due to its lower production costs, high efficiency, absence of heat-affected layers (since lasers and high temperatures are not involved), and minimal tool fatigue.

So of course, when we think about STM, the cost will go on the higher side, but otherwise it is good. However, if it is, we really require atom-by-atom manufacturing or the removal of the atom-by-atom, so high-precision manufacturing is possible using the ECM in this situation. Now again, ECM can be done in two ways. One is maskless, and the other is mask-based, but the latter is more common in ECM with a mask only. That is why we say that ECM through masks is more common. This procedure involves application of the photoresist, and that has been shown here, the substrate, and then we are applying a dry film on that, and the dry film again we are using the photo mask on this, and then we are selectively removing the material in between.

That is what we are showing a surface texture. So that is why it is shown here that application of photoresist exposed to the ultraviolet rays, UV rays, and radiation has also been given, and then selective dissolution of the metal follows that has been shown, and this is a through mask that we are getting. Now here, if you go ahead to the through mask, as I earlier mentioned, there is a possibility of the edge deformation of all the places. How much edge reduction, or maybe edge deformation, can be avoided that will give the accuracy? Our surface will turn out to be a rougher surface, and then the results will not be very good. So when we go for sophisticated machines or maybe manufacturing, and particularly with a mask, we need to really look at what will be the edge effect of those mask-produced textures.

The surface irregularities should not increase beyond a certain point. To illustrate this, let’s explore a case study, although many other examples are available. In this study, the researchers aimed to improve tribological performance through surface texturing. The initial surface roughness of the material was approximately 0.5 microns (0.5 μm). They employed two types of frequencies during the process: a high frequency of about 16.3 kHz, which was applied to the tool, and a lower frequency of around 230 Hz applied to the base. The base experienced a 1D frequency response, while the tool exhibited a 3D response.

Their focus was on enhancing the properties of aluminum alloy Al6061-T6, with its chemical composition shown in the figure. It's well-known that aluminum alloys do not perform optimally under dry, partial, or boundary lubrication conditions. However, in this 2022 study, they demonstrated that even in such unfavorable conditions, the aluminum alloy can exhibit improved surface quality and performance through proper surface texturing.

In this case, no material change was necessary—simply modifying the surface texture led to better wear and friction performance, ultimately enhancing the alloy's tribological properties. The tool used for this process was a polycrystalline diamond (PCD) cutting tool, featuring a nose radius of approximately 400 microns (400 µm) and a rake angle of 7 degrees.

And then this overall setup can be utilized for generating various kinds of surface textures. So various kinds of texture means what will be the depth of the texture in came 14 micron, 15 micron, 16 micron, 17 micron, and they try to really figure out which then the texture is going to give the better performance to us. And then one good point is that they were using a Stribeck curve, and a Stribeck curve is known to figure out what the lubrication region is. We say that in dry lubrication and full lubrication or mixed lubrication, that can be given when we know the operating point. We can figure out using the Stribeck curve based on the operating point whether it is under mixed lubrication, under boundary lubrication, or in full film lubrication. And this, particularly in this case study, they mentioned very clearly that they are going to use a starved lubrication, which means there is not sufficient lubrication, and we can use the word something like mixed lubrication or boundary lubrication. So for starved lubrication, more preferably, I will use the word boundary lubrication, least preferably, or mixed lubrication, but other than these two, we cannot use any other word.

A starved lubrication refers to either a boundary lubrication or, to a lesser extent, only a mixed lubrication. To figure out what the friction and wear characteristics will be, they use a rotating cylinder on the pin triangular test, and this is one of the tests available in their lab. So they've used it, but we can also use any other test setup and any other type of meter. What is the Stribeck curve mentioned earlier? The Stribeck curve is generally given by the coefficient because there is a relationship between the coefficient of friction and the Sommerfeld number. The Sommerfeld number is generally given in velocity terms: velocity into the oil viscosity, whatever they were using, divided by the operating pressure or bearing pressure. You can see here there are three domains of hydrodynamic region: this is a mixed lubrication, and this is a boundary lubrication.

As I understand it, they were considering D-contact boundary lubrication. This type of interaction occurs under conditions of low speed, high normal load, and insufficient lubrication. In the future, with increased load requirements without enlarging system size, the effective load and stresses will rise. When operating speed isn't sufficient, asperity contact or boundary lubrication will likely occur.

This relates to the Stribeck curve, which is often used to assess lubrication regimes. Alternatively, some use the Reynolds-Sommerfeld number or diagram as a design tool to minimize friction losses. By analyzing this, we can determine how to reduce friction—whether by increasing RPM, adjusting the load, or modifying the oil viscosity—to select the optimal load, speed, and lubricant viscosity.

These lubrication regions are not part of the current scope, so we won't be discussing them. In the case study, they provided close-up views where you can clearly see the texture patterns they generated on the workpiece.

This demonstrates the surface texturing process, where they applied both high- and low-frequency vibrations to achieve the desired texture on the surface."

The surface texturing operation was carried out using a CNC lathe machine, as simultaneous multi-axis operation was required. The CNC machine they used had a high resolution of 1 micron (1 μm), which is essential for achieving precise surface texturing. A high-quality tool with excellent resolution is crucial for this type of operation.

This is a tribometer test. They are showing in this case. There is a stationary block. There is a rotating cylinder. The pin can be positioned in the hold of this block, and a load can be applied to the rotating shaft. In this case, they apply two different loads, a 10 Newton load in one situation and a 50 Newton load in another. They then use different rotating speeds, ranging from 100 rpm to 1000 rpm, to plot the blot on the Stribeck curve with ease. So what they use on the lubricant is VG68 viscosity-grade oil. The VG68 viscosity grade, represented by the number 68, provides the viscosity of the lubricant, while its kinetic viscosity is approximately 68 centistokes. So VG grade itself is providing the viscosity of the lubricant itself.

Whenever the sample undergoes wear measurement, it is necessary to clean the sample. The researchers provided a specific cleaning process: they cleaned the sample with acetone and allowed it to dry before conducting further experiments. The table presented outlines the test conditions, using a tribometer in a cylinder-on-pin setup to plot a Stribeck curve.

In the diagram, various surface textures are shown, including textures with depths of 14 microns (14 μm), 15 microns (15 μm), 16 microns (16 μm), and 17 microns (17 μm). The X and Y dimensions remained consistent at 0 to 619 and 0 to 453, respectively, across all cases, with the only difference being the variation in texture depth. These variations are categorized as follows: case 1 with a 14-micron (14 μm) depth, case 2 with a 15-micron (15 μm) depth, case 3 with a 16-micron (16 μm) depth, and case 4, which is largely similar to the others.

The only change in this case is the expansion to 387 instead of 319, while the other dimensions remain unchanged. Case 5 they have kept as 617. So as we are going from downward direction or going from case 1 to case 5, the dimension of these dimples is increasing. So the depth is increasing, and maybe one dimension is also increasing. And then they have plotted this curve. You can see this curve, and then they compared something like a hierarchical texture or a single-scale texture.

A single scale means that almost all of the dimples are the same size. Hierarchical is something like there is a mixture of these, and keeping making single-scale texture is naturally very difficult, and we go ahead with the hierarchical because sometimes we required a shallow texture, we required some empty texture, because of various conditions one will prefer compared to others. So that is why we go primarily in the hierarchical direction. Again, in the first case, where the load is low, it is something like 10 Newtons.

We are able to see the complete stripe as a curve. You can see here that it is increasing in the first, then decreasing, then increasing right. And in my view, particularly from the friction point of view, we should not go with the texturing because texturing is going to give only worse performance from the friction point of view. And it has been shown here that this is a non-textured surface, a red colour that has been showing the best performance. Same thing in this case also, whether you go with the single scale texture or the hierarchical texture. In the cases above, if there is a low load, we should not go with a texture, particularly from the friction point of view.

However, I am not adopting the wear point of view approach. From our perspective, we need to determine whether this will be preferred or not. But from a friction point of view, it is not really required. Going to the higher load that is a 15 Newton, you can see here nothing is going in a stripe or a curve, and this is basically on a star condition, or boundary lubrication, still it has not gone in the downward direction. And here you can see the non-textured is showing a worse performance. While coming to case 2, case 2 in this case is showing the best performance, while in this case, case 3 is showing the best performance. So, it depends what kind of performance, of course; the data are not very good in number; we cannot conclude based on that, but one clear thing about the low load case is that effectively, in the in the low load case we should not think about the texturing, but on a higher load case we really require texture where there is a possibility of the stop lubrication.

Now coming to the wear point of view, here it is shown the 10 Newton and the 15 Newton. Here in the case of the non-textured surface, everywhere it will be naturally constant, and it has a high value as such. So, in case 1, the single scale texture is causing a higher wear rate; even hierarchical is also causing a higher wear rate in case one. The depth is not sufficient. Cases 2 and 3 also exhibit comparable performance, with case 2's hierarchical system performing worse than the non-textured one.

However, in case 3, the behaviour is significantly different. So, preferable, So, this case 3 or maybe the case 4 is preferable compared to case 1 and case 2. So, we should have a slightly deeper texture compared to the shallow texture in this case. When you go to the applied in the higher load side everywhere, the texture is going to give the best performance compared to the non-textured. So, from this, we can conclude that whenever we have a severe load actual case, then we can go to the textured surface.

When we have a partial one or maybe the load is not that severe, maybe texturing will honestly cost more and it may not give that kind of fruitful results. So, texturing also should be done judicially. It is not that we know the texturing we will start doing a texturing. It is because it is going to be costing additional costs, manufacturing costs, and if it is not really giving significantly good performance, then we should not go ahead. However, texturing is one of the very effective methods, and if the texturing is not really giving the overall good results, we will go with other surface engineering technologies so that we get better and better results. Thank you for attending this lecture. Thank you.