

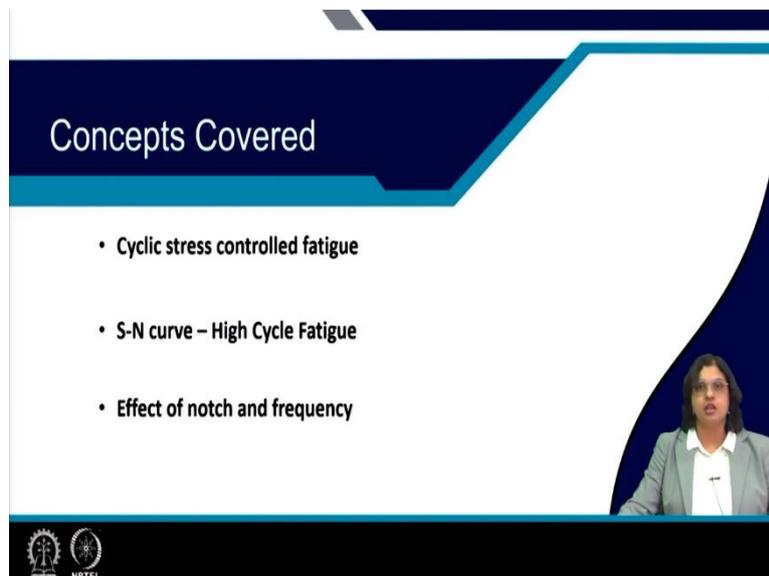
Fracture, Fatigue and Failure of Materials
Professor Indrani Sen
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Kharagpur
Lecture 31
Stress Controlled Fatigue

(Refer Slide Time: 00:29)



Hello, everyone. We are here at the 31st lecture of this course, Fracture, Fatigue and Failure of Materials. And we are continuing on the module two of this course on Fatigue.

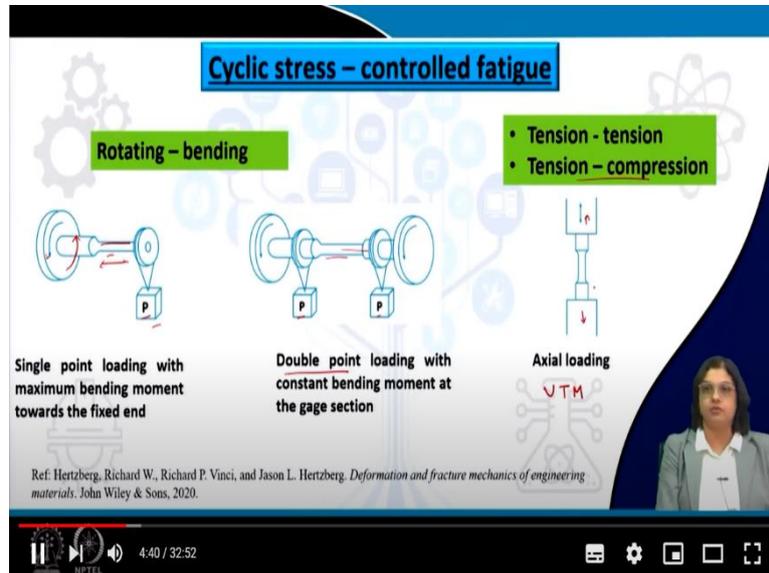
(Refer Slide Time: 0:39)



In this lecture, we will be talking about cyclic stress control fatigue and particular emphasis will be given on generating the S-N curve or the stress versus number of cycles for failure

curve, which is particularly used for high cycle fatigue estimation. And the effect of notch and frequency as well as mean stress on the fatigue behavior of materials will be also discussed.

(Refer Slide Time: 01:07)



So, let us see that how we can actually employ this stress-controlled fatigue mode during testing and how the kind of procedure that will be used for doing the stress-controlled fatigue test. So, we use typically two different kinds of instrument for doing the stress-controlled fatigue test.

First of all is the rotating bending machine in which you can see here that there are two different kinds of machines. In one case, we have the single point loading here. So, we can fix the specimen at this part and then one of the axes is being rotated. And then on the other end, we are applying a certain load so, we are basically hanging this load and this axle is turning and rotating and accordingly one section, one surface of the specimen which is under tension at one cycle will come to the compression side as it is turning to the lower end.

So, we are essentially having tension-compression cycles with R equals to -1 or the stress ratio as we have discussed in the last lecture is the ratio of the minimum to the maximum stress with a mean stress of 0 that will be obtained with R equals to 1 for this kind of rotating bending machine.

Similarly, instead of single point loading, we can also have the double point loading in which the specimen is supported at the middle and then on both sides we are applying certain load, some calculated load which can be converted to the stress values taking into consideration the bending moment and then the wheels on the two sides are rotating and once again the sample

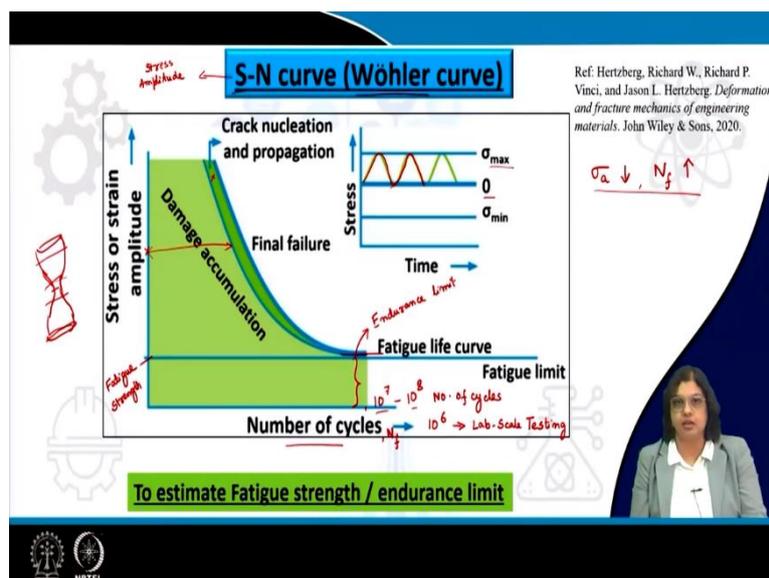
will be in the fatigue, in the tension compression mode, which means that R equals to -1 will be maintained.

So, that typically signifies the rotating bending machine for equal magnitude of tension-compression fatigue. On the other hand, we can also perform the fatigue test using the actual machine or the typical universal testing machine that is used for tensile and compression testing of materials, similar kind of machine having the capability of fluctuated loading, known as the dynamic machine can be used for doing the fatigue test in tension-tension or tension-compression mode, both ways.

So, if we are applying the tension-compression mode, certainly, we may use the compressive stresses of the same magnitude or of different magnitude. We can make any R value of negative values with that, or else what is important here is that we often need to perform the test in the tension-tension mode. As I mentioned compressive stresses are actually beneficial because it is acting in closing the crack or notch or so on, so, we often tend to avoid the compression part in certain cases.

Particularly, when we are talking about the notched fatigue then we may need to apply the tension-tension loading condition and that can be best served if we are using this actual loading. So, in this case the axis of the specimen is pulled or pushed depending on the kind of loading mode that we are using.

(Refer Slide Time: 04:48)



And eventually, what we are obtaining from this kind of testing is the S-N curve which looks something like this. The S here stands for the stress amplitude. As we have seen for the case of

fatigue, there are different kind of stress values which are of significance. Particularly, we have seen that there are stress range or mean stress or stress amplitude something like that. So, out of this stress amplitude is the one that is typically used for constructing the S-N curve. It is also sometimes known as the fluctuating stress.

The x-axis on the other hand signifies the number of cycles that the specimen has survived. So, you can see here, the stress versus time curve which shows this kind of loading that has been used. So, in this case, maximum load and zero load has been employed but we can use it in the tension-compression mode or tension-tension mode based on our requirement. And if such is the case, if the specimen is being employed with such values of maximum and the minimum stress we can find out the stress amplitude and then for that particular stress amplitude how many number of cycles a specimen can survive, that is of importance and that forms the x-axis.

So, basically such kind of S-N curve can be obtained by performing tests on many number of specimens. So, it is not just one test like the tensile tests we can do one specimen and we can generate a stress strain curve which is not like that, in case of fatigue, we need to test several specimen to construct one particular S-N curve. So, basically each test of a specimen at a particular stress amplitude will give us just one data point. For this particular stress amplitude, what should be the number of cycles.

Now, SN curve is also popularly known as Wohler's curve based on the found, the famous scientist Wohler who first found out this way of fatigue testing of materials, which was become very significant, especially when there was a series of railway track fracture has happened and scientists have understood the reason could be fatigue and they have found a way to assess the fatigue performance of the material.

So, what we are seeing here is that first of all as the stress amplitude decreases, which means if we are performing the test with decreasing values of stress amplitude, the number of cycles that the specimen can survive increases. So, that is certainly a very interesting fact. So, as the σ_a decreases number of cycles for failure often also termed as N_f because this signifies the total number of cycles till it fails. So, the N_f increases.

Now, this is quite expected as we are decreasing the stress amplitude obviously the possibilities for the damage to accumulate and lead to crack initiation as well as growth of the crack to final failure decreases and that means, that if we are decreasing the stress amplitude, it has the capability to survive for longer and longer number of cycles. So, this is what exactly is being seen here.

Also, you can see if we are looking into this curve carefully that when we are performing the test at certain stress amplitude let us say here, it is not failing right away. There is some number of cycles that it is surviving and this number of cycles are required for the damage to be accumulated. So, every number of cycles, every cycles that we are employing there is a infinitesimal change in the infinitesimal progression in the defect accumulation or damage accumulation that lead to the crack initiation.

So, basically major part of this total number of cycles till it fails is being used up for this damage accumulation part or the crack initiation part. Once the crack initiate, it hardly takes a few cycles to propagate to lead to final fracture. Since we are performing this test using the unnotched specimen as we have seen the typical hourglass kind of specimen, which does not have a notch in it so, we use a cylindrical specimen, something like this, which does not have a notch in it but it has a pronounced gauge section which is different in diameter compared to the grip section.

Of course, it does not have the extensive part or extensive length of this gauge section it simply forms a hourglass kind of configuration such that those are the regions from which fatigue crack is supposed to initiate, because the stress values here is pretty high compared to that in the grip part as the area is minimized for the gauge section.

But, the major number of cycles will still be used up in just initiating the fatigue crack, in this case, which will be seen here with all this number of cycles that it is able to survive. And then as we are decreasing the stress amplitude, the number of cycles for failure also increases as we have seen. So, what is important, what we can understand from such kind of test is how many number of cycles it can survive.

Now we can see that this is decreasing this relation is valid. Fine, but if we keep on decreasing the stress amplitude, it keeps on increasing the number of cycles. So, where to stop? What exactly, how many number of times do we really need to cycle this? So, for that typically for the case of the high cycle fatigue, we use a number of cycles something like of the order of 10^7 - 10^8 number of cycles, till it fails.

Often for the case of lab scale testing, we use this number of cycles as 10^6 also. Also, for depending on the requirement, service requirement, we mostly use the number of cycles, the limiting number of cycles to be 10^6 to 10^8 . So, that means that the stress level at which the stress amplitude level at which the specimen is expected to survive till 10^7 number of cycles that particular stress amplitude is known as the fatigue strength.

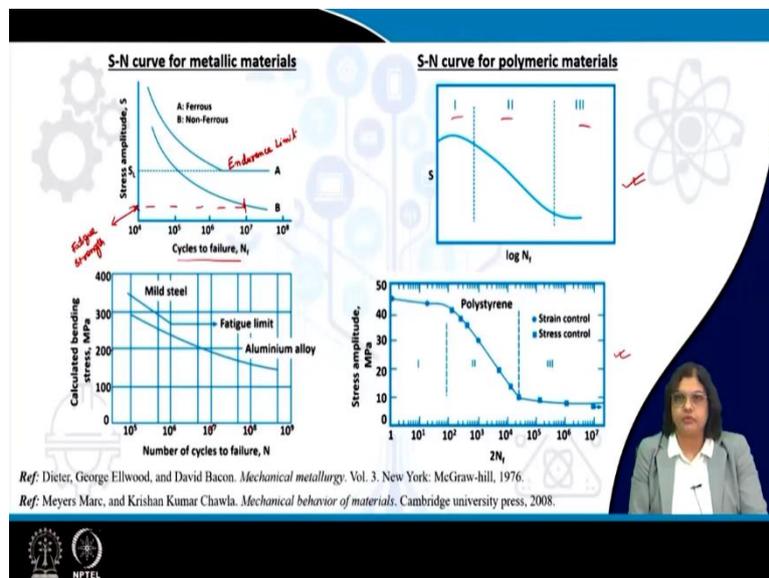
The typical nomenclature for fatigue strength is up to 10^7 cycles but again as I mentioned that based on the service requirement, or based on whether we are doing this on the lab scale testing, we often need to vary this or we do this testing from 10^6 to 10^8 cycles. But then, we need to mention or define, what do we mean by the limiting number of cycles.

For certain materials, particularly for ferrous materials, what we see is that this curve increases. I mean the number of cycles increases as the stress amplitude decreases up to a certain level and then there is like a straight portion of this curve. Now, this signifies the endurance limit, which means that if we are applying the stress amplitude level in this part like lower than this endurance limit, then the specimen is going to survive for an infinite number of cycles.

So that endurance limit is considered as a fatigue strength for certain materials. For those materials, which for the number of cycles keep on increasing like the curve is continuously decreasing trend is being followed, for such cases we define it on the basis of 10^7 or 10^8 or 10^6 of cycles. For other cases, which shows a distinct endurance limit, we consider that as the fatigue strength of the material.

So, the major purpose of generating the S-N curve is to estimate the fatigue strength or the endurance limit of the material.

(Refer Slide Time: 14:01)



And we can see here that for the case of the ferrous materials as I mentioned that we have a typical endurance limit that we can see here at this point and the fatigue strength is determined on that basis.

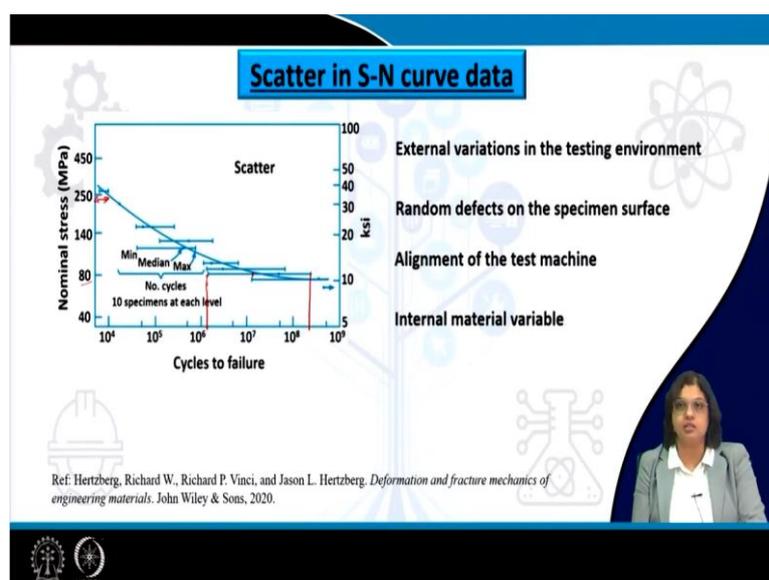
However, for the non-ferrous materials, if we are having a curve with a trend like this, which is continuously the number of cycles is increasing as we are decreasing the stress amplitude, we cannot keep this for really infinite number of cycles, that is not feasible practically. So, we will limit it up to 10^7 number of cycles or 10^{6-8} as I mentioned. So, the corresponding stress amplitude for 10^7 number of cycles which can lead to this failure so that stress amplitude is termed as the fatigue strength of that material.

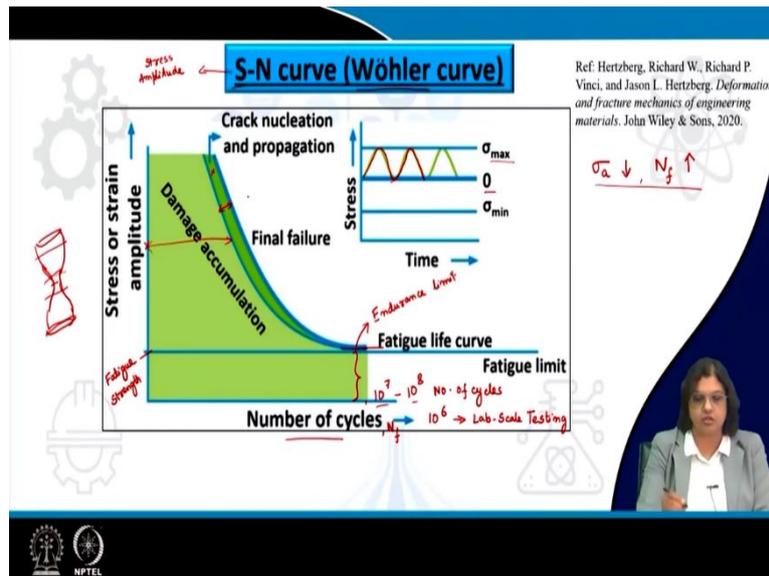
So, here you can see this fatigue test data practically experimentally done data for the mild steel as well as aluminum alloy. And we can see that for the case of mild steel there is a distinct endurance limit but for the case of aluminum alloy, that is not true. We do not get any particular value and either 10^7 or 10^8 can be considered as their fatigue strength.

For the case of polymeric materials on the other hand, they have different kinds of S-N curve and they typically shows a three-stage behavior, you can very well distinguish between the stage I, II and III the graph at the top here shows a schematic representation whereas the one at the down shows this for polystyrene.

Another thing which is relevant here for the case of S-N curve is to understand or appreciate that the x axis here, the cycles to failure are typically shown in the logarithmic scale. So, that we do not show this in the regular scale and we employ the logarithmic scale for the better understanding. So, this kind of typical curve are noted for the metallic system or the polymeric system and based on this we can figure out the strength of the material.

(Refer Slide Time: 16:29)





Now, if we have looked into the curve carefully, we have also seen that there are more than one line that we have shown. Let us look back the curve. So, we can see that there is a span over which this data has been shown. So, this is basically the scatter in the data. Typically, for each test, for each particular stress amplitude, several number of specimens are tested.

And this is particularly to figure out the scatter in the data fatigue data particularly for the high cycle fatigue data are very well known for the existing scatter in the results, which means that for the same kind of specimen having similar dimension, same material, everything remaining same, if we are performing the test at a particular stress amplitude, then also the number of cycles that specimen, let us say we are doing performing the test and three specimens A, B, C of the same material, same specimen dimension, same stress amplitude, then again, this A, B and C will survive for different number of cycles.

And sometimes this number of cycles spans over really an order of magnitude or even more so, we cannot simply ignore that or take the average of this value. So, we have to find a way to assess or estimate the stress amplitude which is of relevance there. So that is the reason that typically fatigue tests are done for multiple specimens for at the same particular stress amplitude level.

So that means if we want to construct or to generate one S-N curve, we first of all need to do the test at several stress amplitude values. And then for each of these values, we need to perform several number of tests just to take care of the scatter in the results. We can also see here that at the highest stress amplitude, the scatter spends only this much.

However, if we are decreasing the stress amplitude, the number of cycles definitely increase but there is a huge span in the data, you can see for this one here we are getting so that is for the stress amplitude value of 80 and we are getting life of 10^6 . So somewhere here till 10^8 .

So, on the basis of this, if we are concluding that this kind of stress level is enough, so that it can get more than 10^7 number of cycles. This may not be true, there could be one specimen which can fail at a stretch, at a life cycle lower than that. And if such things happen in service, we cannot take chances we are talking about fatigue which is of higher concern for something like aircrafts or bridges. So, we really cannot take chances.

Also, for the case of failure analysis, as I have mentioned earlier also that we prefer to have a conservative value, a lower bound value, so that under no circumstances, the specimen, the structure the component is expected to fail. So that makes finding the fatigue strength or finding the exact stress amplitude level at any number of cycles or vice versa, like if we are fixing the stress amplitude level then the exact number of cycles specimen can survive, finding that is very much challenging.

So, the typical procedure followed as per the ASTM standard again we take help further from the ASTM standard for any kind of testing for mechanical testing also. So, what is typically been practiced here is to consider the median values, if we are doing let us say three specimens and at each particular stress level, we consider the median value and then a range is also been quoted. So that means that it is a mandate for fatigue testing to perform multiple tests and at any particular stress level, before we can conclude or before we can have a remark about the fatigue strength or fatigue life of a material.

Now let us look into the fact that why is there so much of scatter in the S-N curve or in the fatigue data. We have seen that for the case of any kind of mechanical testing for that matter, even tensile testing or also for fracture toughness testing, we prefer to do multiple tests. And again, this is always necessary to do multiple tests at each particular condition just to understand how much scatter in the data is. But fatigue is particularly known for scatter. And the reason for this is the following.

First of all, there could be any external variations in the testing environment, if we are doing this at a particular temperature, let us say in a summer country, we are doing this at a higher temperature and someone at other part of the world is doing this at a comparatively lower temperature or maybe I am doing this at a one particular month of the year and then maybe repeating the test at some other month, when the temperature is different, that may also have

some influence, may not be very magnificent one but it may still have some influence on the total fatigue life.

So that is mostly the external variations or any other kind of environment changes that may happen. For example, the humidity or any such things which will actually facilitate or avoid the initiation of the crack or the face of the unnotched specimen. But the most important reason for this scatter is the defects that are present on the specimen surface. That is one of the reason that when we, although we use the unnotched specimen we try to make this as smooth and as well polished as possible.

So, it is very, very important to polish the specimen to the maximum extent to have a mirror finish to avoid any presence of any kind of scratches or machining marks or dents on the specimen surface. If there are any such non-uniformity on the surface, as I mentioned, that fatigue particularly the cracks start from the surface so, if we have the specimen which has any kind of discontinuity on the surface, those should be the area or the possible sites from which fatigue crack will initiate.

So, this is one of the reasons that it is very difficult to manually ensure that if we are doing the three tests, for example, what we have shown for the stress level or stress amplitude level of a 80 MPa it is a no way we can understand or we can quantify that all the three specimens A, B, C which has been tested at 80 MPa has the same number of defects at the surface, which is almost impossible to figure this out and that leads to a huge scatter.

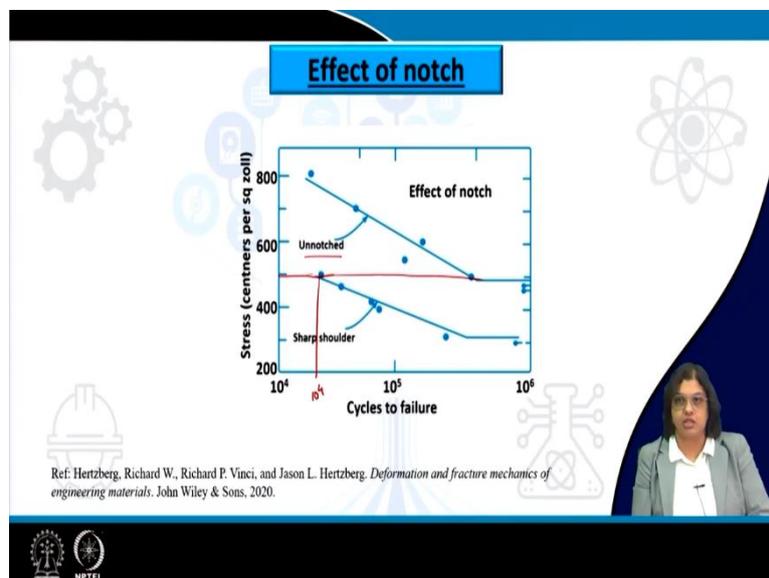
And even if we do, even if we polish it to the maximum extent, when we are talking of using this information for practical application, we do not know how well polished that could be, there could be some kind of stress concentration also, some stress raisers that can lead to the fatigue failure. So, we have to do this multiple tests to ensure that, that can be taken care of.

This is also another very important factor that the alignment of the test machine in case of the rotating bending machine more or less this is quite uniform and that is why it is preferred to at least reduce the scattered level based on the machine alignment, but this is of particular significance when we are talking about the axial method like the UTMs. So, any kind of misalignment for the grips of the which are used for connecting the specimens to the instrument, if there is any such even minor misalignment that can lead to a scatter in the results. So, we have to be extra careful for that.

And also, it is possible that there could be some material defects which are present in the inside like the internal variables, which can lead to a scatter in the results, but amongst all those factors, the surface defects are the most challenging one. There has been studies which showed that once we generate a curve like this, we should be able to figure out the importance of these defects or the contributing external factors that has led to the fatigue.

But for any such cases, it is also important to understand or appreciate that when we are using this in service, we are not sure of whether there could be any such external defects or any such misalignment in the system so that that can lead to the fatigue, early initiation of the fatigue crack. So, we have to be very, very cautious about that.

(Refer Slide Time: 25:47)



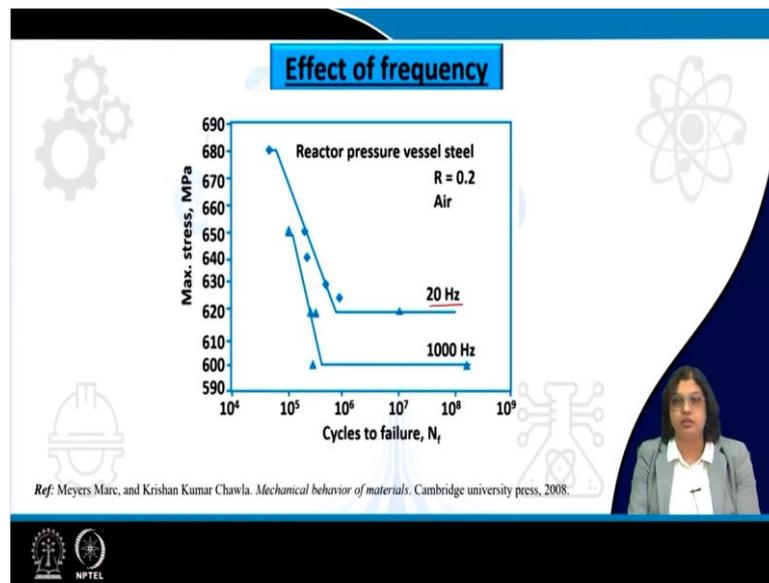
Now, if there is a notch, any kind of notch in the specimen or in the actual component, that will certainly affect the fatigue behavior of the material. In case there is no notch there like the unnotched specimen that we had used for the lab scale testing you can see that the fatigue strength is quite high for any number of cycles.

On the other hand, if there is any kind of discontinuity or notch, that can significantly decrease the fatigue strength or the fatigue life at any particular stress amplitude. So, this is also very, very important that we have to consider this for practical application that whether there is any such kind of stress concentration or not. If there is then we have to perform the experiment also on the notch specimen or we have to maintain some other factors or parameters there.

Again, there are protocols for this also to use the, to perform the notch fatigue and we can use that. But overall, we can see that for example any stress level, if we are talking about stress

amplitude of 500 MPa we can see that for the case of a notched one it gives a life of only 10^4 , something multiplied by 10^4 , whereas, for the case of the unnotched one, it leads to almost 10^6 life or more than that. So that is like the fatigue strength for the unnotched specimen, but for the notched specimen that is not sufficient to achieve the 10^6 life so, we again need to be careful for this.

(Refer Slide Time: 27:33)



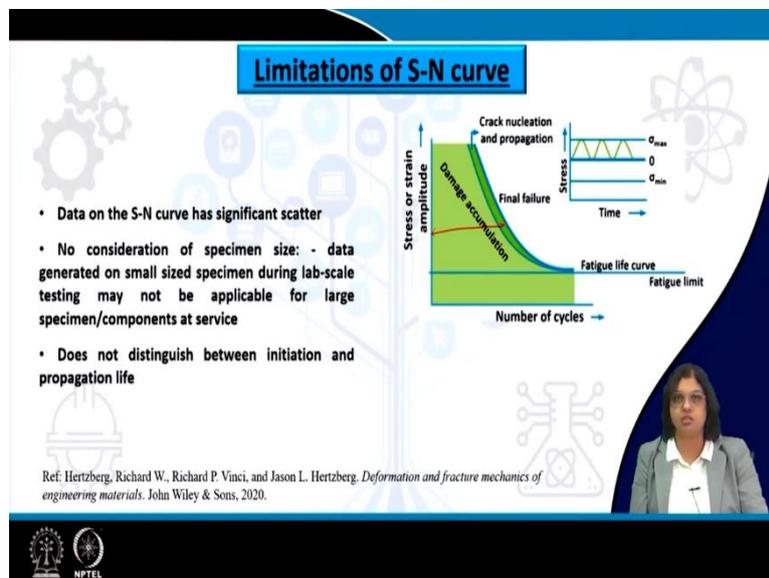
Now frequency of testing also has a big role to play. When we are talking about high cycle fatigue and we know that the specimen needs to be survived for 10^7 , 10^8 or 10^9 number of cycles we also tend to do the tests, perform the tests at a high frequency so, that we can cut down on the number of hours for the entire test.

Now this is particularly relevant when we are talking about lower stress amplitude, when we know that at such stress amplitude each of the specimen need to survive for 10^7 number of cycles. And we also know that we need to do multiple number of specimens. In most of the cases, fatigue test goes on for 40, 50 hours. So, which means like more than a day, sometimes more than two days, and it is often difficult for the UTM to be continuously or the rotating bending machine for that matter to be continuously run for that many number of hours. So, we prefer to perform this at higher frequencies.

That is fine, as long as we are using a reasonable frequencies. Let us say in this case it is shown for 20 Hz, we often perform this at even much higher frequencies like 200 Hz or so. Particularly, for the metallic system, it may vary for different materials as well. But if we are doing this at a very, very high frequency, not only to save the time, but also to appreciate the behavior at the very high frequency conditions.

Often application requirements are such that it needs to be survived very high frequency loading. So for that if we are doing this at high frequencies what happens is that, there is some internal heat buildup, a diabatic heat buildup because of this high frequencies, it has been continuously loaded, unloaded, loaded in the opposite directions and with that the heat that develops there, that generates there that leads to a variation in the dislocation motion also, in case there is any plastic deformation, and that may lead to the change in the behavior and what we are seeing here once again, that when we are talking about higher frequency that leads to lower fatigue strength, or lower life. So, that is also of concern, that one should be careful about fatigue tests, should not be done at very, very high frequencies.

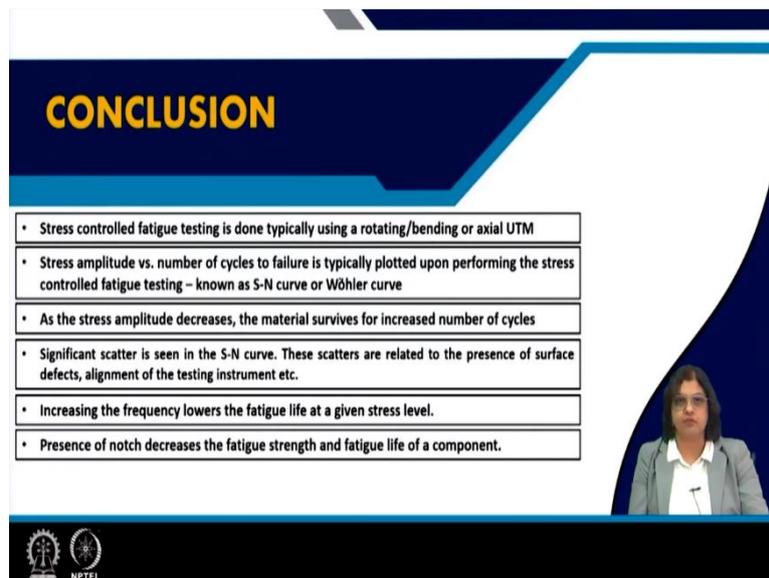
(Refer Slide Time: 30:08)



So, all this kind of makes some of the limitations of S-N curve or the Wohler's curve is based on the significant scatter that we get on the S-N curve, which we have to be carefully consider and also the specimen size is not being considered. We have seen this earlier also that the data generated on small size specimens may not be always the same that it may give for a bigger specimen and that is not very well taken care of in the construction of the S-N curve. And also, is not capable of distinguishing between the initiation and the propagation met.

Most of the, we only know that most of the number of cycles will be used for the initiation of the crack and it hardly requires a few cycles for the propagation of the crack, but it is not suitable for determining the crack growth rate or to quantify the number of cycles, the exact number of cycles that is required for initiation and the propagation. Of course, that is not much of an issue considering that we are doing this on the unnotched fatigue and the entire fatigue life is what is important here. So, that is what is appreciated from the S-N curve.

(Refer Slide Time: 31:25)



CONCLUSION

- Stress controlled fatigue testing is done typically using a rotating/bending or axial UTM
- Stress amplitude vs. number of cycles to failure is typically plotted upon performing the stress controlled fatigue testing – known as S-N curve or Wöhler curve
- As the stress amplitude decreases, the material survives for increased number of cycles
- Significant scatter is seen in the S-N curve. These scatters are related to the presence of surface defects, alignment of the testing instrument etc.
- Increasing the frequency lowers the fatigue life at a given stress level.
- Presence of notch decreases the fatigue strength and fatigue life of a component.

NPTEL

So, let us conclude this lecture with the following points that stress-controlled fatigue testing is done typically using rotating bending or axial universal testing machine. And stress amplitude versus number of cycles to failure is typically plotted upon performing the stress-controlled fatigue testing. So, this is known as the S-N curve or the Wohler curve.

As the stress amplitude decreases, we have seen that the material survives for increased number of cycles. Now for the case of high cycle fatigue, this number of cycles, the limiting number of cycles is typically considered between 10^6 to 10^8 and the corresponding stress amplitude level for such number of cycles is considered as a fatigue strength.

In any case, significant scatter is seen in the S-N curve, and these scatters are related to the presence of particularly surface defects, alignment of the testing instrument or presence of any other internal defects as well. We have also seen that increasing the frequency, lowers the fatigue life, at any particular stress level, and there has been also noted that the presence of notch further decreases the fatigue strength and fatigue life of a component.

(Refer Slide Time: 32:45)

REFERENCES

Hertzberg, Richard W., Richard P. Vinci, and Jason L. Hertzberg. *Deformation and fracture mechanics of engineering materials*. John Wiley & Sons, 2020.

Meyers, Marc André, and Krishan Kumar Chawla. *Mechanical behavior of materials*. Cambridge university press, 2008

Dieter, George Ellwood, and David Bacon. *Mechanical metallurgy*. Vol. 3. New York: McGraw-hill, 1976.

Elements of Fracture Mechanics by Prashant Kumar, Tata McGraw Hill Publication

Fatigue of Materials by S. Suresh, Cambridge University Press publication



Following are the references that have been used for this lecture. Thank you very much.