Fracture, Fatigue and Failure of Materials
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Lecture 39
Fatigue Crack Nucleation

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Hello, everyone, and welcome to the 39th lecture of this course, Fracture, Fatigue and Failure of Materials. And in this lecture, we will be talking about a very interesting concept of Fatigue Crack Nucleation.

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The concepts that will be covered in this lecture are the following. We will be talking about fatigue crack nucleation and then we will be mostly discussing the ways by which the fatigue performance of a material can be improved, because that is finally our main target to have better and improved fatigue strength and fatigue performance of the material. So let us see what do we mean by fatigue crack nucleation.

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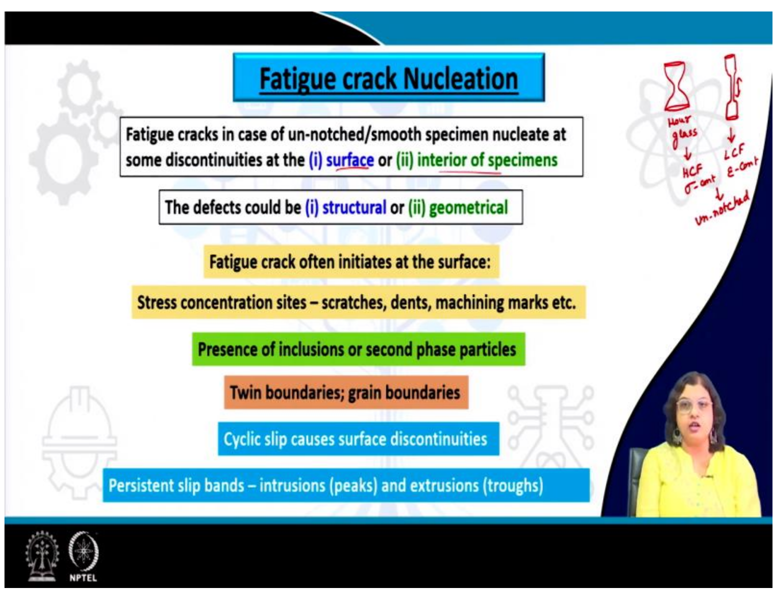

Before we begin please note that so far we were talking about stress controlled and strain controlled fatigue, and this is applicable for both these categories of fatigue, stress control and strain control, particularly when we are using an un-notched specimen. For stress control or strain control fatigue, we typically use either an hourglass shaped specimen or a dog bone shaped specimen, that we have discussed in the very initial lectures on fatigue, and the different modes of fatigue testing.

So in any such kind of specimens, be it an hourglass or a dog bone kind of specimen, there is certainly no notch or dominant crack present there. We either have a specimen geometry which looks something like this, so that is an hourglass specimen that is used for HCF, for stress controlled fatigue testing.

And for axial fatigue, we typically use the dog bone kind of specimen in which we have a pronounced grip section, and then, which is for holding the specimen to the instrument, and then we have the gage section in which all the deformation is happening and we can understand how the material will behave under repeated loading.

So this is typically used for low cycle fatigue or strain controlled fatigue, but we can also use this for high cycle fatigue as well. The point is both of this kind of fatigue the stress controlled or strain controlled, both of this are using un-notched specimen. So if there is no notch to begin with, there is no dominant crack to begin with.

Certainly because of this repeated loading, cracks are supposed to nucleate, supposed to initiate from some locations. And we need to understand that what are those locations where the fatigue cracks are most prone to generate. So to develop this understanding, let us discuss that what are such kind of locations.

Actually, any kind of discontinuities, if it is there in an smooth specimen, that can lead to initiation of fatigue crack under cyclic loading. So this kind of discontinuities or singularities can be present at the surface or at the interior of the specimen. Now surface cracks are or surface defects are more prone to lead to initiation of a fatigue crack or nucleation of a fatigue crack.

And after that, the possibilities of interior defects leading to fatigue cracks will come into the picture, but any kind of, although we assume that the sample is smooth, we try to maintain the sample as smooth as possible. But still, because of some defects, some inherent defects in the specimen or in the material as such, that can lead to crack initiation or crack nucleation under the mode of repeated loading.

So this kind of defects could be structural defect, such as any kind of second phases or precipitate, such kind of defects can act as the possible sites which can lead to crack nucleation or this can be simply geometrical defect, such as let us say, the scratches or dents. Those can also act as defect and those can also lead to incision or nucleation of crack under repeated loading.

So basically if there is any stress strain non-uniformity between this defect as well as the surrounding space which is the matrix, that can lead to crack nucleation, that can lead to stress concentration. And we now know based on the fracture mechanics, that if there is a stress concentration, that leads to maximization of the stress to a very high value.

And in case that exceeds the bond strength of that material, then those bonds will rupture at least at those points, the, the bonds between the atoms will break and that will reach the theoretical values of cohesive strength, and that can lead to crack nucleation. So that is how it begins in the very first place.

Now if you are talking about the common types of defects that can lead to fatigue crack initiation, let us talk about the one which mostly are at the surfaces and fatigue cracks as we now know is more prone to the surface cracks, because surface are the locations which, under repeated loading can lead to the stress non-uniformities and can lead to all the, the crack nucleation at very low applied stress. So that can lead to the fatigue process as such.

So this kind of stress concentration sites could be actually anything. Even when we are fabricating a component, then the machining marks, if you are rolling or doing any kind of machining, then those marks, the scratches, the lines, everything can act as defect because there will be some non-uniformity in the stress strain at those particular locations compared to the other.

So there is if, the scratches are nothing but it is like a peak and trough. So that kind of things, although in very microscopic scale, but even that can also lead to crack initiation.

In case there is a dent or any other kind of stress concentration at the surface, that can very well lead to fatigue crack nucleation, quite early.

Other than that, if there are inclusions or second phase particles as we mentioned as a structural defects, interior of the material, so that can also lead to fatigue crack initiation or fatigue crack nucleation after certain number of cycles. So surfaces are the regions which are most prone.

So if we achieve very low life for a certain specimen and in comparison let us say for the same material, same kind of specimen, everything remaining same, if we are achieving higher life for the second specimen, we may assume that at the first one, the surface defects might have led to the crack and the extent of surface defect could be less for the second specimen.

Remember we discussed about the S-N curve and the scatter in the S-N curve, and at that time also we discussed that it is the surface defects which leads to so much of scatter. And when we are doing the lab scale testing, of course, we want to remove the surface defect to the maximum extent possible.

We need to do very well polished smooth surface. And if such is not the case, like in actual practice, the surface cracks can act as limiting factor for the fatigue performance. And after that, if the surface is perfectly smooth, then also presence of these inclusions or second phase particles or any such things can lead to fatigue crack nucleation and the final failure.

Apart from that, so let us say in certain cases we do not even have inclusions or second phase particles at all, we have made the surfaces also very, very smooth. Even under such cases fatigue crack may nucleate at the boundaries of the grains. Now grains, mostly we talk about poly crystals, so there are multiple grains.

And when there are grains, there are grain boundaries and grain boundaries are nothing but defects. So grain boundaries or twin boundaries or interfaces or phase boundaries, all such kind of things where there could be actually differences in the strain limits or the stress-strain scenario, if we are loading along certain direction, two different grains will deform in different way based on this orientation with respect to the loading direction.

So that can lead to some strain discontinuity or non-uniformity and that may lead to the nucleation of the crack. And most importantly, when we are talking of fatigue, there is another signature defect which generates only due to fatigue or cyclic loading and that is the main culprit for fatigue crack initiation or nucleation, that is the cyclic slip.

We are all very well aware of slip. It is, as a dislocation moves, it creates a slip step at the surface. So in case of cyclic loading or repeated loading also, there are the cyclic slip generates and these are known as the persistent slip bands. It consists of basically intrusions and extrusions.

And these are the locations which are the signature features for fatigue failure, and these are the locations from which fatigue crack nucleates, particularly for unnotched specimen. So we will be seeing how the fatigue cracks nucleates in each of these cases.

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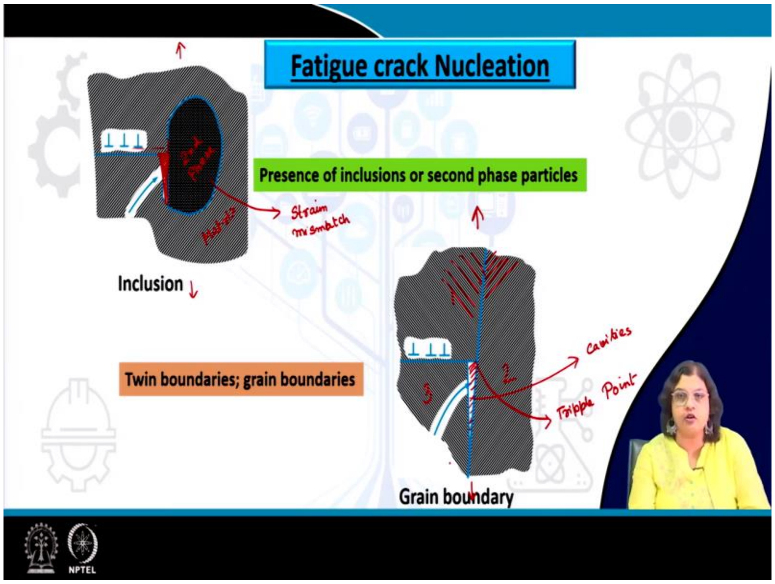

Surfaces are very well understood or we can imagine that. So let us see that what happens in case we have a second phase particle. In such cases, there are these dislocations which can move to the matrix but when it comes to this junction, the movement of the dislocations is being restricted.

Now if we are applying stress along certain direction, and this is an inclusion or a second phase, which is having completely different properties and different deformation capabilities with respect to the matrix. So if this is the matrix phase, and this is the second phase, then obviously there is a strain mismatch.

And this mismatch is the maximum or the discrepancy is the maximum at the junction or at the boundaries between these inclusions and the matrix. So that leads to formation of such kind of cavities under the action of load. And if there, such kind of discontinuities are present, that lead to stress concentration.

And as we discussed, that if there is stress concentration, that helps breaking the bonds, attaining the theoretical cohesive strength of the material and that initiates or nucleates the crack at the very first stage. Now, once the crack nucleates, then it hardly takes a few number of cycles to rupture the entire component or entire specimen as such.

So that is how inclusions are very much detrimental for fatigue loading, and we should be careful of using the right kind of material having the least number of inclusions possible. Also, if even if there are inclusions if there are places where the inclusions are present in clusters, that is even bad news, and we should avoid such kind of structures.

Now, grain boundaries or twin boundaries are again another such things which can lead to the initiation of fatigue crack. For example you can see here, this is the grain boundaries of let us say 1, 2 and 3. There are three different grains here, and this is the triple point, and this is the most prone location for fatigue failure or fatigue crack nucleation.

Because if we are applying stress along certain direction, then this 1, 2 and 3 having different orientations, you can understand this based on the, the stripes that are provided here, that they are having different crystal orientations. And if that is the case, then the movement of the dislocations in all this 1, 2 and 3 will be actually different.

And that means that there will be, again, some strain discrepancy or non-uniformity at the junction of these two, and that leads to formation of this cavities particularly at the triple point where this discrepancy between grain 1, 2 and 3 is the maximum. So it has to release the stress or the, whatever strain mismatch is there, that gets released at those cavities.

And these cavities are nothing but this is just the beginning of the crack to form. So this is what helps to nucleate the crack and then again after repeated loading, these cavities can grow into a proper crack and can lead to final catastrophic failure quite easily.

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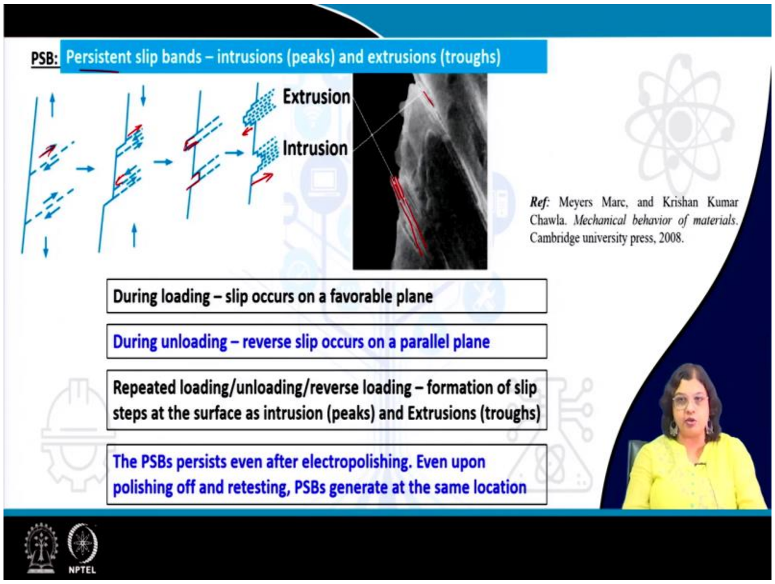

So now let us talk about the persistent slip band, what it actually looks like is something like this. So what happens is that during loading, we know that even during monotonic loading there is slip. And that slip occurs along some preferable plane, some favorable plane.

So let us say this is happening along this plane. And then, when we are unloading, then the reverse slip is happening, which means that slip is occurring on the opposite direction and typically on a parallel plane, not exactly on the same plane rather on a parallel plane because that plane is blocked.

Now, if we keep on doing that, repeated loading and unloading and then reverse loading, tension and unloading and then compression and such kind of things, then this formation of slip steps, both in the forward direction and then in the reverse direction and again in the forward direction and the reverse direction, if you keep on doing like this, this form the steps here. So this looks like the intrusion which are nothing but the peaks and then the trough, which is known as the extrusion.

So these are the, the two things that are being shown here. You see the intrusion here is the peak and the extrusion is the trough. That is how it looks like. This is a real image where you can see that there are these steps which are very clearly seen here. So basically, these are channels through which the dislocations move through the matrix. So these are the regions which are very much prone to initiate the fatigue crack.

We will come to that but before that, let us also talk about this interesting name as persistent slip band. Slip, we all know, what is the meaning of slip and when this is happening in all together more, there are several, like it is forming a band kind of structure. That is how the name slip band is coming.

And this keyword here, this persistent means that even if like, these intrusions and extrusions are formed and we are polishing it off, often we need to polish it off so that we get a smooth surface again to enhance the life so that we do not allow the cracks to nucleate from there.

So we polish it off and then again if we are repeating the test, we see that persistent slip bands are again generating on the same locations. So these intrusions and extrusions are forming also once again on this exact same location. So that is why these are known as persistent. So this is not going anywhere.

So of course, that means that once these intrusions and extrusions are formed, it is very difficult to get rid of that. We can temporarily enhance the life to some extent by polishing and removing this persistent, the slip bands. But it will again come to the picture if we are repeating the loading scenario.

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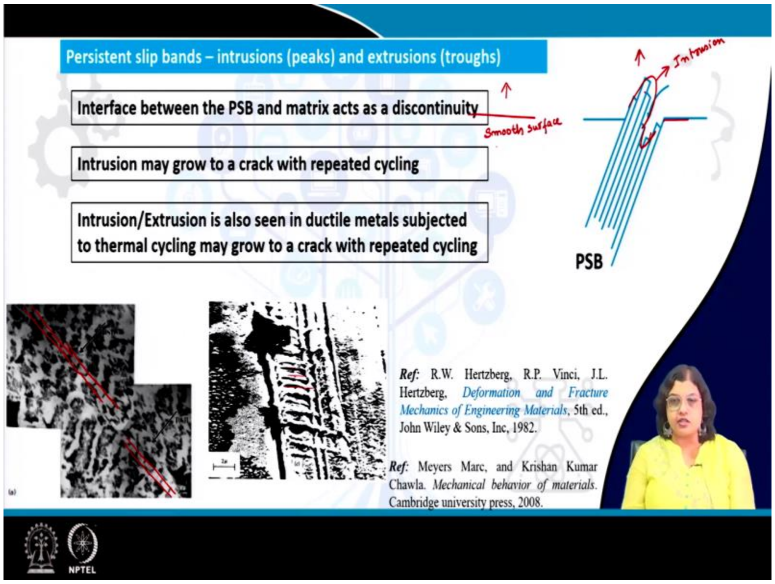

So we have to have a constant monitoring method by which we see that these intrusions, extrusions are forming, we need to get rid of that. We do that and then again we put this back in surface. This is often used in actual practice. Now, what happens is that let us say that we have a smooth specimen surface.

So in case there is no discontinuity, certainly that will not give rise to any crack nucleation. If we are applying stresses in whatever direction, that will not lead to any discrepancy in the strain scenario because there is no non-uniformity or discontinuity in the structure.

But in case we, so let us write that this is we are talking about, the surface, but in case there is this persistent slip bands, then of course this is the peak we can very well see here. So this is the intrusions and this is the location which act as a discrepancy to the stress and the strain.

So the kind of strain that we are generating here versus there is of course not the same and because of this discrepancy, because of this discontinuity cracks are supposed to nucleate from these intrusions. So this interface between the persistent slip band and the matrix. So this is the matrix, and the, this is the peak and the trough.

So this interface is actually the point of, the one which is most prone for the crack to nucleate. This intrusion may grow to a crack with repeated cycling as we have seen. And this is once again, another image in which you can see this persistent slip band very, very clearly. So you can see this that how this is forming like a channel, like two parallel channels, very well.

This is another one which is showing such kind of features here. You can see the steps also very clearly in such kind of images. So basically these persistent slip bands are seen for any kind of repeated loading when there is a non-uniformity in the strain forming. And that means that such kind of features can also be seen in case we are talking about thermal cycling.

Thermal cycling is another very important way for which fatigue is very, very important and of concern. When we keep on applying temperature or removing the temperature, there is a continuous repetition of expansion of the material and contraction of the material.

Now, depending on the coefficient of thermal expansion, this extent of expansion or compression will vary but if we keep on repeating this temperature cycles or we keep on repeating the thermal cycling thing, then obviously that can lead to all those features that we are seeing for mechanical cycling as well.

So persistent slip band, because this is all related to the motion of the dislocation, and this is very well active in case we are talking about the high temperature activities like thermal cycling, so of course this persistent slip bands can be of concern if we are talking about thermal fatigue.

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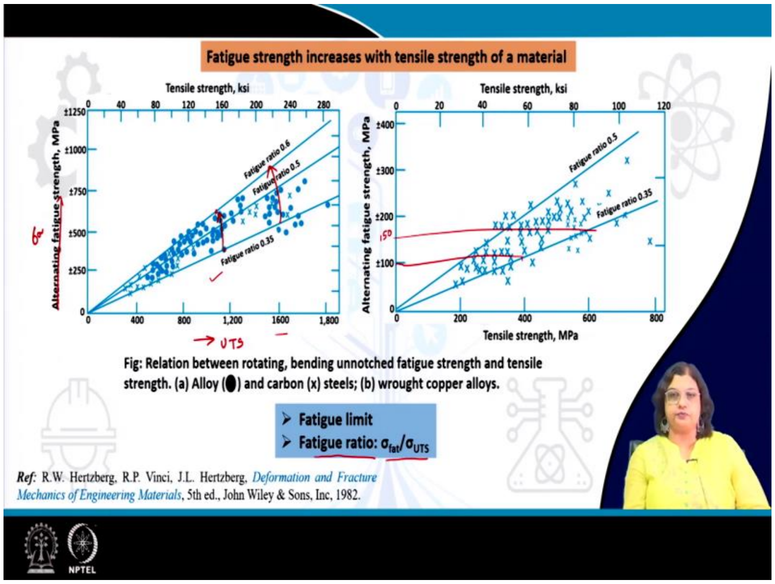

Now the interesting part here is that so far we have seen that any kind of such discontinuities, be it at the surface or interior, those are the locations which lead to early fatigue crack nucleation, and we should get rid of that. Now, it is not always possible to get rid of all such kind of defects because some of the defects are inherent.

For example, the grain boundaries. We mostly work on poly crystalline material. So there should be grain boundaries. Now, we have to look for the ways by which the fatigue performance still can be improved. And when I say fatigue performance, we are talking about fatigue strength.

And so far, as we have seen for the stress controlled or strain controlled fatigue, fatigue strength can be obtained from the unnotched specimen. We assume that there is no dominant discontinuity or defect or crack or notch in a specimen or in a material or in a component.

Under such circumstances whatever stress or strain amplitude values that it can withstand, that is considered, for certain number of cycles, of course, that is considered its fatigue strength. So fatigue strength, if considering that there are no dominant notch or crack existing there, as I mentioned, that even the internal defects or the surface defects like the scratch marks and all, which can lead to fatigue crack nucleation, that can happen only if it is able to break the bonds.

And for that matter, this breaking of this bond and the strength of the material is actually related to the ultimate tensile strength of the material. Of course, the presence of this defect or the stress concentration location actually helps to achieve the cohesive strength of the material, which is, in reality, it is not possible to achieve the cohesive strength for the entire bulk component.

But we may still achieve the theoretical cohesive strength value at the localized region. And that means that if by any way, we enhance the strength of the material, then fatigue performance can be enhanced or rather breaking of the bonds will be very, very difficult and that means that fatigue strength will be increased.

So this is what is shown here with some experimental results where you can see that the alternating fatigue strength, now alternating, is equivalent to the word amplitude. So basically this means the fatigue or stress amplitude. So stress amplitude is along the y axis. So this is σ_a. And in the x axis, we have the UTS.

And we can see very well that if the UTS is increasing, the x axis here is the ultimate tensile strength. And what we can see here is that for a UTS value of 1200 MPa, we can see that the fatigue strength is quite high, close to around 350 or 400 MPa. And if we are talking about even higher value of UTS, for example 1600, we can see that the fatigue strength for certain line is actually even higher to around 500 MPa.

The same thing we are seeing for this case also for another material where we see that for the tensile strength of 400 MPa, we are getting a fatigue strength something like 100 MPa whereas for 600, we actually are getting the fatigue strength of something like 150 MPa. So that means that the tensile strength certainly is directly proportional to the fatigue strength of the material.

Not only that, there is another significance here which explains the relation with fatigue ratio. Fatigue ratio, as has been explained, so that is the ratio of the fatigue strength to the UTS of the material. And in case the fatigue strength, this ratio increases, we again see an enhancement in the fatigue strength.

So for example, for this particular case here, if we are talking about the UTS value of 1200, then for fatigue ratio of 0.35, versus the fatigue ratio of 0.6, certainly has a difference in the fatigue strength value. And we can see that there is an enhancement by almost double the value of the fatigue strength, just if we are changing or if we are in increasing the fatigue ratio.

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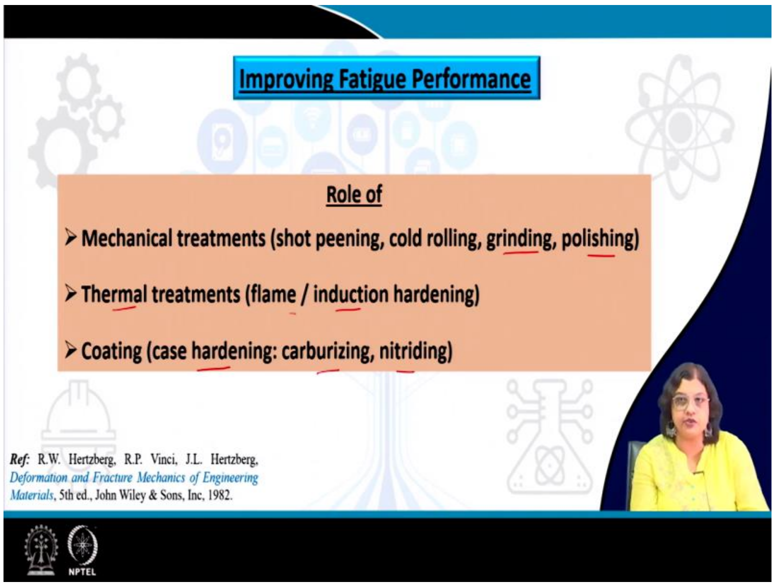

Now as we have seen that the ultimate tensile strength is the one which controls the fatigue strength of the material, then obviously we would aim to enhance the ultimate tensile strength of the material. Now, at the same point, we are also very well aware of the fact that strength and ductility are typically inversely related.

So that means that if you are increasing the strength, then toughness is also going to reduce. Apart from grain refinement, any other way by, through which we are increasing the strength, toughness is going to decrease. And we often talk about a different kind of applications in which we need certain value of toughness.

So we always cannot really cut on the toughness values. Now, what is interesting here is to understand that fatigue life is particularly dependent on the surface characteristics of the material. As we have seen, that it is the surface defects which are most prone sites to initiate or to nucleate cracks even in an unknown specimen.

So if by any way, we can enhance the strength of the, ultimate tensile strength of the surface itself then it will be very difficult to break the bonds at the surface, which means that it will be difficult to nucleate the crack at the very first place. So obviously, fatigue strength or fatigue performance will increase. It can survive for higher number of cycles even for a particular strength value.

And this can be obtained if we do several treatment. For example, some mechanical treatments, like shot peening or rolling of the surface or simply grinding and polishing, this is very, very handy if we are talking about the, even the lab scale specimen, we often go ahead with grinding and polishing to achieve as smooth specimen as possible which is devoid of any such scratch marks or dent marks or machining marks, etc.

Other than that, we can do some thermal treatment such as the hardening of the surface by flame hardening or induction hardening and this can also lead to enhancement in the strength of the surface and that can enhance the fatigue performance. And in turn, coating also has a very, very important role to play in the fatigue behavior of the material and we go ahead with case hardening such as carburizing, nitriding to enhance the strength of the surface which in turn enhance the fatigue strength of the material overall.

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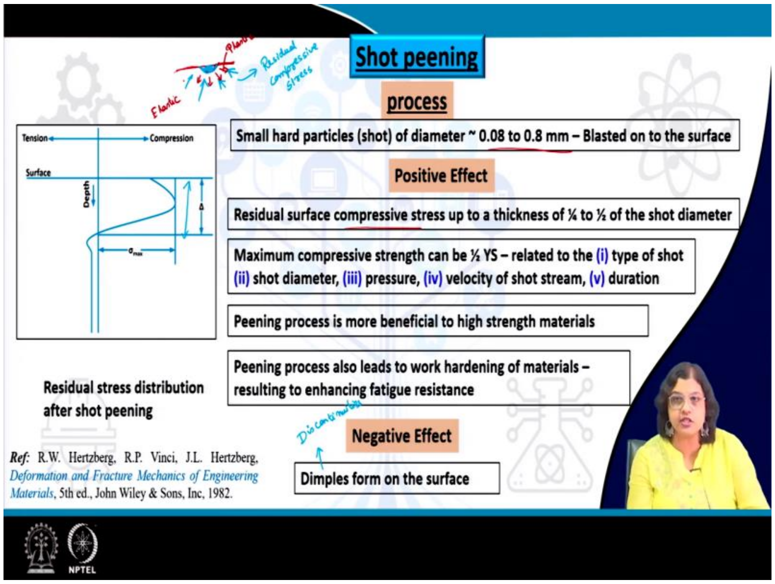

So let us see how the shot peening is done. Actually, in the process of shot peening, we deal with some shots, shot means the spherical particles, hard particles of diameter of around 0.08 to 0.8 mm, and that is blasted on the surface, at a high impact energy. And the positive effect is that there develops, because of this blasting, and it is just been compressed on the surface, and that leads to a residual compressive stresses on the surface.

It forms a, like if this is a smooth surface, and then we are hitting it with a shot. So now we are having a surface like this so obviously there will be some plastic deformation here to attain this kind of shape. Now, the surrounding material, so this one here is plastic. Surrounding material is elastic, which is not allowing it to have any kind of shape change.

And that as a result will, so that interior part will apply some compressive stress to it. So this leads to generation of some residual compressive stress at the surface. So that means that of course, we have also discussed that compressive stress or compression is actually good news for fatigue, because even if there are any kind of defects or cracks that will try to close under the influence of compressive loading.

Or in other words, if you are applying certain tensile stress, part of that will be nullified or will be balanced by this residual compressive stress. So compressive stress is always beneficial for any kind of cyclic loading. So in this case, for the case of shot peening, we achieve this residual compressive stress up to a thickness of around one-fourth to half of the short diameter.

So up to this entire thickness or depth below the surface, compressive stress will be active. And this maximum compressive strength that could be obtained is like half of the yield strength of the material which is quite significant number. And that is related to the type of the shot, what kind of materials we are using, what is the size of the shot, pressure, at what pressure we are impacting the shots with, the velocity of the short stream, the duration of the process etc, all this controls that how much will be the residual compressive strength and up to what extent.

But in any case, this shot peening process is actually beneficial to the high strength material. So higher the strength of the material more effective the shot peening would be. The peening process also leads to work hardening of the material. And work hardening once again leads to enhancement in the strength. So that is another way by which the strength is being increased at the surface.

And based on that we see that a higher fatigue performance or higher fatigue strength can be obtained for a shot peened specimen. But it does have a negative effect as well. Particularly, it forms this dimples on the surface. So this is the, the kind of discontinuities that are forming on the surface. And any kind of discontinuities are actually not beneficial, that actually can lead to crack nucleation.

So this is a negative factor that can lead to fatigue crack nucleation. But the positive sides are so much that that kind of overrules the negative effect. And we often do the polishing to remove those dimple effect, but it still has the residual compressive stress that can lead to have the beneficial effect to be active but not the negative effect.

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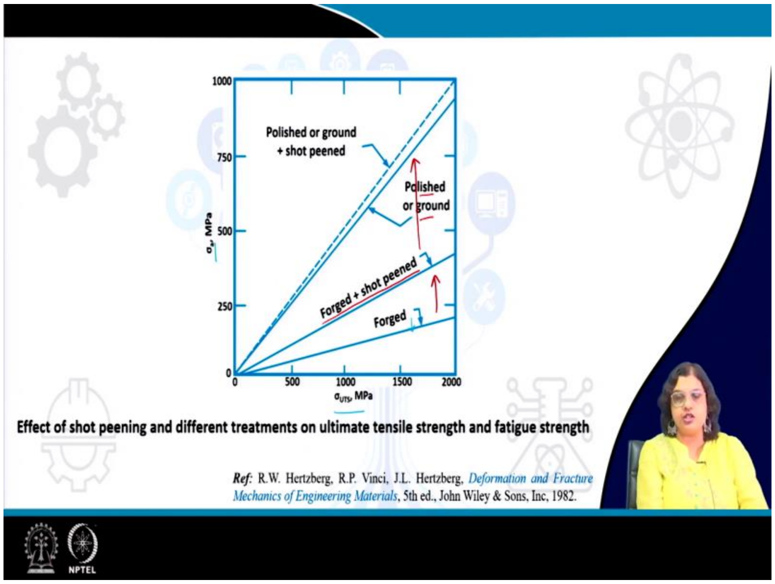

So here is an example. You can see that the stress amplitude versus the ultimate tensile strength is plotted and as we have seen that as ultimate tensile strength increases, stress amplitude of the fatigue strength increases. But not only that, we see that this is the one for the forged specimen, and if we are shot peening the forged component, we see that there is quite some enhancement in the fatigue strength level at all values of UTS.

Particularly for the higher values of UTS, this enhancement is even more. And if we are simply polishing and grinding this to get rid of the shot peening thing, then we are again increasing the strength to even more higher extent. So that is how we can achieve far higher fatigue strength of the material just by the process of shot peening itself.

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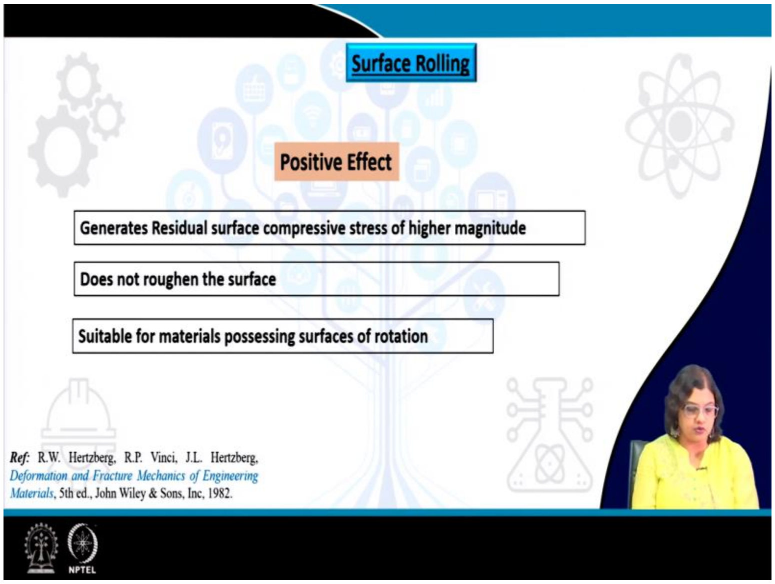

Now let us move on to the next process of surface rolling. So what the surface rolling or the cold rolling does is it actually again because of the process of rolling itself, it generates a residual compressive stress at the surface. Now, this magnitude of this compressive residual stresses is actually quite higher, even higher than the shot peening process.

So in that sense surface rolling is very, very effective to enhance the fatigue strength of the material. Most importantly, it also do not have though that negative effect of shot peening in the sense that it does not make the dimples to appear on the surface, it basically does not roughen the surface. So that also acts as a positive effect.

And it is particularly suitable for materials possessing the surfaces of rotation such as any such machining marks or any such scratches that can generate, if you are using, for example let us say the lathe machine or so, then if such component is simply surface rolled, then the surface will be smooth also and there will be this compressive residual stresses also that will lead to an higher or enhanced fatigue performance of the material.

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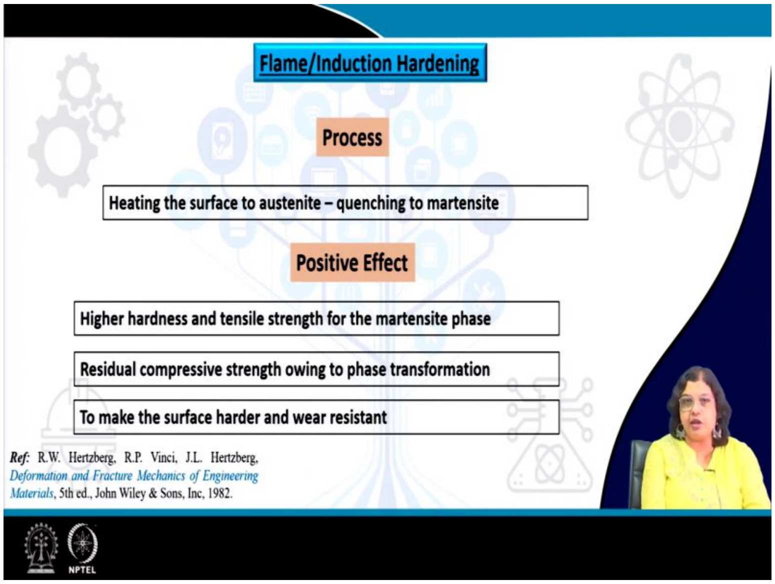

Flame or induction hardening, so that is a thermal treatment procedure by which the hardness of the surface can be enhanced. So what it is being done typically, for steel this is explained that we heat the surface to the austenite level and then we quench it quickly to make it martensite.

Now, we know that martensite has a higher strength and hardness compared to the austenite phase. And as a result this martensite, now the surface is martensite, not the entire structure itself, now this martensite will certainly, will have higher strength and hardness so that means it is difficult for the cracks to nucleate on the surface.

Now not only that, considering the volume of the martensite being higher than that of the austenite, this change in the volume due to the phase transformation also leads to generation of residual compressive stresses at the surface. And once again we know that residual compressive stresses is a good news. We want to achieve that.

And in case this flame or induction hardening is done to achieve this martensite, we get not only the strength enhancement due to martensite presence but also due to the residual compressive strength, the crack nucleation will be difficult. And that makes the surface harder and wear resistant as well as fatigue resistant.

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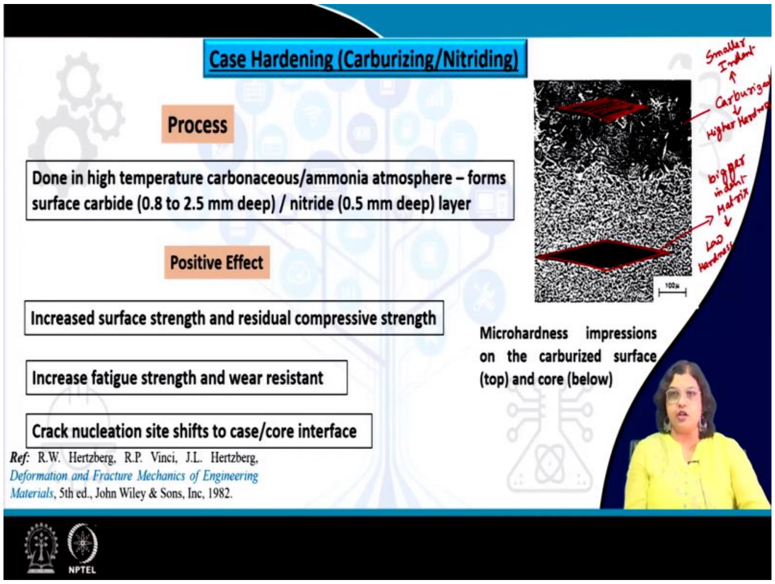

There is another way by which the surface condition can be improved, and that is a kind of coating or case hardening. And what we do here is the process of carburizing or nitriding in which the specimen or the component is actually heated in a temperature in an atmosphere in presence of carbonaceous atmosphere or ammonia.

And in the first case, in presence of carbonaceous atmosphere, it forms the surface carbide layer which is having a depth of around 0.2, 0.8 to 2.5 millimeter as well as in case of ammonia atmosphere, it forms a nitride layer. And that is of depth, something around 0.5 millimeter.

Now because of this carbide and nitride, of course they have much higher hardness compared to the matrix, and this increased surface hardness or surface strength as well as this, again this residual compressive strength because of this mismatch between the volume of these two, the carbide and the matrix or the nitride and the matrix, that leads to this residual compressive strength which acts positively to enhance the strength of the material.

So that also increases not only the fatigue strength but also the wear resistance of the material. And particularly, crack nucleation in this case, so it is not happening on the surface anymore because the surface is being hardened. And rather, the crack initiates now at the interface between this case hardening part, so that layer of the surface which is being hardened and the interface. So that, and the matrix.

So that interface between the case hardened zone and the matrix that is where the crack is expected to nucleate now. So we basically are shifting it a little downward towards the interior, and that means it can survive for higher number of cycles. So these are some examples, the micro hardness impression, as you can see, the top one which is a carburized layer.

And you can see the impression size here which is red thing here. So this is like a rhombus shaped indent, impression on the carburized part. So this is the carburized case, and this is the matrix. And you can obviously understand that the impression is much bigger for the case of the matrix.

So bigger impression means lower hardness means that is it has penetrated to a very large extent. So bigger indent is noted at the matrix. And this signifies lower hardness. On the other hand, for the case of the carburized condition, we see smaller indent and that means obviously, it is difficult to penetrate, so that means it has higher hardness. And if such is the case, then the fatigue performance will also increase in case of the carburized or nitrided component.

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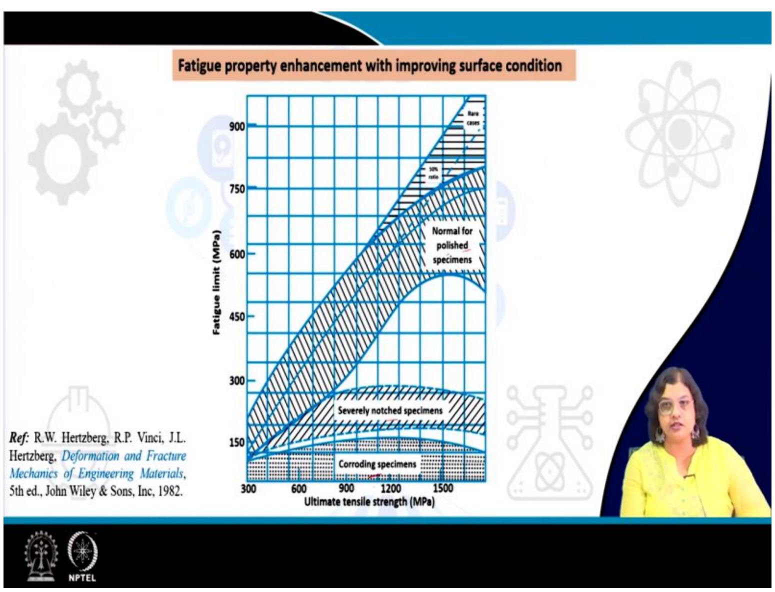

So this is another results that has been shown here. We can see that for the notched or corroding specimens, the fatigue strength is quite low. And this relation between ultimate tensile strength and fatigue strength, this direct proportionality is also not maintained. Rather, if we are polishing it, we can see that as we are increasing the ultimate tensile strength, fatigue strength increases.

Not only that, for any particular values of ultimate tensile strength, simply by polishing the specimen, we can achieve a higher fatigue strength because we are removing the scratches or any such defects on the surface, which certainly enhances the fatigue life and the fatigue performance of the material.

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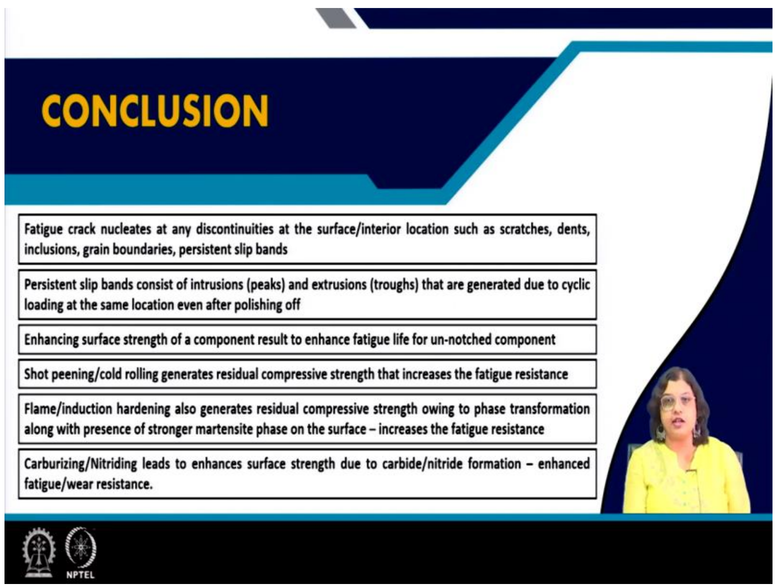

So with this, let us conclude this lecture with the following information that we have seen that fatigue crack nucleates at any kind of discontinuities or singularities at the surface or at the interior, and this could be scratches or dents or inclusions or grain boundaries or even persistent slip bands.

And persistent slip bands is the one which is a signature of fatigue deformation or cyclic deformation, and it consists of typically intrusions and extrusions, and it actually persists, so it comes back at the same location even if we polish it off and then again re-test it.

Enhancing the surface strength of the component by any measures actually increase the fatigue life of the unnotched component or fatigue strength or overall fatigue performance of an unnotched component. And one of the way to achieve higher surface strength is through shot peening or cold rolling that generates the residual compressive strength, and that increases the fatigue strength because it makes the crack nucleation very difficult.

On the other hand, we can also do flame or induction hardening that generates not only residual compressive strength into the phase transformation, but along with that, it also develops a martensite phase which has higher hardness and that also enhances the strength of the surface.

Carburizing and nitriding also lead to an enhancement in the surface strength due to this carbide and nitride formation, and owing to that, we achieve higher fatigue strength, higher strength of the surface, higher wear resistance, etc.

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