Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 23
Non- destructive testing – Part 4

Hello and welcome to the 20th lecture of the course on corrosion, environmental degradation, and surface engineering. In this lecture, we are going to continue on non-destructive testing, and we will cover the main two techniques: acoustic emission testing and stress strain DIC testing. So, what is shown in this slide is that a very clearly green-coloured visual inspection is clear; ultrasonic testing has been covered; radiography has been done; magnetic particle and and liquid penetration tests have also been covered. Now thermographic testing was covered in the previous lecture, but in this lecture, I also want to continue and want to give one or two examples, and after that we will be covering acoustic emission and stress strain DIC testing. Now let us start with thermographic testing. We place significant importance on this testing because it allows us to capture detailed thermographic images of surfaces, and even beneath surfaces or within volumes. Since we understand that any temperature above absolute zero (0 Kelvin) results in emissions, this method is invaluable for mapping and analysis.

For this reason, we intend to cover the topic over two slides. In the previous lecture, we discussed how this technology—specifically thermographic testing, or active infrared thermography—is highly promising due to its efficiency. While 'efficiency' is a relative term, what we truly seek are faster results, enabling us to quickly capture and interpret thermographic images.

Necessary actions can be taken promptly. From an institutional perspective, when we need to capture images in the field and obtain immediate results, thermography testing is highly effective. One of the major advantages of this method is its ability to detect corrosion in metallic shells, which is a common issue in structures like overhead tanks, pipes, and containers. These are areas where corrosion frequently occurs, and thermographic testing is extremely useful for quickly capturing images that indicate corrosion in such casings.

This is why we emphasize that corrosion in metallic shells, such as above-ground tanks (which are difficult to access), submerged pipes, or storage containers, can be effectively detected using portable infrared thermographic non-destructive testing.

So, this is a major advantage. One thing is that it can be portable. There are small cameras, and then we capture, and if there is some sort of thermal mapping and it can be converted to visual photographs, then it will be very useful. Now one more point comes: why is it more important? You see, the infrared inflection equipment is more cost-effective compared to the ultrasonic thickness gauges. So, whenever the cost comparison comes, UT will be treated as a bit more expensive compared to infrared. Of course, it depends on what kind of sensors we are choosing and what kind of cameras we are choosing. I am just giving data on average; it is not that it will always be right. Somebody has brought a much better camera, and somebody is using a sensor that is relatively cheaper compared to the best sensors available. In that situation, UT will be slightly cheaper.

In this context, we're discussing average values, and it's worth noting that IR inspection equipment tends to be more cost-effective than ultrasonic thickness gauging. This is especially true for applications such as above-ground tanks, pipes, or containers, particularly when it comes to metal casings used to store or transport petroleum products, which are crucial in the petroleum and power generation industries.

The portability and cost-effectiveness of thermographic testing make it an excellent choice. To illustrate, consider a few examples: in earlier discussions, I didn't mention the importance of a heat source, but recent findings show that if a good heat source is available, along with a properly positioned camera, the results are significantly better. When a heat source directly impinges on a test object—represented by a yellow color in the demonstration—the emissions from the object in response to the light result in clearer images. These images can be stored either in the camera or on a computer.

Subsequently, these stored images can undergo noise reduction, image enhancement, and other processing to yield better results. This demonstrates how effective IR thermography can be after the necessary computer processing is applied.

If the camera has an inbuilt processor, which is a very costly camera, then it is ok; otherwise, you should do it on either a laptop or computer, whichever is available to us. So, this overall has been shown, and then we have taken an example from one of the references, which was published in 2020. They did this experimental testing, particularly corrosion-related coating corrosion-related testing. So, they use a powerful LED source that, as a heat source, they have used in the imager of a camera and computer, and then a reference sample because thermographic images need to be compared with references also. So, again, this is a relative comparison compared to some examples that have been given.

Let's consider an example where we have a tank that we want to use as a reference. We can fill it with water, sand, or leave it empty. So, I can really detect in all three cases what the results the results willresults will be. So, in this situation, another point has come: whenever the test object is black, its emissivity will increase if we paint a black or if we paint it black on the objective piece. So, this is written here to improve the absorption of the thermal radiation sample surface, or generally black paint. It can be any kind of paint; in this reference, they use a matte acrylic dye.

Then they used a powerful LED in the heat source, and then they kept a very low frequency as such. Another one is the distance of the heat source and the distance of the camera; these are also parameters. Which really affects that is that we require experience, and after the experience, we can really figure out what the really appropriate distance is between the camera and object and then the camera and heat source. So, they have written here that the LED heater was kept around 0.4 meters away from a reference sample. Another one is that this camera was kept around 1.1 meters away from a sample to record the temperature to map the temperature. So, these are the points that are really required: what will be the distance of the heat source from an object, and what will be the distance of the camera from a test object? Similarly, in the variation, we can figure out that at some places, some angle is giving better results compared to others. So, that will be the kind of iterative procedure that really requires a few iterations to come up with the right results. So, this is what they have shown, and then they presented the number of thermographic images that I am trying to show.

They use a tank thickness of around 2 mm, 4 mm, 6 mm, and 8 mm. So, they varied the thickness of this tank, and then they took some images. So, initially, the raw image had a signal-to-noise ratio of 5.6, but after processing, it increased to 223.1. So, this is postprocessing; it is an important thermographic image alone and will not give very sharp images. So, that is why they have shown 5.6 to 223.1. Similarly, when the thickness was 4 mm, they got a signal-to-noise ratio of 4.7 from the camera, but they improved to 9.2 after doing the processing, image analysis, and other processing, and then at the length, it may be said that when the thickness was 6 mm, they got a much lesser signal-to-noise ratio of 1.9, and then after processing, they increased this to 4.6, and when the length was outside the thickness of 8 mm, they found a signal-to-noise ratio of 1.7 and that was improved.

So, overall, the thickness of the sample, if it is reduced, gives a very high signal-to-noise ratio, which is also important. So, that is why they have done it, and then they will be showing here that these thermal waves are compared to thermal waves as continuous sources, and then pulse thermal and pulse waves. Then they found that this TD and the NDT were already in the name we are giving for non-destructive testing, but T has been added in this case, which is thermographic non-destructive testing. We refer to T and D as the outcomes of thermal waves in the reference sample. So, this is related to thermal waves, and while this figure is something like a pulsed pulse thermographic non-destructive testing, In this comparison, the results demonstrate a similar situation with a signal noise ratio of 3.2, which can be further improved to 9.7. Similarly, in this case, we can improve the thickness to 4 mm and the signal ratio to 6.8. And then conclude that if we give a pulse of thermal waves, or maybe say it is not continuous, then the pulse mode will give better results as such. Now, it has been mentioned here that, due to the shorter observation because of the pulse, we are sending and closing this temperature or heat to the object, and then we are closing it.

So, this is due to the shorter observation interval and the reduction of heat dispersion. So, heat dispersion also reduces, and they concluded that pulse T and D T and D T will be better options or that they will give a crisper defect image. Another one is that there are so many parameters in this. So, go ahead with that because there is a signal-to-noise ratio of 1, there is a temperature, and then we need to really predict with the temperature mapping. What kind of crack, whether the surface crack or maybe the subsurface crack, or maybe the volumetric crack or something like that? So, there are many, many parameters.

So, in that they added one, the mathematical model, which is something like what we call principal component analysis, is also popular in machine learning algorithms. So, they utilise that kind of PCA to detect what is really good and so that they can predict the results, and based on the PCA results only, they concluded that this pulse T and D T will be better options. So, if I want to really express what PCA is, I can say that PCA is a principal component analysis. It has a number of applications, particularly when the dimensional data are large. When we have too many variables, we do not have a definite relationship available to us. So, in that situation, PCA will be a better option. Before that, the method will try to figure out some sort of relation and then make a smaller number of equations, even though we have too many variables. What are the key variables that most significantly impact the results derived from PCA? The goal of principal component analysis is to reduce a large number of dependent variables to a more manageable subset. This allows us to identify a few variables that can be treated as independent, even when many dependent variables are present, and a fully defined relationship among them is not available.

So, when we do this, and that is why we often say these are data-driven approaches, and then and then particularly surface engineering is more governed by a data-driven approach, that is why the PCA plays an important role. I can make any linear combination of the dependent variables, depending on what kind of curve field method has been used, or maybe the additional advanced method has been utilised, which can give some sort of combination. Then a lesser number of equations and then more control parameters—how do we really control the signal-to-noise ratio, and then how do we interpret what kind of cracks or what kind of corrosion mechanisms are happening? What is the depth of the corrosion when we use a PCA, what is the corrosion depth? So, these are the very important things from there. Again, in a different manner, I can say the features can be extracted and analysed using the principle component analysis, which could include identifying the train with corrosion. Therefore, if I am truly interested in understanding corrosion, a Principal Component Analysis (PCA) will prove to be highly beneficial. So, it is not only the PCA that can be used only for thermographic testing; it can also be used for other things. That is why learning the PCA will be important for us, and the number of things that, if I have a relationship, I can figure out what the corrosion rate is, how it is really progressing towards a thickness, and then how it is really going to impact the environment or how the how the environment is going to impact the corrosion. These kinds of things can be utilised.

That means we do a lesser number of tests, but we will have better and better results, and then we do not have to do too many tests to get just the results, again mentioning that we do not have a definite relationship available. If there is a definite relationship available, then I do not really require a PCA. If there is no definite relation available and we want to extract the relation, then PCA will be very helpful to us. Now one more point: we have talked about the IR emission, but there is another kind of emission, which we call an acoustic emission. What is acoustic emission? We use this method to identify and assess how materials respond to stress. When a material is loaded, it undergoes stress or strain. If we can correlate the emissions generated by the material in response to this stress, and accurately diagnose these emissions, it becomes a valuable technique for analysis. This is why we'll be discussing this technique in detail over the next 3 to 4 slides.

Let's consider acoustic emission in non-destructive testing. Acoustic emission refers to elastic or transient elastic waves that are generated by localized sources within a material. These localized sources can include flaws, cracks, surface irregularities, or structural integrity faults. By analyzing these emissions, we can effectively assess the progression of damage in the material.

Acoustic emission can be used to monitor the initiation and progression of cracks, providing continuous tracking of such events. This method is particularly valuable when 24/7 observation is required, making acoustic emission one of the most powerful tools for round-the-clock monitoring. The data obtained from this method is not only useful in the short term but can also be applied to long-term analysis.

For example, with accurate models, we can predict corrosion rates over time—estimating how much corrosion will occur after 10 hours, 100 hours, or 1,000 hours—allowing us to schedule plant shutdowns for maintenance at the appropriate time.

In this approach, it's essential that the sensor or transducer is properly attached to the surface or material being monitored, as the effectiveness of acoustic emission relies heavily on this attachment. Once attached, the sensor captures emissions, which are then analyzed through time or frequency analysis. A comprehensive database is necessary to interpret these results effectively.

If we do not have a database, then we really need to do some sort of lab test in our lab if a database is available. However, many times we buy this kind of complete equipment, and the company that supplies it has a complete database and their own library, and then they predict what kind of failure we are really getting into. So, in this case, when the material is subjected to strain, deformation, or whatever you say, elastic waves of high frequencies are produced. So, the main thing is that when the material is subjected to strain or deformation, elastic waves of high frequency will be produced, and these sensors can detect those things because the sensors are attached to a surface itself; very close to the surface there is no gap, and then, whatever the high frequency seeing, that is where they are getting, or maybe elastic waves they are getting, they can really capture, they can record it, and then when it is detected and analysed, we can figure out what kind of problems are there. We have to have a data base to say, Ok, maybe the 10 hertz frequency means what, 10 hertz frequency this much amplitude means, what if the amplitude did increase is what kind of fault will be there, or maybe we are continuously doing that kind of time analysis, then initially crack was much this much smaller now the crack is continuously increasing, and then we need to really give a kind of signal for the overhauling or the maintenance. So, it is a very important tool from a maintenance point of view, from an overhauling point of view, and for giving valid advance information on how the material is not behaving.

So, again, it is not an absolute method; it is a relative method; it follows a trend analysis, and if we want this to be an absolute, then we need to really have a very strong data base with us, very clear-cut interpretation, and then maybe an advanced analysis technique along with us. Now, I am trying to cover one example that was published in 2005, and then this is related to gear, and as I mentioned, we are covering the caustic emission techniques. So, they have used a curve in this gear setup, and this has been shown in Figure 1. It clearly says test rig gear box in a back-to-back arrangement. What is the meaning of the back-to-back arrangement? We use two identical pairs, one left-hand side and one right-hand side. So, we can cancel many noise-related things.

So, they use two identical oil bath-lubricated gear boxes, and then, just to accelerate the test, they use a very rough gear. So, they can get a very good response to that, and then another thing is that they seeded the faults. So that they can really calibrate the sensor based on the technique, they can establish a technique. Where we are intentionally giving a fault to the gear surface. So, they have introduced a pit; they also introduced a flying-related edge, and they have created a fault on that. So, that is why they did it, and of course, this whole setup was run for the three different test settings. That is what they use for the three torque settings: one is no load at all, no power transmission, only rotation. Then in the second case, they operated with a 55 Newton meter, which is a torque value, and after that, they had a double that value, which is a 100 Newton meter, 110 Newton meter. The whole setup was run with an AC three-phase AC motor, and the power was given as 1.1 kilowatts, and they operated at a 745 RPM. So, this is just really to predict what kind of frequency we will be getting and what kind of signal and noise we will be hearing. We required the sensor location, and they have shown the two locations. As you can see here, the gear has been shown, but the gear has some sort of casing; this casing has been there, and then they have put a low sensor on that casing. So, that means there is a rotation of the casing, and the rotation of the casing signals that the sensor cannot be fixed easily. So, they use a slip ring arrangement, and a slip ring arrangement is a special arrangement particularly for rotating the sensors. Then in another one, they have used a sensor on a bearing housing that is generally stationary, and that is why they use this sensor on a bearing housing. So, what is the advantage, and what is the disadvantage? Most of the time, we do not have to go with the slip ring arrangement, which is slightly costlier and maybe will wear out very fast, and we need to replace it frequently while coming to the bearing housing. It is static; it does not move or rotate.

So, that is why, really, the sensor can be easily fixed on that. However, this bearing casing is slightly away from damage. So, there is a possibility of the attenuation of the fault; maybe the fault is on the higher side, but we are not able to get out of bearing when the sensor is attached to the bearing housing, or maybe we are getting an alarm in an extreme case that is not at the initial stages. Just to differentiate, that is why they have used the two different sensors. So that they can compare these two sensors.

The acoustic emission sensors mentioned here exhibit linear behavior within a specific frequency range, which is why the range of 100 kHz to 1 MHz was selected. Within this range, the sensor operates linearly, allowing for easier data capture. However, it's important to note that each sensor requires calibration, so every time this type of sensor is used, it must be recalibrated to ensure accurate results.

As mentioned, these sensors are used on components such as the pinion that drives the gear. While the exact gear ratio (40:90) might not be immediately relevant, this data becomes important when analyzing frequency matches. Additionally, these acoustic emission sensors are applied to rotating components.

So, that requires a slip ring arrangement. So, if the rotation is happening and then the signals are getting transmitted to a stationary device, that is, they have used it, and then this is the slip ring arrangement with a preamplifier, because every sensor requires pre-amplification or maybe post-processing. We need to really remove the noise. noise will be coming from the surroundings, and sometimes people use some sort of isolation device. So, the surrounding noise should not come. However, it depends on what kind of noise level comes along and what kind of cost we can really afford to spend on this kind of setup. Now, as I mentioned, the two kinds of faults they really created are not directly diagnosable; they are created.

They are able to pinpoint the exact location of the fault, which makes it easier for the algorithm to predict and map the values accurately. However, in real-world scenarios, faults may naturally occur or develop during the process, making diagnosis more challenging compared to intentionally created faults. Despite this, they have successfully identified faults here.

To summarize, the authors operated a gearbox, and as mentioned earlier in the lectures, wear mechanisms occur when there is relative motion and load. In this scenario, they applied both, leading to some degree of wear. Initially, this wear is known as 'running-in wear,' where the two surfaces begin to smooth out by removing surface asperities. During this period, the overall wear rate is quite high, as illustrated by the bathtub curve discussed in our lecture. After the running-in phase, the wear rate typically decreases to a much lower level, potentially resulting in ultra-mild wear.

So, in this case, the authors ran the setup for 15 hours, and then they treated these 15 hours as a running-in period. Then another thing they felt was that there is a possibility of background noise, but background noise will be there when there is a load and there is no load. So, just to differentiate from what they did initially, all the readings were taken without defect, and then initially with low without load, which is 0. Then they ran an experimental setup for the 30 minutes they collected the data, and then again, they kept equipment for the stationary condition for some time. Again, they operated this at the 59, 55 Newton meter, and then at the 110 Newton meter.

So, initially, without a defect, and after that, with a defect. So, the overall results can be compared to show that acoustic emission is a good comparison purpose or relative performance compared to the absolute value, which is what they did. One set without load, then 55 Newton load, then 110 Newton load, and a similar set were repeated when the faults were seeded, and there were two types of faults. Therefore, an overall mental test requires a minimum level of performance. However, we know that a single test will not give reliable results because everything is statistical.

So, naturally, it has to be operated a couple of times; it is not a one-time or two-time operation; it may need to be operated a number of times. As I mentioned, they seeded the fault on the surface. The pit that formed on the clear teeth was located in close proximity to the pitch line, with a surface diameter of 1 mm. However, when it comes to the fault on the gear addendum side, So, they kept a kind of rectangular fault that was around 12 mm by 3 mm.

The fault was significant enough to be detected even by sound alone, but they used acoustic emission to precisely understand what was happening, setting a sampling frequency of around 10 MHz. This high frequency allowed them to capture and analyze the signals accurately.

Now, let me present the results of their work. In the figure shown, the data is raw, without any post-processing. Initially, two faults were introduced: a 1 mm fault on the pitch line. The first signal was recorded under no load conditions, and even in this case, some signals were detected.

When a load of 55 newton-meters was applied, the signal amplitude increased slightly and became more distributed over time, reflecting transient behavior. With a load of 110 newton-meters, the amplitude increased further compared to the 55 newton-meter load, as shown in the figure.

The time-domain analysis indicated that something was wrong, but when the data was converted to the frequency domain and segregated by different time intervals, they found that the fault was more pronounced in the higher frequency range (C region). They were able to detect the exact fault they had introduced in the C region, with the RMS value of the signals increasing accordingly. The comparison showed that even under no load, there was detectable data, which further increased with the 55 newton-meter and 110 newton-meter loads.

And this is the central tooth, and seeing where the seeded defect was inserted shows the greatest RMS value for a pitch line defect that was seeded to the surface. Now, to compare both the sensors, which sensor operated on the bearing casing? Another sensor was mounted on a gear on a sleeve, and it has been shown that when the sensor was mounted on the gear sleeve, another sensor was mounted on a bearing casing. Now, they are able to show that there is a huge attenuation. You can see here that the values they are showing are far lower compared to the word value that has been shown on the gear. So, mounting the acoustic emission sensor on the bearings is not really giving good results; it will have a slightly higher side signal-to-noise ratio, and we need to really raise it. Post-processing to really extract some fault while coming to the sensor, which is mounted on the gear sleeve, will be slightly costlier because we need to use a slip ring arrangement along with the sensor. So, that is slightly costlier, but there you can find that it is really giving a very good response, and they found 44 dB attenuation at one location and 26 dB attenuation at another location.

So, they concluded that as the sensor is close to the fault, it will always be better, whether it is rotating or stationary, but you should keep it there. So, as I mentioned earlier, we also need to detect the sensor and the fault that was created or maybe generated immediately. So, we should know the root cause of failure, and that is why the AAE will be more useful for continuous monitoring. Continuous monitoring of the AAE sensor on a bearing case shows a loss of acoustic emission, compared to the sensor that is connected to the gear mesh. So, that is what we indicate: that even the same technique, but in a different location, will really impact itself and give different kinds of results.

So, this is the location that they mentioned that they need to blame, and the bearing location is something that needs to be blamed. And then another thing that they mentioned was that the ball and rollers are not fully complementary to the bearings we use. Fully complemented means that not every space has been obtained and occupied by the balls. Many times we have a separation between balls, like when we are using 9 balls, or maybe 11 balls, or 12 balls. Naturally, there will be some gap, or maybe in the rollers there will be some gap. So, when the ball is directly under load, that time signal is on the higher side.

After about 10 to 15 degrees of rotation, another ball comes under maximum load, resulting in strong, sharp signals. This occurs because the bearing used has some discontinuities—it doesn't contain all the balls or rollers, leading to significant signal attenuation. However, if we use fully complemented bearings, like needle roller bearings, we might get better responses in this situation. In such cases, the sensor can be placed on the bearing housing, and with fully complemented bearings like needle rollers, almost every circumferential space is occupied.

In contrast, larger rollers or balls usually have some separation, allowing them to bear both static and dynamic loads effectively. This is why, in such cases, changing the bearing or sensor location could significantly impact the results.

Now, let's consider another example related to corrosion testing, where acoustic emission is again employed. This method is particularly important because corrosion, once it starts, can propagate and lead to failure. Stress corrosion cracking (SCC), as discussed in a 2020 reference, is a type of fracture that often initiates with surface roughness or dents acting as the starting point.

If the material is tough and there's minimal atmospheric corrosion, or if the environment is not corrosive, we may not see these faults, leading to better results. However, in cases where signals are detected from the beginning, it becomes crucial. As the corrosion progresses, the sensor plays a vital role in determining how much time remains before maintenance or replacement is needed.

For SCC, acoustic emission testing is particularly critical for continuous monitoring, as it provides early warnings when faults are approaching uncontrollable limits. This allows for proactive maintenance. SCC is a leading cause of failure in various industries, and accurate detection of crack initiation and propagation is essential. Even if a crack has started or irregularities are present on the surface, it's important to assess whether they're significant enough to grow. If they aren't, and no additional corrosion mechanisms are in play, there's less cause for concern. But if the crack begins to grow and receives activation energy, it can quickly propagate.

So, that is where we require this kind of testing, and as I mentioned, in-situ monitoring of the transition from initiation to propagation is very helpful. So, this is a major advantage of acoustic emissions for the number of industrial sectors or industrial units. This has been taken from this reference, and another thing is that they need to be carefully positioned close to the test material. Now, in this case, particularly, they wanted to use it in a UTM, and in the UTM itself, you can see that the dog bone sample they have made and they have kept a sensor 1, sensor 2.

As a result, the complete reading keeps coming. So, how is the crack initiating, becoming activated, or becoming active, and then how is it propagating on a surface that can be detected using acoustic emission?

So, the advantages and results are being highlighted here. Corrosion can involve various mechanisms, including uniform or generalized corrosion, pitting, and crevice corrosion. In extreme cases, multiple failure modes may interact, such as stress corrosion cracking, which can also involve tribological wear and fatigue phenomena alongside corrosion.

Given the complexity of corrosion processes, acoustic emission testing becomes crucial. It is essential to have a comprehensive research base or database to accurately correlate the responses from the sensors with specific types of corrosion—whether uniform, pitting, or crevice corrosion.

To address this, it's important for sensor manufacturers to conduct extensive research and develop software that can accurately identify and differentiate between these types of corrosion. When sensors capture and analyze signals, the accompanying software should be able to identify whether the issue is tribocorrosion, crevice corrosion, or pitting corrosion, providing valuable early warnings.

Additionally, metal dissolution during corrosion involves the conversion of metal into ions, with anode and cathode reactions taking place. At the anode, iron is released into the solution, while at the cathode, electrons are captured, leading to the formation of hydrogen ions, which then convert to hydrogen gas.

So, that is what they are saying. So, whichever M n here that there is an acoustic emission will be there again, the cathode acoustic emission will be there. If there is a thick oxide and there is some sort of cracking in the thick oxide again, there will be an acoustic emission. So, whatever the corrosion-related phenomena, we are able to observe that there is some sort of acoustic emission, and then we need to differentiate between frequency and amplitude. So, figure out what kind of corrosion mechanism is happening. So, from that point of view, the acoustic emission technique is very good for determining the kind of corrosion, and they are trying to utilise the ongoing corrosion process that can be diagnosed using the acoustic emission.

We've discussed the stress-assisted corrosion damage mechanisms that contribute to acoustic emission sources. To summarize, the formation of hydrogen bubbles due to cathodic reactions, as well as the initiation and propagation of cracks, are key aspects observed through acoustic emission. This includes phenomena such as thick film surface coating restrictions, slip deformation during plastic deformation or twin deformation, and the fracture or decohesion of surface material. Non-metallic inclusions on the surface can also generate distinct acoustic emissions.

Accurate diagnosis requires a sensor and associated units to identify which acoustic emissions correspond to specific phenomena, such as hydrogen bubble formation, crack propagation, or destruction of thick surface oxides. The paper provides examples of such signals, showing one time-domain signal converted into the frequency domain using FFT (Fast Fourier Transform). The frequency signal, around 10 kHz, is relevant to hydrogen gas evolution. The diagrams A and B illustrate the acoustic emission waveforms related to hydrogen gas evolution, including both time-domain and frequency-domain waveforms.

Now, compared to coming to C and D, the time signal has been shown in C, which is related to the rupture of oxide film, which is there on a surface and we call a rupture of the passive film, and D is a kind of frequency analysis of that. However, if you look at this range, it is from 0 to 1000 kHz, and this range is from 0 to 100 Hz. So, there is only this much difference. And then in the second diagram, they have expanded.

So, we can see that much more clearly, and the third again is from 0 to 1000 kH. So, ranges are more or less than the A, and then the B and F are the same, while in the case of the D, it is expanded. So, to see what the variation is on the surface, Now the E and F figures are basically to observe that the AE waveform corresponds to the metal dissolution. So, in this paper, they are trying to analyse that.

However, there is a amplitude difference here. We find 0.04 here, whose amplitude is 0.028, while here, whose amplitude is a much lesser 0.007. So, this is almost one-tenth of the other responses. So, that means the rupture of the passive film will have a much lesser response compared to the evolution of the gas, the metal dissolution, or maybe the corrosion in action, which is the initiation of the corrosion. So, all the signals or all the failures will have the same characteristic frequency, and that is why we required a complete database.

What is the characteristic frequency for H2 liberation, or maybe the breakage of the passive film or metal dissolution? If this is this is the characteristic frequency, we can really immediately diagnose that this kind of failure is happening due to this kind of corrosion. That is, as shown here, the broken film has a low amplitude peak, and the peak has been shown at roughly 50 kHz. So, here we can see 50–70 kHz. Something has been shown here. So, it is roughly 50, and then we say the anodic cathodic hydrogen bubble evolution happens around 50 to 70, but the magnitude will also be higher.

The magnitude of the signals is relatively small, indicating that the rupture of the passive film occurs. However, the magnitude increases significantly, even though the ranges remain the same, due to the cathodic and anodic reactions involved.

In the final part of the presentation on acoustic emission, the focus shifts to analyzing signal data over time. Individual signals are plotted as white dots, while cumulative damage is represented by black dots. The analysis includes both instantaneous and cumulative failure data.

The red line in the graph shows a steady increase from approximately 10 seconds to 1,000 seconds, reflecting the rupture stage. This indicates that the acoustic emission associated with heat energy rises continuously from 1,000 seconds to 100,000 seconds. The plot illustrates the evolution of acoustic emission heat energy, with open circles representing individual measurements and black dots showing cumulative acoustic emissions. The red line tracks these cumulative emissions over time. This experiment was conducted on a material with a specific style or characteristic.

So, what really comes out is what is really diagnosed from this. You say that change over time in total acoustic energy, acoustic emission energy, needs to be tracked and will really indicate what kind of failure is going to happen, and if one is a different kind of failure, then what is the stage of the failure? Now, if it indicates stage 3 is like a very high-alert kind of hazardous situation that is coming out, So, stage 3 is a high-risk zone, and that is, after the 10,000 cycle, this is the initiation of a high-risk zone that needs to be. If we are able to judge using this kind of acoustic emission testing, that is sufficient for the maintenance person to really act on that. And so, what we are seeing in the in the recording of the initiation and initiation of SCC and subsequent crack propagation provides a comprehensive and compressive understanding of the damage evaluation. So, basically, the acoustic emission method is very good if you want to really understand the complete mechanism.

So, this is important for us now, and this is what we have covered. Now, there is another technique, which may be the last entity technique, which we are covering in the course: a strain digital image correlation. So, it is, as such, not a new technique. What we are saying instead of putting in the sensor, like in an acoustic emission OA sensor, is that the sensor, is that the sensor is very near to the damage, and where the damage is initiated will be very good. So, however, if we are putting a sensor on a rotating component, what will happen in this situation? There is a possibility of using sophisticated equipment like a slip-globe arrangement, and then blood will also wear out very fast, and we need to change over time. So, to avoid that, we have good image capture technologies and then digitisation technologies if we start capturing the images, something like 5 frames per second, and then we try to analyse and compare what happened earlier and now what is happening. So, we can really figure out whether the stress is increasing, stress is decreasing, strain is increasing, or strain is decreasing, and if we are able to correlate strain with a real failure, then it will be a very good technique.

So, this is what has been covered in the stress strain digital image correlation testing. What has been shown in this case is that if you look at the figure,, there is a reference set and then the actual set of deformed images, and then what they are covered, and then there will be kind of a node, or maybe node 1, node 2, node 3, node 4, or maybe many other points in this. Whatever then depends on how many points we want and what kind of magnification is possible. So, through that, these are the possible things for us, and then if we track, we will be able to find out what the new position is. So, here it is shown that the two dots, something like an initial dot, have been given a p value, and then the nomenclature p and the second dot have been given the nomenclature q, and if you look at that deformed position, the nomenclature has been given p prime and q prime.

So, this is exactly what we do in the finite element method. In the finite element method, we determine what kind of deformation there is, and based on that deformation, we try to figure out the strain that strains those things. So, this is the finite element method or numerical method. Here, we will then capture the image if we already have assigned the dots to the surface. We can really track those dots, and by tracking those dots, we can really find out the values, the stress, and the strain. So, the same finite element method with image analysis can really give much better results, and it becomes a non-destructive technique as well. So, this is relatively new and still progressing, and I believe that there is a lot of future after this technique in this case. So, what can we say is non-destructive? This is optical because we are capturing the images and measuring the deformation and strain distribution on the surface specimen and structure.

So, again, this complete thing is coming from a surface analysis. It is not a subsurface because, as a subsurface, we will not be able to capture the images and see the deformation. However, if, because of this subsurface failure, some sort of impression is coming onto the surface, it can be captured; otherwise, this technique will be only for the surface. And this digital image correlation, the DIC, basically captures a series of images; it is not a one-image, two-image image; it can be many images, and then it captures the different deformation states covering the entire surface. So, the thermographic images that the whole surface captures get captured easily, and that is why they are very good. So, in this case, the whole surface gets captured because we are capturing a number of images and the whole surface.

So, we are not just concentrating on one place, like a UT; you need to keep a sensor near that, while in this case, the whole surface can be captured. So, sensors will not really be required very near the crack; they can be slightly away, and then we will need to have good cameras or good analysis software. So, what we are seeing in this case is that advanced image processing algorithms are applied to the images to detect and interpret them. So, detection is one thing; otherwise, interpretation. So, again, the software plays an important role, understanding science will play an important role, and then we really required a few iterations, or maybe we required a good database and a few iterations to match our own situation or our own system where the failures are happening.

So, DIC is basically an advantage where the surface itself is irregular or the surface is going through too much expansion or compression. So, wherever there is a complex shape, a complex surface is sure to come, and then we can go ahead with the DIC, and then if the advantages compared to the traditional sensors, which we have covered in a few earlier techniques, And then, as I mentioned, it covers a complete surface—not only the localised one, but a complete surface. So, that is why it is important to have sensors that are difficult to mount on complex surfaces, and images will be a better option compared to those sensors. Now, digitally, DIC, as I say, relies on matching points. That is what has been shown here, whatever the point in this case, P and P prime.

So, there is a comparison. A P and a P' can be compared. What is the difference between the values? What kind of transformation matrix do you need to use because we are going to cover the 3D x, y, and z parameters? However, in this case, we are showing only the 2 x 0 and y 0, but we can also compare them in 3D. So, in this case, matching on the surface, then before and after deformation, and before deformation, what was the status after deformation? So, again, it is a relative comparison, and then it is not absolute. Relatively, we can figure out what kind of deformation is really happening and whether it is progressing at a much faster pace and a quicker pace compared to the other, which may be surface or other loading conditions or may be in corrosion cases.

For this purpose, a subset of digital images is analyzed as the specimen moves and deforms. While comparing many images is computationally intensive, advances in computational power make this feasible. Post-processing, such as noise removal from images, is more manageable compared to handling raw data. As technology progresses, particularly with the rise of machine learning and artificial intelligence, these methods become increasingly effective and valuable.

To compare strains, a three-dimensional approach is used, with coordinates labeled as (x, y, z) and initial positions denoted as (m_1, m_2, m_3). A transformation matrix is employed, similar to those used in MATLAB programming or finite element methods. Strains are calculated based on the measured displacement of points on the object's surface. For example, if there are 1,000 points on a surface, tracking their displacements allows us to determine the strain and strain rate.

Strains are defined within a dimensional plane on the surface, and digital image correlation data can be converted into a triangular mesh if needed. The key difference between this method and finite element analysis is that the latter uses increasingly finer meshes to achieve more detailed results, whereas digital image correlation directly assesses surface strains based on image data.

However, in this case, it will be generally given that the triangular size is slightly bigger than the noisy level, which will be far better. So, when computing a strain on each triangular, the smaller triangular tends to produce noisy strain data. So, we try to keep slightly bigger data compared to finite elements, and therefore, the larger triangular triangles are preferred for more accurate results. However, infinite-element smaller triangles are preferred, or, of course, there is always some sort of numerical limit. Anything less than that will give more inaccurate results.

So, we always have those limits. In this case, we maintain slightly larger triangles. These triangles are inherently planar; compute a strain on each triangle using the same equation commonly found in the FEM method. So, we really do not really require a separate kind of algorithm. Finite element algorithms or finite element software can be utilised with this kind of method. By applying strain calculation to each triangle, a comprehensive understanding of strain distribution and behaviour across the object surface can be obtained.

Now, I will just take one example. In one of the papers that was published, I am just trying to make a reference to that. Say the surface of a rocket can be marked with the grid of the markings; that may be the number of dots we can keep, and then we make the rocket itself, and then we keep tracking using the DIC method. We can produce colour maps; we can use counter plots or vector fields, whichever is required now. If I am interested in displacement, I can make a displacement with the time, change the velocity with the time, or accelerate with the time. So, that is why I try to examine and comprehend the structural behaviour and performance of the rocket, and applied force plots can be provided for the visual depiction.

Let's consider an example involving a rocket impacting a stationary surface. To utilize the strain Digital Image Correlation (DIC) method, we can mark a grid of points on the rocket's surface. By tracking the displacement, acceleration, and velocity of these points, we can generate plots of these values. For enhanced visualization, we can use color maps and color plots to represent the data on the surface more effectively.

The example pertains to high-speed impact dynamic and deformation analysis of a target rocket system. In this context, the target is a stationary surface, and the rocket is the object undergoing impact. The details of this setup are illustrated in the reference materials provided, with a zoomed-in view showing the rocket striking the stationary surface.

We see that the rocket can also be divided into five different tail planes: the tail pre-flight case centre and the nose. So, there are five different subsections in a rocket, and then we are trying to figure out what the response the response will be, and in this case, you can see how this rocket is crushing that has been plotted. Same thing speed of the rocket, how it is varying and how it is impacting the surface; it has been shown that this is my ion acceleration; it has also been shown of the different surfaces, the nose centre, and all this. So, individually, we are not fixing sensors on the rocket surface. We are making a number of dots. You are able to see the dots on the rocket and the stationary surface, and we are trying to correlate that with what was happening at a point of maybe 0, on the one nanosecond earth surface, and maybe the dot number one, and maybe what is happening at the dot number one is 2 nanoseconds, 3 nanoseconds, or 4 nanoseconds. So, it becomes computationally intensive, but we are able to really diagnose without using the sensor, which we believe is the sensor.

In this scenario, the camera effectively captures images that provide valuable responses. The goal is to observe and analyze how the rocket and stationary surface interact. Specifically, we are interested in tracking changes in shape, displacement, distortion, and deformation of individual points on the surface.

While capturing and processing numerous images can be computationally intensive, recent advancements in computational power and processing speed have made these methods feasible. Techniques that were difficult to imagine 5 or 10 years ago are now possible and offer much faster results.

So, in this case, particularly while the rocket really gets deformed, we know it will get fired. So, it is subjected to external forces. Now, when this external force for the rocket hits the stationary surface naturally, there will be deformation. Now, there will be some assumption, as we are assuming that the stationary surface will not cause any major breakage, and much of the displacement will be changed only in the localised zone where the rocket is getting hit. So, we really need to do this kind of testing. As I mentioned, the data-driven approach, which is the future, or maybe you know, has already started. People are using this kind of method for that purpose. Finally, I'll discuss a 2020 publication that employs a digital image correlation technique in a compression test.

So, the compression test has been shown; in this case, you are able to see the specimen, and this specimen has been enlarged, as shown over here, and in this specimen also, we are able to see some sort of dot on the surface right. And then another thing is that we are able to see the two cameras that are capturing the images, and the cameras also capture some distance from a specimen; they are not just attached to the specimen. Another thing is that when we are using this kind of compression testing machine, there are some sort of safety doors. So, in the situation they had, they kept the protective panel door open.

So that the cameras can really capture the images with a good resolution. And then the two cameras, and then both cameras, have been linked to this computer system. So, that continuous capture of the images happens, and then they use, of course, an aluminium bar an aluminium bar to mount this camera, which is an aluminium bar, and then they use some sort of vibration isolation pad. So, there is no noise coming from the bar to the surface, and then it is again in a vibration-free environment. And then another thing is that, in this situation, they also use a kind of LED studio light to capture the image in a proper light.

As I mentioned earlier in the TD case, we use the good light. So, emissions are happening properly, while in this case, the images that are captured are also proper. And then what they calculated was that they found something like 5 frames per second, and then for each dot, they took around 50 images. This implies that they apply the specified load condition, maintain the same load for 10 seconds or perhaps even longer, and then capture 50 images. So, another result is acceptable. Now one question keeps coming to mind: the camera, if they are magnified, can really find out what the surface cracks are.

However, in this case, they are tracking that initially the point does not have any kind of surface crack, and after that, they are determining how the crack is propagating and to what level it is going. So, initially, there was no visible crack on the on the surface, and the surface cracked even though they were using 5x magnification of the glass, and then they mounted and used this kind of random speckle pattern, and then they kept a size of 0.5 micrometres, which is substantially high. They then kept this size.

So, at least 9 pixels can be utilised, or maybe at least this speckle is being captured by 9 pixels. So that we are able to see what kind of distortion is happening to the surface. And then this is the 0.5 mm already; I mentioned the black ink. This kind of pattern can be made using the black ink or by spraying on it. However, we know the spray will not be that uniform.

However, it depends on the kind of circumstances or the available resources we can utilize. So, you can see here undistorted the specimen and then here we when the load 44.5 kilo Newton compression load has been applied on the surface and then this is a strain been shown in this bar chart. We can see here the strain red means no as such strain and then compression strain is going on the reverse side. So, this is the worst-case kind of violet colour, and then before that there is a blue colour, and then green is slightly better, but in this case, generally, we go hard with the red colour as a major worry, but in this case, the minimum worry we are going for is the compression side.

So, this is a pattern in which we are able to see red, yellow, and greenish colors. So, this zone clearly indicates that there is a possibility of failure, and that is what we are trying to show: initially green, then green and blue, and then blue and violet. So, that has been shown, and finally, they are able to show that there is a fracture on the surfaceTherefore, this technique proves to be highly beneficial for non-contact types, as it eliminates the need for a sensor. When applied to a compression test, it yields a similar example. However, it's important to note that tracking on a surface presents a limitation, as it's impossible to pinpoint the exact location of the fracture. . So, naturally, in reality, we require a couple of techniques together; one single technique will not be able to give complete results.

So, if you are using two or three different techniques, So, one is confirmation, the other is the other is validation, and 100 percent comprehensive results can be obtained when we go with the two techniques together. Thank you for attending this lecture. We will cover the next lecture on the selection of techniques and come up with some algorithms. So that it can be utilised and then quantitatively selected as an appropriate technique for our work. Thank you.