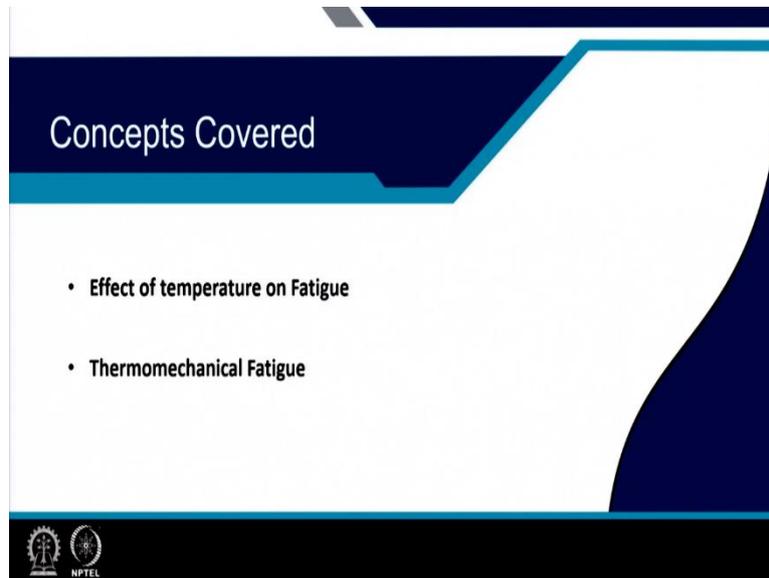


Fracture, Fatigue, and Failure of Materials
Professor Indrani Sen
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Lecture 50
Effect of Temperature on Fatigue

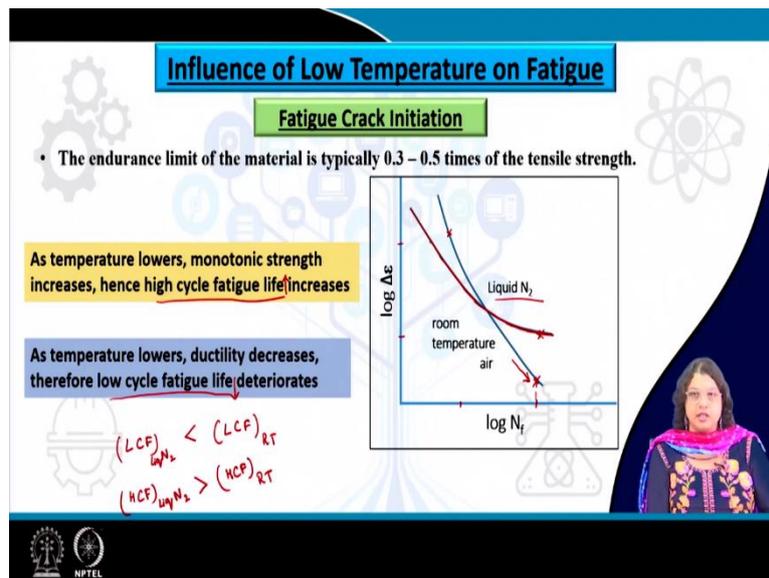
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Hello everyone, and welcome to the 50th lecture of the course. Fracture, Fatigue, and Failure of Materials. And this is the last lecture of this module on fatigue. And in this particular lecture, we will be talking about the influence of temperature on fatigue. And the exact concepts that will be covered in the lecture are the following. We will be talking about the influence of temperature and, not only high temperature we should also understand how the fatigue behaviour of a material changes under the influence of low temperature. So both of this will be discussed in this lecture.

And then, after that we will be introducing the concept of thermo mechanical fatigue. Now, thermo mechanical fatigue is a special variation of fatigue in which there is a thermal cycling also associated with the mechanical cycling, so the superposition of both the thermal and the mechanical cycling of course changes the behaviour in a different way, and this is very much related to the actual service condition, and that is the reason that thermo mechanical fatigue will be discussed in this class because we are mostly concerned about the failure of materials and how that can be obtained through different mechanical deformation behaviour.

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So, let us talk about the influence of temperature and particularly low temperature. And when it comes to fatigue we have already seen through this entire module that fatigue is related to two steps, fatigue crack initiation and then fatigue crack propagation. So, fatigue crack initiation is particularly related to the stress or strain control fatigue of the unknown specimen which is typically known as the high cycle fatigue or low cycle fatigue for the stress and the strain control fatigue respectively.

So, let us see how does if the lowering of the temperature influences the fatigue crack initiation mechanism. So typically, without any influence of temperature or corrosive atmosphere in general, fatigue strength of a material or endurance limit is something like 0.3 to 0.5 times the tensile strength. So, if we do not know the fatigue strength of a material at all, based on the tensile strength of the material we can simply make it as 0.3 to 0.5 times and that gives us a rough estimate of the fatigue strength, even without doing the experiment.

But in presence of temperature, both high and low temperature of course, these numbers are not relevant and we need to understand that how the fatigue behaviour is being changed. So, what happens at lower temperature is that the monotonic strength of the material such as the yield strength increases, so we increasing the temperature, reduces the strength, and reducing the temperature increases the strength something like that, because the plastic deformation is being restricted.

And since, the high cycle fatigue or the fatigue crack initiation through the stress control mode that we have seen the typical SN curve behaviour. That kind of fatigue life is actually related to the strength of the material that is the reason that we do several service treatments

to enhance the strength of the surface to arrest the initiation of the fatigue crack. So, lowering the temperature in that sense appears beneficial as it leads to an enhancement in the high cycle fatigue life.

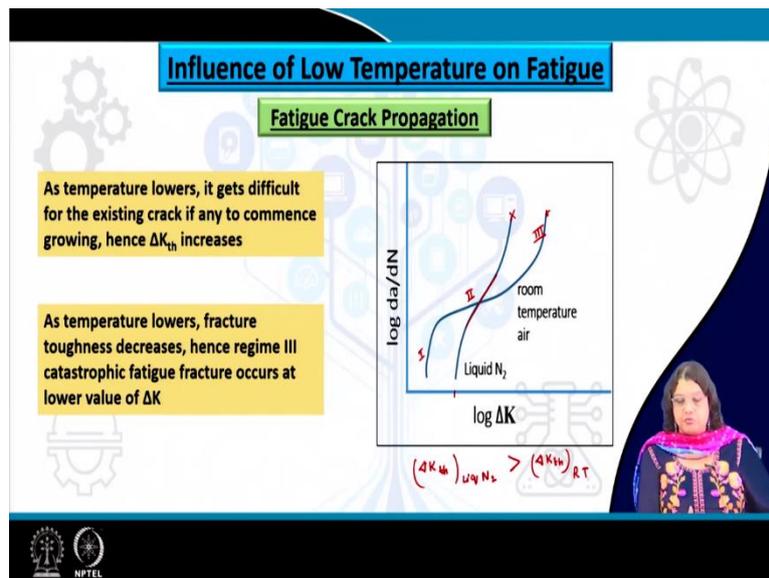
But when it comes to the low cycle fatigue life, things are completely different because strength and ductility in general are inversely related. So, what happens is that at low temperature, the ductility decreases, the ability of the dislocations to move is lower at low temperature, and that leads to a lower value of low cycle fatigue. So, in general although the high cycle fatigue enhances, the low cycle fatigue decreases if we are using the fatigue or if the service condition is involving low temperature.

So, this is a schematic representation of how the strain versus strain range versus number of cycles to failure are varying for the air or room temperature condition, in the ambient condition, so this blue one here as well as a red one signifies the liquid nitrogen. And you can see that for any particular strain range value, if we can see that if we are talking about a higher strain range value which is particularly suitable for low cycle fatigue, we can see that the one at room temperature in air actually survives for a longer number of cycles compared to that for the one at liquid nitrogen.

So, that means that the low cycle fatigue in nitrogen or liquid nitrogen, so liquid nitrogen typically applies to very low temperature is actually lesser than the LCF life for that in room temperature. On the other hand, if we are talking about the high cycle fatigue, so let us say N_f value of something like of this order, we can see that for such cases the strain range that specimen can survive at this particular number of cycles is much higher for the case of liquid nitrogen or at low temperature than that at room temperature.

So, here we can however say that HCF in presence of liquid nitrogen is actually greater than the HCF life at room temperature. So, once again there is a dilemma and based on the actual service condition we can understand that whether low cycle or high cycle fatigue will be relevant and based on that we can use a material for, if we know that there is a room temperature or a low temperature application.

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Now, when it comes to fatigue crack propagation however, there is again a completely different behaviour that can be seen, if we are talking about the fatigue threshold versus the crack growth rate in case of regime II. So, as the temperature lowers, it gets difficult for whatever existing crack or notch is there to start the growth of the crack.

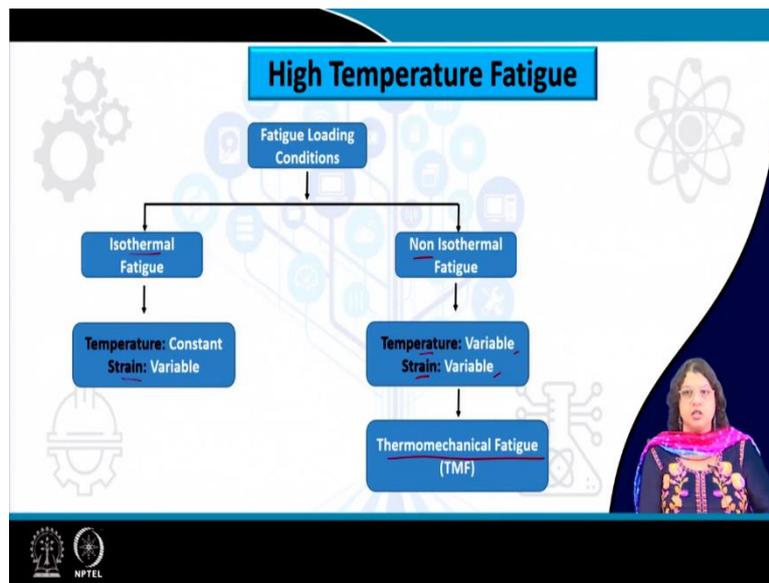
So, that means that ΔK_{th} or the threshold value of the stress intensity factor required for the initiation of the growth of the crack that particular value increases at lower temperature, so that appears as a good news, and we can consider this as a beneficial effect of lowering the temperature.

However, if you are talking about regime III, so at the high ΔK regime at that point fracture toughness, actually is controlling the failure behaviour. At lower temperature however the fracture toughness decreases, and that means that at regime III, the catastrophic fatigue fracture can occur at a lower value of ΔK . So, that means that lowering the temperature does not appear beneficial if we are talking about the final fracture. It may delay the initiation of the growth of the crack, but once the crack grows then it will be fracturing at quite a lower value of ΔK .

So, this is the schematic representation of the da/dN versus ΔK curve, and you can see that while at room temperature it has a typical stay regime I, II, and III with a prolonged regime II with much lower crack growth rate. On the other hand, when we are doing the test on the same specimen, same material we can see that at liquid nitrogen the crack growth rate is quite faster for the case of regime II, although the ΔK_{th} is significantly lower or higher.

So, ΔK_{th} for liquid nitrogen is higher than that of room temperature. However, fracture occurs at a much higher ΔK value for the case of room temperature and in comparison, low temperature leads to fracture at quite a low value of ΔK . So, we again have to optimize the exact condition or the exact material or the temperature level to utilize it for any particular application.

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Now, if we are talking about high temperature fatigue, of course high temperature fatigue has a very strong role in influencing the overall failure characteristics, and particularly it has a detrimental effect in most of the cases. We will look into more details, but in general there are different ways by which the high temperature fatigue is can be characterized based on the service requirement. So, one of this that we are generally use is the isothermal condition. Isothermal means when the temperature is kept constant, it is high temperature, but the temperature is a particular a fixed one.

So, in this case, the strain is variable because strain is what we are cycling based on the requirement and that leads to actually fatigue loading. So, temperature is constant mechanical loading is being cycled. On the other hand, there could be non-isothermal fatigue and that is what is known as thermo mechanical fatigue in which both the temperature and strain, both the parameters are variable, and actually both are cycled.

So, we can cycle the temperature, we can cycle the strain there can be, they can be cycled simultaneously or in a different way, but whatever it is the influence of both thermal fatigue as well as mechanical fatigue can lead to a variation in the properties.

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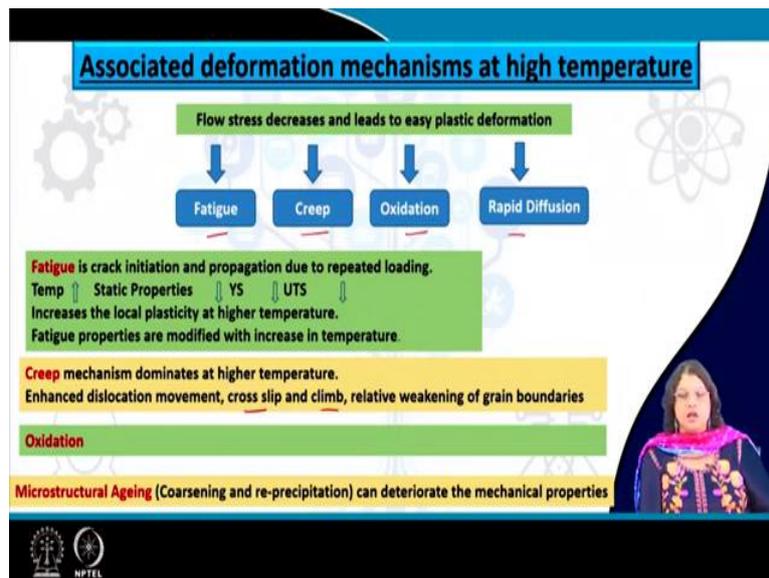
The slide features a blue header with the title "Influence of High Temperature on Fatigue". Below the title, there are two text boxes containing bullet points. The first box states: "Failure of critical components in aircraft engines and power generating plants is due to cyclic loading at elevated temperatures." The second box states: "Fatigue crack nucleation in an alloy at elevated temperatures is influenced by a number of different microscopic processes which depend on the - temperature, applied stress level and environment". In the bottom right corner, there is a small video feed of a woman in a purple and blue patterned top. The slide also includes decorative icons of gears and an atom, and logos for IIT Bombay and NPTEL at the bottom left.

- Failure of critical components in aircraft engines and power generating plants is due to cyclic loading at elevated temperatures.
- Fatigue crack nucleation in an alloy at elevated temperatures is influenced by a number of different microscopic processes which depend on the - temperature, applied stress level and environment

Now, why is it important to study the high temperature fatigue behaviour of a material at the very first place? As we are all aware of the critical application of materials for fatigue related applications, for example, in aircraft engines and all where fatigue is of serious concern and where high temperature is also of serious concern, so of course we need to understand that how the material behaves under the combination of high temperature as well as cyclic loading.

And fatigue crack nucleation in an alloy, at elevated temperature is typically influenced by a number of different processes. And these are dependent on the extent of temperature, the degree of temperature that we are applying the applied stress level, as well as if there is any other kind of environment present other than high temperature, so all this actually controls the fatigue behaviour of the material at high temperature.

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So, actually when we are talking about high temperature unlike the room temperature one there are several mechanisms which are acting simultaneously, other than fatigue. So, fatigue is of course there, because we are mechanically loading it under cyclic condition. Not only that, when there is at high temperature, there are the possibilities of creep deformation, oxidation as well as diffusion.

So, depending on the environment, so all this act simultaneously and that influence the overall fatigue performance of the material. So, in general fatigue is related to crack initiation and propagation as I mentioned. And as the temperature increases, typically the strength of the material decreases. And not only that the plasticity level also increases at higher temperature, and this in general affects the fatigue behaviour as we have just now seen in case of the low temperature, so the reverse happens for the case of high temperature.

But there are also the possibilities of creep, and again the high temperature leads to enhanced dislocation, motion and that is related to the increased tendency for cross slipping and climbing and that associated with the relative weakening of the grain boundaries or the grain boundaries sliding mechanisms, all gets active and this being also mechanical deformation strategies, so the material will behave in a different way in presence of temperature or in absence of temperature, that means at room temperature.

Along with that, oxidation is another very prominent features that we have seen. Particularly, when we are talking about the presence of corrosive atmosphere or any other such atmosphere that can lead to formation of the oxide products, oxide products in some cases are passive and that influences the mechanical deformation behaviour further. Now, along with

the all this deformation behaviour microstructurally also if we are performing the test or if a certain component is being in service at a high temperature for the for a prolonged period of time, there are possibilities of microstructural aging also.

If we are applying a particular constant temperature for a prolonged period of time that may lead to coarsening of the grains, so again, grain size or microstructural size controls the strength of the material or other static and cyclic properties of the material and obviously that will also change if there is any variation in the microstructure.

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The slide is titled "Influence of high temperature (isothermal) on fatigue". It contains the following text:

- The mechanisms responsible for the inception of fatigue flaws can be generally grouped into the following categories:

Cracking induced by cyclic slip

- At $T > 0.5$ homologous T – wavy cyclic slip
- Increase in SFE and thermal activation accounts for cross slip/climb
- Kinematic irreversibility is enhanced by increased oxidation
- Poor microstructural stability leads to crack initiation

Grain boundary cavitation

- At $T \sim 1/3^{\text{rd}}$ to $2/3^{\text{rd}}$ melting T – creep deformation
- Cavities nucleate at g.b. triple points, particles, interfaces due to strain mismatch
- Loading waves with long hold times at the tensile stresses leads to increased easy initiation of cracks

The slide also features a small video inset of a woman in the bottom right corner and logos for IIT Bombay and NPTEL at the bottom left.

Now, there are the mechanisms if we want to look into in details that how high temperature fatigue is actually been occurring, there are different kinds of mechanisms that are occurring. First of all is the cracking induced by cyclic sleep, and this is applicable at a temperature which is greater than 0.5 times the homologous temperature and that actually leads to generation of wavy cyclic sleep.

Moreover, the increase in the stacking fault energy as well as the thermal activation leads to generation of cross slips and climbs and all this leads to increased deformation, however the kinematic irreversibility is enhanced by the increased oxidation. And in general, along with all these the poor microstructural stability leads to the crack initiation. And once the crack initiates then also the repeated cyclic loading makes it easier for the crack to propagate and lead to the final fracture.

Along with that, there is also a mechanism related to the grain boundary cavitation that can lead to high temperature fatigue failure. And this is particularly applicable at a temperature

range of one third to two third of the melting point, particularly related to the creep deformation behaviour.

So, what happens is that, at that high temperature there are cavities which forms, particularly at the triple points of the grain boundaries at any particles or interfaces and this kind of cavities are related to the strain mismatch or non-uniformity. When there is a loading condition, these loads are not equally distributed at all the grains and that particularly at the triple points this leads to generation of the cavities.

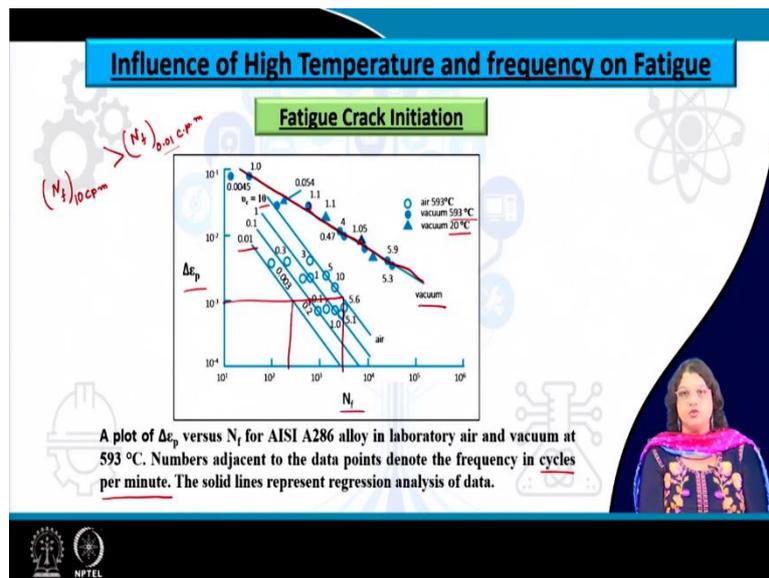
Loading waves with long hold times particularly in the tensile stresses side that may also lead to increased tendency for initiation of cracks. And once again, the crack initiation will lead to early fatigue fracture.

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The slide features a blue header with the title "Influence of high temperature (isothermal) on fatigue". Below the title, a yellow bar contains the text: "• The mechanisms responsible for the inception of fatigue flaws can be generally grouped into the following categories:". A white box with a black border lists three bullet points: "- Grain boundary sliding and the attendant development of wedge cracks,", "- Nucleation and growth of voids at inclusions and precipitates,", and "- Oxidation and corrosion". The slide background includes faint icons of a gear, a lightbulb, a tree, and a flask. A small inset video of a woman is visible in the bottom right corner. The NPTEL logo is at the bottom left.

There are other kind of mechanisms such as the grain boundary sliding and the development of wedge cracks or nucleation and growth of voids, this is specifically if there are inclusions and precipitates once again due to the strain mismatch and non-uniformity that can lead to the release of the stress as the formation of voids. And once the voids form, they can coalesce also leads to bigger crack and that can lead to the final fracture in case of cyclic loading are also acting simultaneously. Oxidation and corrosion are always detrimental in most of the cases that can lead to the early onset of fracture.

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Now, once again frequency plays a very important role as we have seen for the case of corrosion fatigue. It is the high frequency that is preferable to retard the growth rate of the crack. In this case also, with presence of high temperature frequency also plays a lead role, so let us see how is that.

Now, if we are talking about the fatigue crack initiation you can see that this is the strain range, the plastic strain range, so basically the strain controlled or the low cycle fatigue kind of behaviour and the x-axis is the number of cycles for failure. Now, you can see that this solid line here, so let me just point it with the red and you can see that this one is the test results at vacuum, okay, done at different temperature at 20° centigrade as well as close to 600° centigrade.

So, quite a large jump in temperature, and you can see that the triangular points here are for 20° and the circular points are for 600° and you can see that more or less the values match with each other. So, basically no significant differences in temperature is found if we are doing the test in vacuum. But if we are not, if you are doing it in simple air and then there is a strong role of frequency on the fatigue behaviour.

So, in this case we are doing different kind of frequencies of 10 to 0.01. And you can see that now this is represented as cycles per minute, once again and you can see that if we are pursuing the test at higher frequency, let us once again talk about a particular strain range of 10⁻³ and you can see that if we are applying higher frequency of 10 cycles per minute, we can achieve quite a high number of cycles in comparison to the one in which we are applying lower frequency of 0.01.

So, what we can see here is that the N_f for the case of 10 cycles per minute is much greater than N_f for 0.01 cycles per minute. And this is not only related to these three orders of magnitude difference, but if we are talking about any such intermediate values of frequency, we can see that there is a continuous enhancement in the number of cycles that a specimen can survive if we are increasing the frequency.

The reason once again is related to the availability of time. If we are pursuing the test at very high frequency means that lesser time is available for whatever damage that is bound to happen that will be restricted. On the other hand, if we are pursuing the test at lower frequency or if the service condition is such that the temperature is or the loading cycle is being pursued at lower frequency, that may provide sufficient time for the fatigue damage to initiate and grow and that can lead to early onset of the fracture at a much, comparatively much lower number of cycles.

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The slide is titled "Thermomechanical Fatigue (TMF)" in a blue box at the top. Below the title are four bullet points in yellow and green boxes:

- ✓ Fatigue caused by the combined thermal and mechanical loading with respect to time
- ✓ Temperature as well as strain vary cyclically
- ✓ This type of loading is more detrimental than isothermal fatigue operating at maximum temperature
- ✓ Most frequently found in start up and shut down cycles of high temperature components

Handwritten notes in red ink are present next to the second and third bullet points:

- Next to the second bullet point: $T_{max}, T_{min}, \Delta T$
- Next to the third bullet point: $\sigma_{max}, \sigma_{min}, \Delta \sigma$

A small video inset of a woman is visible in the bottom right corner of the slide.

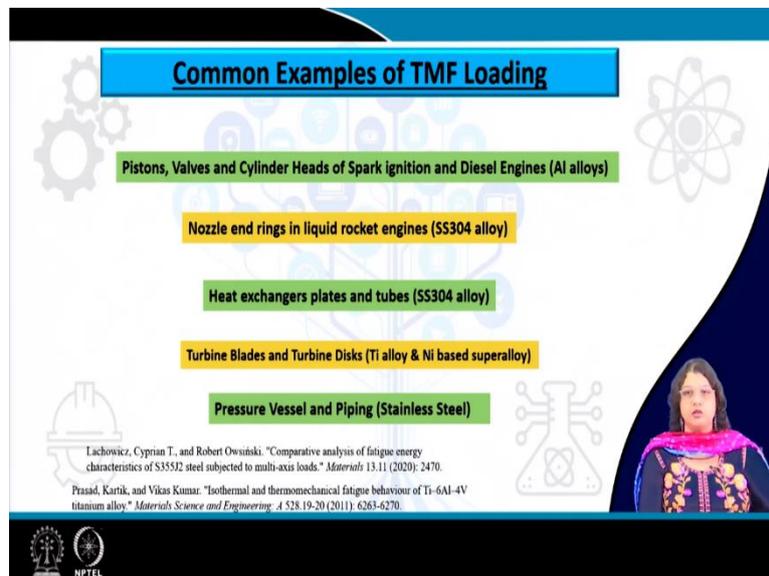
Now, let us move on to the more complicated case when we are cycling both the temperature as well as the loading condition. So, there is a combination of both the thermal and the mechanical loading cycles. And based on that actually this type of loading is certainly more detrimental than the isothermal fatigue operating at even the maximum temperature.

So, thermal cycling is when we are changing the temperature from a low temperature to a high temperature, so here we have basically T_{max} , where T stands for temperature and $T_{minimum}$. And once again, we have all the other parameters like ΔT or the temperature range and all other parameters maintained here.

On the other hand, based on the mechanical cycling we definitely have σ_{\max} , σ_{minimum} , or strain ϵ_{\max} , $\epsilon_{\text{minimum}}$, stress or strain range etcetera. So all these are being active. And then we have the control of different parameters which can lead to variation in the properties in a different ways. So, most frequently such kind of thermo mechanical fatigue damage is found during the start-up and shut down cycles of the high temperature components.

You may often notice that in certain industries or where we use the high temperature instruments, we are often asked not to turn it down or shut it off very frequently, once the engine runs, we should better keep it going and we do not shut it down or without any particular reason, we tend to run it continuously. Because the more time you are starting it and shutting it down the more will be the chances for the damage.

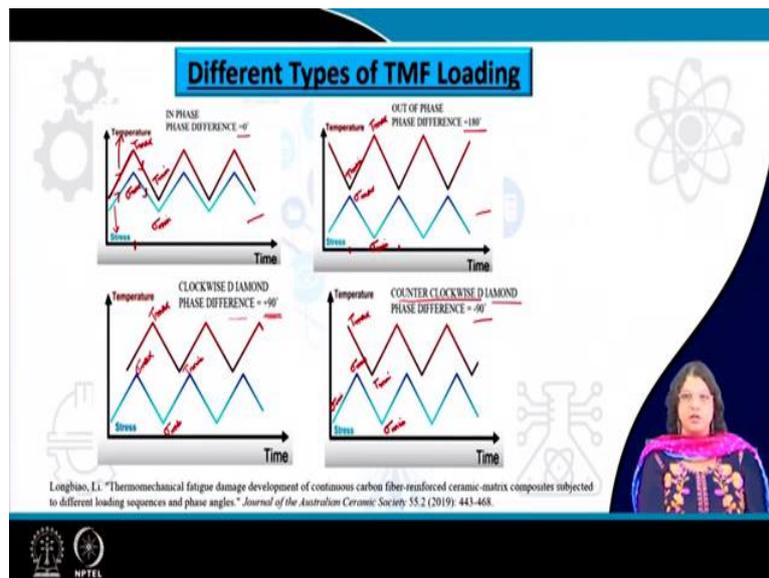
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So, common examples of thermo mechanical fatigue loading is seen in case of pistons and valves and cylinder heads of the spark ignition and diesel engines this can be seen particularly for aluminium based alloys. On the other hand, nozzles and rings in liquid rocket engines which are made of very high grade SS304, stainless steel-based alloy.

And heat exchangers, plates and tubes, etcetera, there also the thermal cycling and mechanical cycling are being acted simultaneously. And as I mentioned that the turbine blades and the turbine discs of the aircrafts, mostly made of titanium alloy or nickel based super alloy are the one, along with pressure vessel and piping, these kinds of applications are very much concerned about the thermo mechanical fatigue. And we often need to understand this or pursue the test to understand the fatigue life of the component based on the thermal cycling as well as mechanical cycling.

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Now, there could be different ways by which the thermo mechanical fatigue loading can be applied. The first one, which is the most usual one, is the in-phase cycling in which the temperature and stresses, so the red one here signifies the temperature and the blue one signifies the stress.

And we can see that the maximum values of temperature, so T_{\max} which is the peak value or σ_{\max} , these are occurring at a particular time, same time, for all the cycles. And that is why this is known as in phase, when the phase difference is 0° . So both the maximum values of temperature and stress are being acted simultaneously.

And then, gradually it is coming down to the minimum value of T_{\min} as well as σ_{\min} , again coming at the same point of time. So, that means that the slope of the increment in stress and temperature as well as decrement in temperature and stress are also following the same value for the temperature and stress, and this is the in phase 1.

So, let us see the out of phase 1 in which case the phase difference is 180° , so what it means is that we have the maximum of the stress here, but the minimum of temperature at a particular time, and this is happening for all the cycles. On the other hand, we have the maximum of temperature and minimum of stress at a certain time.

So, in this case the phase difference is 180° , so it is just completely reversed. We are applying maximum stress, but we are applying minimum temperature and then again we are applying maximum temperature but that is associated with minimum values of stress.

So, obviously there will be difference in the properties when we are applying the in phase or the out of phase loading conditions. And not only that, there are other kind of variation also which is known as the clockwise diamond, where the phase difference is plus 90° , what do I mean by that is it starts at the following point where it actually starts at a 90° difference in the value.

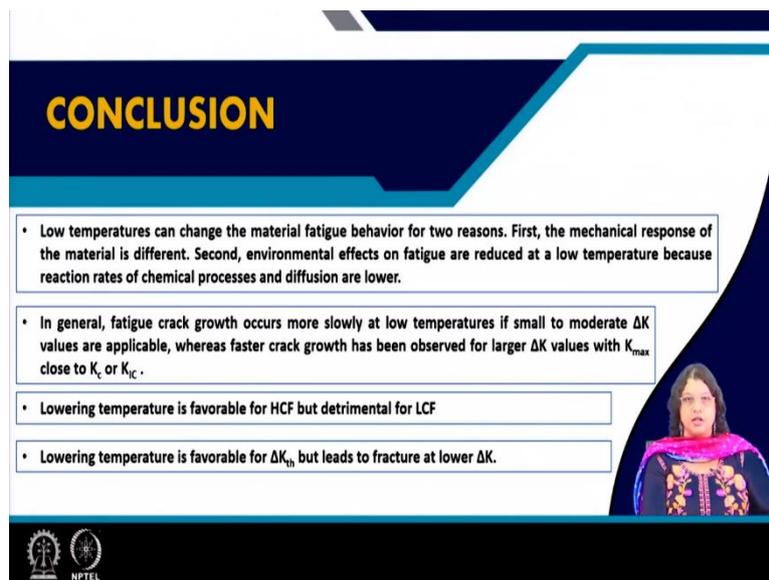
So, we have the temperature maximum as well as the stress maximum difference by 90° , and same goes for the temperature minimum and the strain stress minimum. So, that is why this is known as the phase difference is 90° . And this is known as diamond considering the shape of this pattern, and this is a clockwise one because we are moving along the positive direction, so the plus 90° that is why this is known as the clockwise diamond.

On the other hand, there is a counter clockwise diamond also which says that the phase difference in this case is -90° . So, that means that we are having the temperature maximum and that is associated with the minimum of stress and after that the maximum of stress. And the difference for this maximum, and the maximum stress, and maximum temperature as well as the minimum temperature and minimum stress level is actually -90° .

So, since we are moving in the opposite direction now, this is known as the counter clockwise, and once again based on the shape this is the diamond pattern that we are applying. Of course, for all the four conditions the properties that we will be achieving out of this different loading conditions will be completely different.

So, first of all there is a cycling of temperature as well as mechanical loading and then again if depending on how these two are correlated, the sequence of these two are correlated, based on that the properties can be even different.

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CONCLUSION

- Low temperatures can change the material fatigue behavior for two reasons. First, the mechanical response of the material is different. Second, environmental effects on fatigue are reduced at a low temperature because reaction rates of chemical processes and diffusion are lower.
- In general, fatigue crack growth occurs more slowly at low temperatures if small to moderate ΔK values are applicable, whereas faster crack growth has been observed for larger ΔK values with K_{max} close to K_C or K_{IC} .
- Lowering temperature is favorable for HCF but detrimental for LCF
- Lowering temperature is favorable for ΔK_{th} but leads to fracture at lower ΔK .

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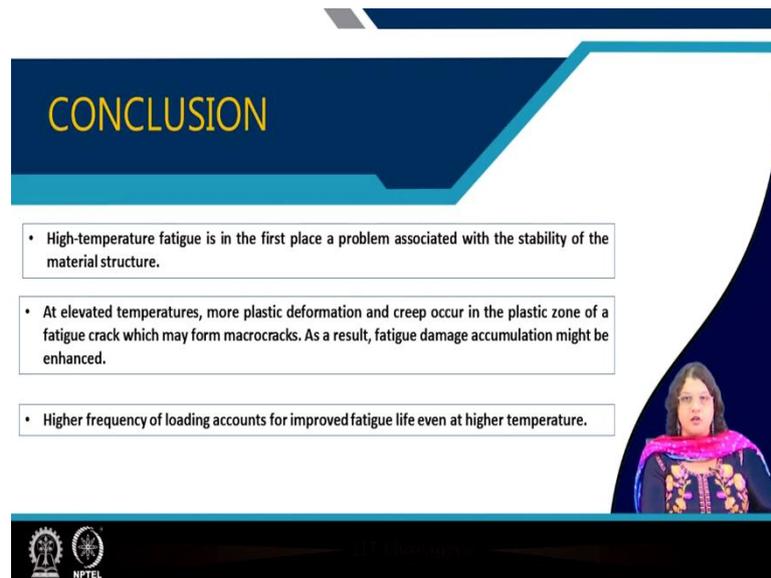
So, in conclusion we can say that the low temperatures can change the material fatigue behaviour and this is related to two prominent reasons. First of all, the mechanical response of the material is different at low temperature and also if there is any environment that is present there, effect of that will be also reduced at low temperature because the reaction rates of the chemical process are also lower.

In general, fatigue crack growth occurs more slowly at low temperature. If small to moderate, ΔK values are applicable. However, faster crack growth has been observed for larger ΔK value, so when it is near to the K_{max} which is close to K_C or K_{IC} , that is a critical value for the fracture toughness, at that point the crack growth rate becomes very faster even at low temperature.

So, low temperature is typically favourable for high cycle fatigue, but detrimental for low cycle fatigue, that is what we have seen, and that is related to the mechanical properties of the material in the monotonic conditions which is increasing, the like the strength is increasing, at lower temperature, but the ductility is reducing at lower temperature.

On the other hand, lower temperature is found to be favourable for ΔK_{th} . ΔK_{th} actually increases at lower temperature but at lower temperature fracture occurs at a low value of ΔK , so that also have to be kept in mind and we basically needs to optimize for particular application scenario at low temperature.

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The slide features a dark blue header with the word "CONCLUSION" in yellow. Below the header, three white boxes with black borders contain the following text:

- High-temperature fatigue is in the first place a problem associated with the stability of the material structure.
- At elevated temperatures, more plastic deformation and creep occur in the plastic zone of a fatigue crack which may form macrocracks. As a result, fatigue damage accumulation might be enhanced.
- Higher frequency of loading accounts for improved fatigue life even at higher temperature.

In the bottom right corner, there is a small video feed of a woman with glasses and a pink shawl. At the bottom left, there are logos for IIT Bombay and NPTEL.

Now, when we are talking about high temperature fatigue, this is a problem associated with the stability of the material structure also. So, there are different mechanisms which are acting simultaneously like creep, oxidation as well as the microstructural coarsening, diffusion, etcetera. At elevated temperature, more plastic deformation and enhanced creep may occur in the plastic zone of the fatigue crack, and this may lead to formation of micro cracks. As a result, fatigue damage accumulation might be enhanced.

On the other hand, we have also seen that higher frequency of loading accounts for improved fatigue life, so this is similar to the corrosion fatigue behaviour where we have seen that higher frequency is actually beneficial because it applies to lower amount of time, for the reactions to not occur or not fully finalize. And that will lead to a higher value of life, at higher frequency.

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CONCLUSION

Thermomechanical fatigue refers to the fatigue damage under simultaneous cycling of the stress/strain levels as well as temperature.

Fatigue, creep and oxidation are the main mechanism for TMF failure.

Out-of-phase loading is the most detrimental types of loading as it generates higher and positive values of mean stress.

In-phase loading exhibits compressive mean stress during TMF loading and hence it accounts for maximum fatigue lives.





We have also seen that how thermo mechanical fatigue is important to be studied and this includes applying the fatigue damage under simultaneous cycling of stress or strain level as well as temperatures. Now, fatigue creep oxidation all these are simultaneously occurring as well for thermo mechanical fatigue as well, and out of phase loading, out of the different kind of loading that we have seen out of phase loading is the most detrimental type of loading the reason behind this is that it generates a positive mean stress.

And we have seen over this entire fatigue lectures that positive mean stress is actually leading to lower value of fatigue strength or lower fatigue life, overall lower fatigue performance in general. In phase loading on the other hand exhibits, compressive mean stress during the thermomechanical fatigue loading, and that will account for maximum fatigue life out of the four different kinds of thermo mechanical fatigue that we have seen.

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So, following are the references that has been used for this lecture. Thank you very much.