Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 22
Non- destructive testing – Part 3

Hello and welcome to the 19th lecture of the course on corrosion, environmental degradation, and surface engineering. This lecture is on non-destructive testing, and it is a third part of this lecture. In this topic, we have already covered visual observation, or visual inspection, and visual testing. We have done ultrasonic testing and radiography testing, and we will not be covering magnetic particle testing and liquid penetration testing in detail. So, we will be just giving some sort of main features of these two tests, which we will be covering in this lecture: AD current testing and thermographic testing. In our next lecture, we will be covering acoustic emission testing and stress strain DIC testing, which is an emerging technology or testing procedure.

So, we have covered a number of tests, and I am giving more and more lectures on non-destructive testing. The reason is that I believe that it is a future where a number of start-ups can be started, we really require many sensors, we really require very good algorithms to simulate the real environment, and in other words, a digital twin. So, this kind of technique will be very useful to correlate what is really happening in a real situation and how to correlate with damage, surface damage, or surface degradation and really get a real performance. In one of my earlier lectures, I highlighted that most designs people create tend to be static. They often overlook the dynamic and time-dependent characteristics in their entirety. However, with digital twins, it is essential to consider both aspects—comparing what was initially designed with what is actually happening in real time. This ongoing comparison allows us to make necessary adjustments to the software design as needed.

So that we can take proper maintenance also. Now coming to these two techniques, MPT and LPT, So, what we are mentioning here is to locate the surface or near-surface faults in a material. If we want to use a magnetic particle test, then it will be used mostly for ferromagnetic material and non-ferromagnetic material. We will not be able to use this kind of technology or magnetic particle technology. Another one is a liquid penetration test, which is basically done for the surface and subsurface. We will have some sort of doubts about this technology.

So, now coming to the MPT, the magnetic particle test, we use ferromagnetic material particles; it can be iron or iron oxide. However, as per my knowledge, if we use pure iron, then the results will be better compared to iron oxide (Fe_2O_3) because of the retainability and then even the magnetic field that will be generated with ferromagnetic particles. So, for ferromagnetic particles, we can use iron or iron oxide (Fe_2O_3), and they are all spread generally on the surface of objects, and a magnetic field is generated. We can now generate a magnetic field using a permanent magnet or an electromagnet. Now what is the advantage with the electromagnet that we can go ahead with the variable magnetic field? Also, based on the current that is applied to the electromagnetic we can generate a variable field.

So, electromagnetics will be a better option compared to permanent magnets. Now what are the real characteristics of this system? Whenever there is a fracture, there will be disruption of the north-south lines. If there are only two poles in the north pole and south pole and the whole system, then this flux line will be well directed and there will not be much problem. However, if that magnet breaks in a number of parts, then there will be many north poles and many south poles as well, and that disturbs a complete magnetic field as such, and we try to figure out if there is a magnet disturbance in a magnetic field or not. So, that is why we say a magnetic field line will get disturbed if there is a defect or crack near the surface.

Even just below the surface, if there is a crack, there will be some sort of north south flux line will be disturbed, or it may not be following the normal path as such. Now because there are too many north and south poles, what will happen is that the particles will be clustered around those spots only wherever these lines are merging with each other, and then this particle will get assembled over there, and that is an indication there is a crack, a defect, a discontinuity, and the flux line is not getting a continuous path. This explains that magnetic flux will often leak where there are cracks or defects in the material, revealing traces that indicate the presence and nature of these defects. However, this method does not provide 100% quantification; it is more of a qualitative measure. While it helps identify the problems, determining the exact size of the crack may not always be possible.

Moving on to the Liquid Penetrant Testing (LPT), this test is typically performed on non-porous materials, and most materials used in such tests are non-porous.

However, in the recent time there is a some research on a porous materials also. So this LPT will not be able to you will not be able to utilize for that. So, metals ceramics plastic will be better option in the situation. So whenever there is a non porous material and I am assuming most of the materials are non porous like a metals or non porous ceramics in the elastic. However, more and more research is also happening on the porous material to reduce a density of the materials.

However, the Liquid Penetrant Testing (LPT) is generally limited to non-porous materials. The reason for this is that if the material is non-porous and has a surface-breaking defect, the liquid penetrant will seep into the defect due to capillary action, which is a key factor in this process. The properties of the liquid penetrant are crucial in this context.

Once the liquid penetrant is applied to the surface, it is left for a while to allow it to seep into cracks or pits, leveraging capillary action. After this waiting period, a developer is applied. The developer is a white powder that is sprayed onto the liquid, where it adheres to the penetrant, revealing traces of crevices or pits. This method provides qualitative information about the defects but does not give a complete picture of the crack's depth.

There is a crack, some sort of capillary action happening, and information will come to us. So we need to rectify. So these are basically qualitative tests, and quantification may not be absolutely possible using this kind of test. However, experience matters a lot. People who have been utilising this kind of test can really predict a lot about it, but here the skill will play a major role compared to the test procedure or the testing method in the situation.

That's why we're not looking to go beyond this, as many new techniques have emerged over time. Our focus will be more on eddy current testing and thermographic testing. Let's start with eddy current testing.

There are numerous sensors available on the market, particularly from various companies that use eddy current sensors. The main advantage of eddy current sensors is that when an electric current is passed through a coil, it generates a magnetic field. This magnetic field then provides results that help in detecting defects.

Eddy current testing is primarily used to evaluate and identify defects, but it's important to note that this method is limited to conductive materials.

If the material conductivity is not very good, then the eddy current will not be able to give us results. So, one constraint is that if the materials are conductive, eddy current testing can be utilised on them, and we will be able to find the crack even at a depth of 10 mm. I am using the word 10 mm, which is basically for aluminium alloy, but as a material changes, this depth will vary, and we really require good stimulation, good testing, and modelling. So that we can get good results on that. Now let me explain this complete principle. We say the magnetic field is produced around a coil, or sometimes we use the word probe.

The coil is built into the probe itself. So we can use a coil or we can use a probe, and then often people use alternative current (AC) through it. However, in these states, some tests are now available with the DC current, and some people use the pulse current. So different kinds of currents can be used; every current will produce a magnetic field, and if we have a good characterisation of those currents and the magnetic field, or perhaps a good relationship, is established, we can utilise any kind of current. So whichever is favourable is for our post-processing and will give us good results.

So in this case, we are mentioning a generalised case. In the generalised case, AC is most commonly used because it passes through the coil and generates a magnetic field. When the magnetic field is generated, it is brought to the material, which is electrically conductiWhen we try to oppose the magnetic field in an electrically conductive material, it generates eddy currents. Therefore, we need to understand the type of eddy currents that are generated. This depends on the number of parameters, and with a deep understanding of these parameters, we can perform a thorough simulation and estimate accurately. ll. So what we can say is that this coil creates eddy current within a material that is being investigated, whatever material we are trying to investigate, and then these eddy currents are generated when we bring this coil near the conductive surface. Now it depends on the many parameters, like material properties, which will be a major issue, then what kind of electric current we are giving and then what kind of frequency we are giving to the coil, or may be the current coil, and then the frequency it will really affect our results to, or may be say overall results.

So this is what we say. The eddy current will generally be generated mostly by a continuous path, but if there is a discontinuous path, we will be able to say there is some fault in that. So this is what is mentioned here: the defects differ in conductivity and material geometry. So there are many parameters that are defective. One parameter change in the conductivity is another parameter change in the conductivity, which basically comes when the material is getting corroded, and whenever there are corrosion layers that keep coming on the surface naturally, its conductivity will vary, and we can estimate that also. If I know the conductivity of aluminum and I'm using the same sensor, which is properly calibrated, I can monitor changes effectively. However, if multilayers start forming on the surface or if material is being removed, we can detect an increase in the gap, indicating a higher material removal rate, which requires attention.

In summary, any defect will alter the material's conductivity, and if you can detect these changes—along with changes in geometry, whether it's rectangular or cylindrical—it will disrupt the eddy currents. By diagnosing these disturbances in eddy currents, we can identify the underlying issues within the system.

This allows us to detect defects and anomalies, whatever the difference is, in a material by analysing the same thing. We need to know what the analysis is, how eddy currents are supposed to be generated, and where there is a disruption. Why is there a disruption? Is it because of a defect? Is it because of the corrosive layer? Is it because of the removal of material? Is it because of a change in geometry? Therefore, by gaining a thorough understanding of these parameters, we can accurately determine the causes of surface degradation and material degradation. Now the eddy current testing, which is a short form, we are writing eddy current testing. ECT. ECT utilises AC current. As I mentioned, the frequency can be anything from 1 kilohertz to megahertz. A higher frequency will have a different current. If portions are very thin, we will go with a high frequency, but if you record a greater depth of the eddy current, I will go for a lower frequency. So that is why we say the eddy current frequency can be 1 kilohertz to 2 megahertz. When it is flowing through the coil, it will create a magnetic field around it.

Now lower frequencies can travel in a material, so the depth of penetration will be higher with a low frequency, while higher frequencies are more attuned to the surface flow itself. So if I go for the higher frequency, it is very suitable for the thin section because it will get attuned to the surface only, or may be the subsurface to some extent. So the depth of penetration will not be very high, of course; there will be an upper limit and a lower limit, and then we can calibrate according to that. Now whatever the disturbance, this is the disturbance that comes, and then if we are able to judge it in terms of voltage, frequency, and current, if we are able to get this either through this using the same coil in which current has been passed or we can use a secondary coil also where the magnetic field is getting generated. We can detect that, and we can interpret that the way we have mentioned our ultrasonic testing. We can have two sensors on opposite sides of the surfaces or the system, or on the same side, one sensor. So it can transmit the waves and also receive them.

So in a similar kind of thing, we can have two coils or we can have one coil also. The one coil that means it is sending and then receiving also means that both things are happening. Of course, the overall economics will be there, but naturally, the control circle needs to be very costly or may be much more complicated compared to the two coils. So these are the merits and demerits of single coils or double coils. Different companies use different kinds of principles, and then it depends on what is available issues and what we want to achieve, whether cost is the main criteria or lesser complexity is the main criteria. We can choose what kind of sensor will be useful to us. So now this slide shows a broad view of eddy current testing. As has been shown, this is some sort of electromagnet. You are able to see these are the coils and then the electromagnet, and then when we are passing AC current into this, we are able to see the blue colour line. These are the magnetic lines; they can be north poles or south poles, and when there is a continuous line, there is no disturbance.

When an electrically conductive material is brought near the coil, eddy currents are generated, as shown by the red lines on the surface. If there is any flaw on or beneath the surface, it will disrupt the eddy currents, which is indicated by the yellow area. This illustrates the basic principle: when a current is induced in the coil, it generates a magnetic field, represented by the blue lines in all three electromagnets.

When the coil is placed close to the conductive material, alternating currents (eddy currents) are generated, as shown in red. If there is a defect on or below the surface, it will disturb the path of the eddy currents, as depicted in orange or yellow. This disturbance can be measured by the coil, allowing us to identify different types of cracks and their depths.

Accurate results require extensive data and sophisticated algorithms. This is a growing field, with increasing demand for sensors and non-destructive testing methods to develop sustainable solutions. These solutions extend the life of components and systems, preventing failures or minimizing their impact, which is crucial in today's context. Improvements in sensors and technology can lead to successful startups in this area.

Additionally, when using a material with higher conductivity, the generation of eddy currents and the strength of the signal improve, resulting in a better signal-to-noise ratio. Conversely, low conductivity materials produce weaker eddy currents, yielding less accurate results. Even small changes in the material composition, such as adding 0.1% of a new material or using nanocomposites, can affect electrical conductivity, necessitating a calibration constant for accurate measurements.

Magnetic permeability is also important because it determines the depth of eddy current penetration. Greater permeability allows the eddy currents to travel deeper into the material, enhancing the accuracy of the results.

So, that should be done. Now, however, one more constraint and one more problem comes at temperature. An increase in temperature will reduce a magnetic field, and it depends on the material whether thermal conductivity or electric conductivity will increase or decrease. So, you can say the temperature affects the electrical conductivity and magnetic characteristics of the test material. So, that is why we really required temperature compensation. If the temperature is 55 degrees and we have done a calibration on 30 degrees, there should be some compensation, either a constant compensation or perhaps recalibration will need to be done. So, these are the new things that are really required; it is nothing like an entity that you pick up, set up, and apply to some material, and the results will be very favourable. No, we require real understanding; we need to have knowledge, and that will give us good returns.

Now, another one, as I am using the word lift-up factor, which is basically distance. So, what is the distance between this electromagnet and the surface? If the distance is much smaller, naturally, the strength of a eddy current will be on the higher side, and if the distance is far away, then eddy current generation will be less. So, this is also important. So, what we say is that the strength and interaction of eddy currents affect the lift-up factor, i.e., the distance between the coil and the surface of the test item. That means, whenever we have another chart available or software, we need to have some relation; it can be a linear relation or a non-linear relation.

If it is a linear relation, then we need to give a range, which may be 1 mm to 2 mm. This will be a linear range, or something like that, or from 0.1 mm to 1 mm, there will be a linear range. Otherwise, we need to use a non-linear relationship. A non-linear relationship can be anything; it depends on what kind of sensor we are using and what kind of electromagnet we are using. So, those things are important. So, we require a calibration constant, we require temperature compensation, and we really require some sort of relationship between the eddy current and the lift up factor in this situation.

So, these are important aspects to really and then execute the current test research. Now I mention something about the depth of penetration, and then there is something like a current density, or we say that these are the factors. So, then there is some available literature in this that I am just trying to highlight, but we say the eddy currents are basically at the closed loop. In this case, almost all the currents try to close the loop because of the induced current circulating, and this kind of eddy current is generally perpendicular to the flux line. Another thing is that eddy currents are concentrated near the surface adjacent to the excitation coil, and their strength decreases as the distance from the coil increases. So, near the coil near the electromagnet, the eddy current density will be on the higher side, but as the distance increases, the density will come down.

Another thing we say is that the eddy current density decreases exponentially with depth. So, it is a non-linear relation, as I mentioned earlier, a linear or non-linear relation. Now this is the way that this decrease in the current density will be exponential, and that is why these eddy currents are skin effects. However, as I given one example then aluminium it can be the depth can be 10 mm also. So, however, when we think about the 10 mm, we need to have a non-linear relationship and need to have proper software, and then only we can do a good test.

Of course, it is applicable up to 10 mm, but it will not have the same effect at 9 mm and 10 mm. So, we required a good relationship; we really required a good mathematical formula or maybe some modelling to come up with that. So, to come up with the right results, So, however, I am mentioning that the eddy current density decreases exponentially with depth, and that is what we call a skin effect. And another one is that the depth of penetration of the eddy current will depend on the frequency of the excitation current.

If excitation current frequencies are on the higher side, naturally, the depth will be much lesser. So, it will be basically an inverse relation or reciprocal relation that has been shown here. You can see here that the depth shown in mm is inversely proportional, or maybe it is proportional to the square root of 1 over f ($\sqrt{\frac{1}{f}}$) , f here is a frequency. We've provided this relation solely for comprehension, but what does the d represent? This d is a standard depth of penetration; how do we find it? We say that in this eddy current, the density has decreased to 37 percent (37%); almost two-thirds of the eddy current density has come down, and then that is what we are using for distance d. This does not mean the eddy current stops at that depth; it can go beyond that as well.

However, the current density will be very weak, or maybe low, on the lower side, and then reliability, or maybe, will be questionable in this case. So, four figures have been shown, but here we are showing the low frequency of 10 kilohertz. We are showing here that when this d depth, which has been shown in the black colour line, is indicated here as the standard depth of penetration, there is a black colour, and then there is a red colour. This has been shown for the three standard depths, and then what we are showing is an EC density. So, EC density has been shown with the big dots and black coloured dots, and frequency penetration has been shown with the blue coloured dot.

You are able to see that these are the blue-coloured dots as such and then these are going down, and then this is what has been mentioned. Now look at this one medium frequency (1 megahertz) that is above the surface. That means this is not a good option, this is also not a good option, and this is also not a good option. So, it depends on a material and kind; even in this case, that can be distance; we also need to choose appropriate system sensors and then material, which means that if the material conductivity is lower, we need to either place the electromagnet very near the surface or may be required to have some sort of good relationship to predict the right results. Relative permeability has demonstrated this.

It has a relation also with relative d, but the exact relation is not known. It can be simulated; it can be modeled. However, there is a relationship between d and relative permeability. Similarly, there is a relationship between d and electrical conductivity, and that relationship needs to be understood and developed appropriately. I am just trying to hide what the important parameters are when we think about current-based testing or eddy current-based non-districtive testing.

We will just give a couple of examples here. There is a paper published in 2015, and the title of the paper says fatigue crack length sizing using the flexible eddy current sensor array. Now, in this case, they say that we do not have to use only one sensor because we need to scan the surface, and with only one sensor, we will not be able to get very fast results, quick results, and then manageable results as such. So, they use a kind of array of sensors. It can be 64 sensors, it can be 100 sensors, and then whenever there is a scan of the sensor, a laser will be shown here.

Several sensors, possibly as many as 64 elements, have been displayed. So, and then they print the circuit on one flexible strip. So, it can follow the contour of the surface also, and there is a very close proximity between the sensor, the sensor, and the geometry. So, the strength of the signal will be very good as such. Even though we supply a very minimum current to generate a very low magnetic field, because the proximity is very good, the surface signals will be very good, and now that they are using multiple sensors, naturally, calibration will be required. So, they did a calibration also, and then they did some sort of simulation, and that is what has been shown.

However, when they selected the number of sensors, they found that sensor arrays mean multiple sensors that are connected to each other and integrated with each other. They outperform the single-element sensor. A single-element sensor, which was a common practice, will give a very delayed signal, and then we need to disturb the geometry as well, and mostly those are not on the flexible strip. So, the distance will also be less or will be on the hard side compared to the multiple array system. And then, when they say that with the sensor array, they are able to improve efficiency, resolution, and coverage area because coverage area is more important for us.

It is on the surface and the whole surface. If we have a very miniature sensor, naturally, you say we need to be scanned with some speed, and instead of that, if we go with the multiple sensors, and as I say, the multiple sensors are basically a printed circuit. IIt is not a single sensor hanging around, and then we are trying to move from one surface to another. o, eddy current detects subsurface cracks and corrosion, and of course, we are taking the example of aluminium, as I mentioned earlier, up to 10 mm depth, and the measurement can happen. If we choose the right frequency and the right sensor suit, the multiple sensor we select properly, then we can get this kind of result, and this kind of result is more important, as I was mentioning about the magnetic particle or liquid penetrant. Compared to that, this kind of eddy current testing will be much better or they will provide much better results. So, you have been utilised for the welded junctions or welded structures, and we know that in the welded structure there will be some sort of crack, or the crevice is cracked, or there may be fatigue cracks, and that will be damaging.

If a crack is detected, it will need to be bridged, filled, and thoroughly understood using these types of sensors. This kind of testing can also be applied to painted or coated surfaces to detect cracks in the coating, which could otherwise lead to the formation of crevices and the potential for electrochemical cell formation, causing significant corrosion damage. Detecting such issues early is crucial.

Now, regarding the simulation and experimental results, they aimed to replicate real conditions since it’s not feasible to conduct infinite experiments. They began with experiments, then moved on to modeling, where they simulated cracks with a length of 5 mm, a width of 0.2 mm, and a depth of 0.5 mm. The question was whether the software could accurately reproduce these cracks, and indeed, they were able to generate a 5 mm crack length, as shown in the results. If the length of the trapezoid increases, it indicates a longer crack—if it extends beyond 5 mm to, say, 7 mm, the trapezoidal length will increase accordingly, signaling that the crack has grown and requires immediate action.

In my opinion, eddy current testing is very useful, particularly for conductive materials. However, if there is a thin coating of oxide, oil, or other contaminants, the calibration constant may need to be adjusted. Once familiar with the system, this method can be utilized for extended surface life.

The same authors also tested this method on two other specimens with different crack widths—0.1 mm and 0.2 mm—and another specimen with multiple cracks of varying lengths: 3 mm, 5 mm, 7 mm, 9 mm, and 11 mm. They did this to calibrate and validate the method they developed, ensuring it was accurate, especially in simulation algorithms.

They used 7075 aluminum alloy for these tests, with the crack conductivity measured at 18.5 mS/m. The dimensions of the first specimen were 250 by 250 by 20 mm, while the second specimen had a reduced thickness of 10 mm. The first and second cracks had widths of 0.1 mm and 0.2 mm, respectively, while the five cracks varied only in length, maintaining a consistent depth and width of 0.2 mm and 1 mm. The simulation results, shown in red, matched the experimental results closely, demonstrating that the mathematical models were accurate.

Mathematical models are important, though we won’t cover them in depth in this course. Instead, we'll introduce simple relations to aid understanding. Each system requires a different mathematical model, and all variables must be considered, which is why more experiments are needed, though not an infinite number. If simulations can accurately reproduce experimental results, the model can be validated and used effectively.

So, we need to first understand, then choose a particular situation, then those kinds of experiments can be done; there may be some iteration, and finally, results will come out that will provide a good, sustainable solution for us. Now, what will happen in the case of corrosion? So, in my previous lecture, I mentioned corrosion. Whenever there is corrosion, there will be weight loss and weight gain, both of which need to be considered, and that has been shown here. This in Figure A has been shown: there is an electromagnetic coil, there is a steel surface, and then there may be some sort of coating in between. Also, there is a possibility of some sort of air gap, which is what has been shown over here. Now, what is the second case? It has been shown that there is a possibility of corrosion.

Now, whenever there is a possibility of corrosion, the thickness will increase. If the thickness is increasing naturally, the depth will change, and we need to predict that the depth is changing, which is a very rare case, and something may be causing corrosion. So, that is an indication, and then, of course, electric conductivity and magnetic permeability will also change. These parameters must be taken into account, especially since porous materials, like those prone to corrosion, have greater porosity compared to steel surfaces. This porosity also needs to be considered in the analysis.

In the third figure (Figure C), material loss is shown, whereas Figure B illustrates material gain. Figure C demonstrates the material loss, where predictions and modeling can account for various scenarios—whether the medium is air, has infinite thickness, or represents the actual thickness of the material.

There are four figures labeled A, B, C, and D. In figure A, uncorroded steel is shown. Figure B depicts corrosion with an increase in thickness, figure C shows corrosion with metal loss, and figure D illustrates corrosion where the metal has been replaced by air. In figure D, we account for air properties with modified conductivity and permeability.

To explain further, in steel, there is a possibility of iron oxide or hydroxide formation. If the environment is dry and free of moisture, iron oxide will form. However, if water is present, hydrolysis will occur, leading to the formation of hydroxide, as shown in the figure.

Now, why is this important? The reason is that the presence of corrosive products alters the electromagnetic characteristics of the material. For example, hematite (α-phase of iron oxide Fe_2O_3), magnetite (Fe_3O_4), and maghemite (Fe_2O_3) are all products of steel corrosion. On the hydroxide side, we might encounter ferrous hydroxide $Fe(OH)_2$, ferric hydroxide $Fe(OH)_3$, or goethite.

The change in electromagnetic characteristics is significant because, for instance, hematite is a semiconducting material, while goethite has lower conductivity than hematite. Although the steel surface might have the same magnetic permeability, the presence of oxygen, which leads to oxide formation, or the presence of water, which causes hydroxide formation, alters the material's conductivity.

This is why goethite exhibits lower thermal conductivity compared to hematite. Magnetite, on the other hand, has higher thermal conductivity due to the increased transfer of electrons. Magnetite (Fe_3O_4) is a ferromagnetic material, while maghemite (Fe_2O_3) behaves similarly, though with different properties. Magnetite, in particular, can exhibit permanent magnetism. Although steel itself is not a permanent magnet, magnetite, as a corrosive product, can act as a weak permanent magnet, or a ferrimagnet. It is not as strong as neodymium iron boron magnets but does retain some magnetic properties.

So, the kind of sensor that we are trying to use will be different. And then we say that this iron oxide and hydroxide are less dense; naturally, the properties will change; these are less dense compared to the pure steel; and then another possibility is that volume will increase, and then because of the water absorption, because of oxygen absorption. So, the layer thickness is going to change. Initially, the corrosion layer will thicken, and over time, it will thin down. So, an increase in thickness decreases in thickness.

When using these techniques, it's essential to consider all relevant factors. We shouldn't be surprised by unexpected results; understanding the mechanisms of various processes helps us anticipate and incorporate these factors when developing software or code. In this case, they used pulse eddy current instead of AC current, which requires a response based on the material's conductivity. Conductivity, permeability, and material thickness must all be accounted for to achieve accurate results.

Next, let's consider an example of corrosive testing. How do we calculate early-stage corrosion as thickness increases? Will the performance of a steel sample differ if it is coated? If a surface is coated to reduce corrosion or oxide formation, will it be effective, particularly in a marine environment? After testing, they concluded that even a coated surface could not fully prevent corrosion in a marine environment.

So, this is what they mentioned, and then, of course, they made all the plate samples, and the reference has been taken from this 2012 publication, where the steel corrosion characterisation using the pulse eddy current system is what they have done. They use mild steel samples, and some of the uncoated samples are coated, and then, just to avoid the kind of atmospheric corrosion, other samples really get atmospheric corrosion. They were exposed to it for 1 month, 3 months, 6 months, and 10 months, and the table has shown that for the uncoated cases, they were uncoated and covered with some sort of paint to prevent corrosion and coated surfaces as such. So, they took a couple of examples and tried to figure out what happens over time, when the corrosive environment is there, and how eddy current will really respond to that, and then they generated some magnetic field currents on the curves. So, you can see here that the pv has been presented on a vertical side, and then horizontally, there is an exposure time. This curve is continuously increasing from uncoated to coated. So, coated and uncoated are near, but they are not really showing much of a of a significant difference. What is the p v? p v is a maximum difference then the ΔB^{norm} and how do we calculate the ΔB^{norm} is basically normalized values and the v in the B whatever the signal which is coming, and then B reference in the search whatever the signal they have taken from a non-corroded, and B is been corroded signal and then the ΔB is basically difference into the signal which has been from a corroded surface, and then a non-corroded surface the difference between the signals and then to normalize these signals they divided for maximum value of B with a maximum value of B.

So, it is less than 1. Similarly, B ref is also less than 1, which is why we are getting a very low value on the vertical axis. But we are finding that with exposure to time, this value is continuously increasing, but it is no prevention of corrosion; it is continuously increasing as such. In the second case, the response is continuously coming down, and the eddy current is giving a very low response, even at its maximum. That is what has been shown here with exposure to time. So, the exposure response of B is continuously decreasing. So, B reference and non-reference, whether B coated or not,. We do not find much variation in B, and then over time, because of the corrosive layer, the response will come down, as has been shown. However, it is absolutely different when they are trying to make a difference that is continuously increasing. Now, addressing the issue of corrosion height, surface roughness will continuously increase due to corrosion, the accumulation of material on the surface, or the presence of corrosive porous materials. They also found that at the micron scale, the corrosive layer consistently thickens over time. All of this can be effectively monitored using eddy current testing.

And in reality, as you can see in the photographs after 3 months, there is a corrosive layer on the sample, and this has significantly spread increase, and then we are able to see the loose particles keep coming out, flaking off, and then further increase. So, what we are able to see with our naked eyes and then eddy current also give a similar kind of response. This does not mean that we are using eddy current testing; mostly, we require a testing calibration. So, when we are not able to reach the surfaces, we are not able to see them, and then eddy current can also give a close system response. On surfaces that we are not able to see, or on surfaces below, there is a subsurface crack. The same thing must be happening if the crevices are corroding; the same process will occur there also, and eddy current can give a response to our naked eyes, and maybe visual and visual techniques will not be able to help us.

So, from that point of view, I can say the eddy current testing is a good tool and should be utilised, and there are more and more chances of opening a company and getting better and better results because this kind of testing is continuously required. If we want to do some innovation, we want to change a material, change a process, or utilise the same material for a new application. This kind of testing will build confidence, and it will really give us good results. So, what we're saying is that the correlation between the pulse eddy current (EC) properties and the exposure duration needs to be established. The author has demonstrated this correlation, but it can vary from one material to another. The relationship they provided may not apply to every material, but it serves as an important starting point. It shows that a strong correlation exists, and if we can calibrate and identify it, we can develop similar techniques. This is useful because once the relationship is known, future corrosion rate estimation becomes possible, and in many cases, early detection of cracks can be identified or evaluated well in advance.

Now, this is what we have covered for the eddy current-based testing. Now, we are trying to cover the second testing, which is a TT. Basically, we do not use the word infrared here, of course. That overall technique is called infrared thermography testing. However, in brackets, I am writing TT because, in short form, it is known as TT testing as such, and now, in this test, it is again the same kind of taking an image and doing analysis. In this situation, we use infrared cameras to detect and see the distribution of temperature. Now, why are we emphasising temperature distribution? The reason being that with a heat source, infrared will come out, and with a naked eye, we cannot judge, we cannot observe, but with a camera, we can capture, we can analyse that, and that is the overall test technique. So, in this case, we use infrared cameras to detect and see the temperature distribution across the surface of the object.

Now, in this case, a camera captures infrared radiation that is emitted from a surface. Because we are not able to see the infrared radiation, what a camera does is change the colour, and then they give a colour-coded image or thermal mapping that we can see. So, from invisible things, this camera gives some visible things to us, and then, even though it is an indirect measurement, we can get a kind of good correlation with that. There is a principle that every object with a temperature above absolute zero will emit infrared radiation. And as a temperature increases, IR radiation is willing to increase continuously, and the human eye cannot see IR radiation. That is why there is a need to convert this radiation into something that we can see, and that technique converts to a thermal map or colour-coded images. Now, what are the correction factors for which we are required? Naturally, again, there is an environmental temperature coming. So, a compensation difference will be required, the emissivity of the object again will be important, and the and the emissivity of the object will be different.

Many times, these kinds of products are painted black. So, the emissivity increases, and another thing is, what is the distance between the camera and object? Lesser the distance, better the results, but we cannot. There is something rotating, and we cannot keep a camera directly in contact with the surface. Naturally, we need to keep some distance, and what is the difference and what that difference will bring? Naturally, we need to work on the difference in a signal, not in absolute signals. Another thing that I say is that this infrared thermography can detect the anonolomous, the variation in a heating pattern, misalignments, and damaged components. If there are particularly mechanical systems or if there is some sort of difference in material, those can be seen. If there are cracks, some sort of pores, or some sort of void in a surface, those can also be seen.

Instead of really going for fracturing it and then looking at the SEM and all, instead of that within a surface, whatever the anonolomous things are, we need to identify them. Even in a motor, some sort of friction occurs when the higher-side bearing shaft is not able to rotate properly. We can detect that the bearings are misaligned at some point. At some point, the temperature on the higher side can be figured out, or if there is some sort of leakage, it may be that a liquid is leaking out. We can identify this with this kind of thermograph as well. Now thermal images can visualise the surface temperature, and one important point is that often we feel that thermal images can give a complete shape. No, it is not. It gives only the temperature variation; it can really map the temperature, but it cannot really map the complete organ, a complete object, or something like a complete system as such. So, there is a possibility of some difference in this, even though the word is image. It does not mean that this camera is able to find the infrared radiation and convert the infrared radiation to the thermal map.

So, we find only thermal maps; we do not find real objects as such. So, it is an odd image as such; however, we are using the words thermal imaging and visualisation from that point of view. So, the camera cannot see inside; it can only give thermal thermography. Now, how this infrared thermography works is very simple. We say that we apply infrared to the object, which can be even the human body as such, and then we find some sort of thermal mapping, and then thermal mapping can be given this kind of. So, this is what I am trying to say, even though the image is something like that, but I will get a thermograph something like this. So, it is not a replica; it is not a real photograph; it is a thermal image, and you are well aware that in COVID time, we use this kind of camera extensively to find out what the temperature of the body is and then whether the person has a high temperature or a low temperature, or something like that.

But we also know that this kind of camera really gives a different kind of results. If we buy a low-cost camera, a low-cost camera, it will give very bad results, but if we go with a costly camera, it will give good results. We need to know what the parameters are and how many more parameters are there. What are the other kinds of software that are being utilized? So, many times, hardware costs will not be as much as software costs, and it is important to note that in recent times, we have required more and more sophisticated modelling and software compared to hardware. Of course, hardware also needs to be improved, and testing needs to be improved. Data needs to be obtained to go ahead with a data-driven approach as such. So, however, these are the very well-known examples that are used in thermal imaging, and then what is really done in this case is to detect infrared emitted from objects. Whatever the object, it will emit infrared. Of course, first we are throwing some sort of spectrum and then maybe some sort of light, and then the infrared is coming from this person and getting captured on the camera, and then the final display is coming as a thermal mapping of the system.

The same thing has been mentioned over here, and then finally, we get the image. So, we can elaborate on the on the infrared light emitted by the object. It is generally captured by the focus lens, and then it is generally scanned by the number of infrared detectors or arrays of the detector; use the word phased array. Here the maximum difference comes if the phased array or detectors are very good, then the cost will also be increased on the higher side, and then these detector elements, which capture the infrared radiation, can create a thermograph. So, this is important if the lenses are good or maybe there and then the phased array is good, then we can get better and better results, and then, of course, this thermograph can also be coloured coating, but it can be converted to the thermal infrared electrical impulses, and then we can do a signal and then the conditioning or signal processing of those things, and we can improve the quality of the image as such. So, there will be a number of impulses, and then combinations of impulses need to be analysed properly to generate a final thermal image. So, again, there are many subunits in between signal processing that need to be very good in this case. If we do not have good filters or signal processing units there, then we will not be able to get very good results. So, again, it can be a very negligible cost of 30,000 or 40,000 rupees, or it can be very costly if you like rupees; it can go even above 10 lakh.

Thermal imaging offers numerous features, making it crucial to develop increasingly advanced tools. The importance lies in its ability to capture complete thermal images from a distance and deliver rapid results. This is possible because the data is displayed on a screen, allowing us to obtain either digital data or, alternatively, convert thermal images into electrical signals or impulses, which are then translated into measurable units.

Now, I want to discuss an example related to gears. The focus today is on creating lighter materials and components to achieve better results with fewer losses. In industries like automotive or aerospace, using lighter materials leads to greater efficiency and performance. However, this also increases the risk of more frequent failures.

So, if we are able to predict the values well in advance, we can do a good optimization. So, this case study is basically for that purpose, and we have picked it up from 2022 literature. They use experimental investigation on a crop propagation path in spur gears. This is the spur gear, and they made three kinds of spur gears: gear 1, gear 2, and gear 3. In all three, they have kept the pitch circle diameter the same, the width of the gear also the same (22), the number of teeth the same, and the and the module also the same what has been changed. They change the rim thickness, they change the MB, they change Mw, and then they change the CR. What is the MB, and there is a backup ratio? They use a lesser dimension for the rim; you say the rim dimension is related to the tooth height. The tooth height is the same because modules are all the same; in this case, the tooth height remains the same. However, when we are thinking about MB as a 1, that means there is only one relation, and when you are thinking of MB as a 0.3 or 0.5, naturally, that rim dimension has decreased in this case. Now, of course, they analyse 1 and 2, because this is the worst case. 0.3 is the best-case scenario, and if we know the results, we can interpret it as another gear. However, I am going to give results of 1 and 2 only. Now, this is in this case a web ratio; they again give the web thickness related to the face width.

However, they were limited to just 10%, which allowed them to significantly reduce the weight of each gear while still predicting the potential outcomes. Their goal was to develop a fail-safe design. A fail-safe design means that if the system does fail, it will notify us, allowing for necessary corrective actions to be taken. This ensures that any failure is safe rather than catastrophic. Additionally, due to the ongoing pressure to reduce weight, they also decreased the thickness, web ratio, and backup ratio of the gears.

And these are important for any mobile industry aerospace automobiles; that is why they try to make a gear with a thin rim. What is your problem with a thin rim? If there is a subsurface crack, if there is a thick rim, crack propagation will take a longer path, but if there is a thin rim, even a small crack can immediately reach the surface. So, it will have a much lesser distance to travel, and then there is a possibility of failure in that situation. So, this is what we say: the propagation of the fracture will be much faster in thin sections, and that is why they are more probable to go for catastrophic failure, which should not happen. So, the fail-safe failure happens when the crack propagates through the tooth. In this particular case, they found that if the tooth is only fractured, then there is no problem as such, but if the fracture and the crack start from a tooth and it reaches the shaft surface or the inside, something crack starts from here, and it moves to the inside, then there is a possibility of catastrophic failure.

They aimed to ensure that if a fracture occurred, it would happen near the surface or just beneath it, rather than deeper within the material. This is not a typical failure; it's an intensive bending failure that occurs when a gear tooth is subjected to jamming or an extremely high torque or load. Normal corrosion wear, pitting wear, or general gear wear would not lead to this type of failure. However, when there is significant jamming, seizure, or a sudden application of very high torque or load, this kind of failure can occur.

The focus was on understanding how infrared thermography could be used to detect such failures. This example illustrates how a fail-safe system can provide advance notification, allowing for appropriate maintenance actions to be taken.

As I mentioned earlier, there's a continuous trend toward using better materials and improving inspection methods. If we have the right tools—whether they are mathematical models, simulated data, or experimental data—we can implement better maintenance practices. In this example, they used a fatigue testing machine to perform bending-related tests, with an inbuilt punch to apply pulse loading on a gear tooth. This wasn't real gear meshing; it was a hammering action designed to cause gear tooth failure, which they successfully demonstrated.

So, this is kind of a felt safe, and then the kind of cracks are going to develop on this side only. So, the failure will occur according to this, and then they feel that the removal of the one gear tooth is a safe site. However, the crack is initiated over here; you can see cracks here, and if they propagate inside, then that is a disadvantage. So, that is why they wanted to avoid it, and then they found that when they are making a thin rim, the crack propagation happens towards the surface and to the root side or inside of the rim, which is not correct. So, that is why the correct reactions are required. So, I am just explaining that what they have done is use a thermal camera to monitor the heat profile on the surface through fillets.

They were able to precisely determine where the crack would initiate because they used pulse loading and impacted only one specific surface. This allowed them to position a camera to monitor the crack's initiation and progression. For example, in Gear 2, the crack propagated inward, while in Gear 1, it moved toward the tooth removal side. For their purposes, a crack propagating inward was undesirable, whereas tooth removal was not.

Both the reference material and the gear materials were coated with black paint to achieve an emissivity close to 0.95. Higher emissivity improves the signal-to-noise ratio and provides more accurate temperature readings. Figure 5 illustrates this, showing Gear 1 with visible failures and ductile cracks progressing toward the tooth failure side, rather than the rim.

In contrast, Gear 2's crack progressed toward the rim, which they wanted to avoid. The thermography was used to monitor the surface temperature profile during the bending test, producing a surface heat map that highlights discontinuities and cracks. The crack was identified as shown, although the color in the diagram may blend with the tooth color, making it harder to distinguish.

Innovative material design and testing approaches are crucial for improving performance. We will continue discussing non-destructive testing in our next lecture and aim to complete the topic by Lecture 20.
Thank you.