Fracture, Fatigue and Failure of Materials

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Lecture 36

Strain Controlled Fatigue (Contd.)

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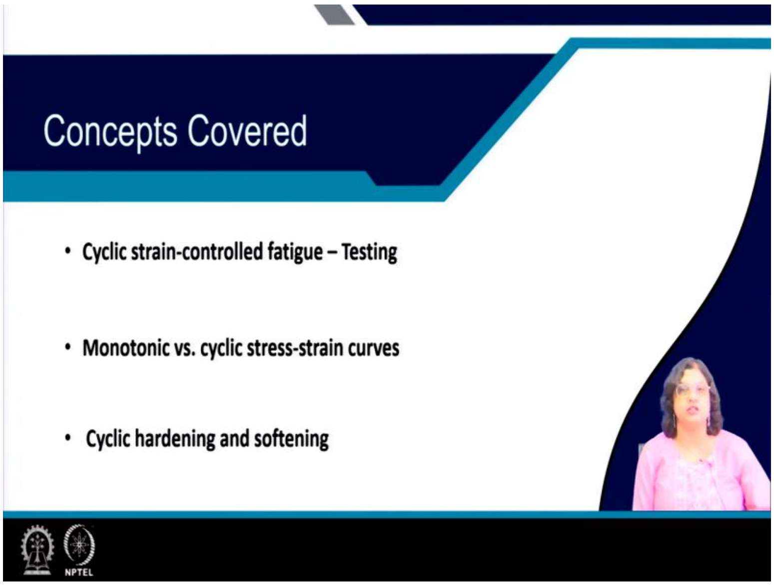

Hi there, we are at the 36th lecture of this course Fracture Fatigue and Failure of Materials and in this lecture also we will be continuing the strain control fatigue. The particular topics that will be covered in this lecture are the following we will be talking about the different modes of testing by which the strain control fatigue can be determined at the lab scale and from there we will also try to distinguish between the cyclic stress strain curves that we are generating from the fatigue test versus the monotonic stress strain curve that we can generate from the simple tension or compression test.

So, what are the major differences and what could be the reason whether we can predict those kind of differences in advance without even doing the test those kind of topics will be discussed in this lecture. And we will be also talking about cyclic hardening and softening we have already introduced the concept of hardening and softening and the cyclic loading and in this lecture we will see that what are the actual reasons for those.

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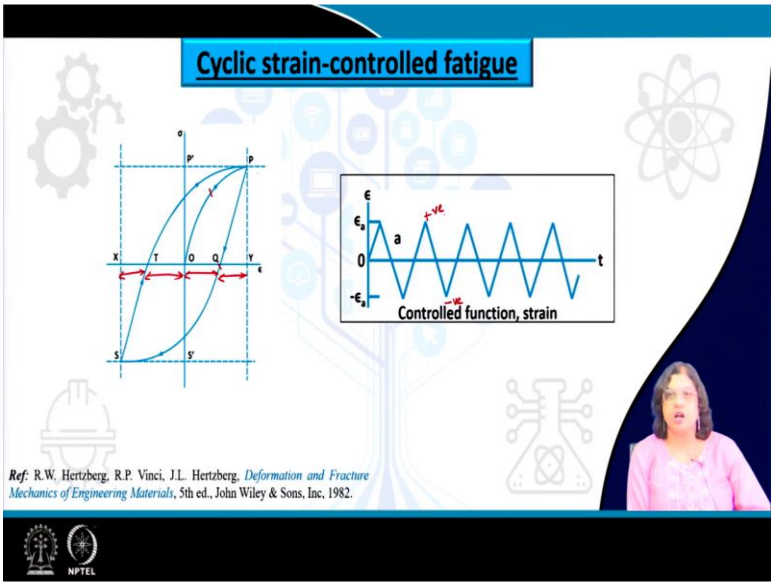

So, let us begin with where we have left in the last lecture about the fact that when we are doing Cyclic strain control fatigue we are typically applying the stress level which is exceeding the yield point of the material such that there is some amount of permanent deformation in the specimen and when we are unloading we are coming back to the point Q such that we have some amount of elastic recovery certainly this Q y and X T are the sections of the strains which can be recovered elastically but this entire section T O Q is what has been already deformed plastically.

So, permanent deformation. Now, this is for one cyclic of tension and the compressive loading we can get a hysteresis like this and that can be attained if we are applying strain versus time cycling. So, in this case we have seen that there are several cycles on which we are applying some particular values of strain in the positive direction and similar magnitude of strain in the negative direction. So, tension and compression and this we are doing for several number of cycles and eventually after hardening and softening we are supposed to get a stabilized stress strain curve which looks something like this. So, this kind of stabilized hysteresis loops we can we should see.

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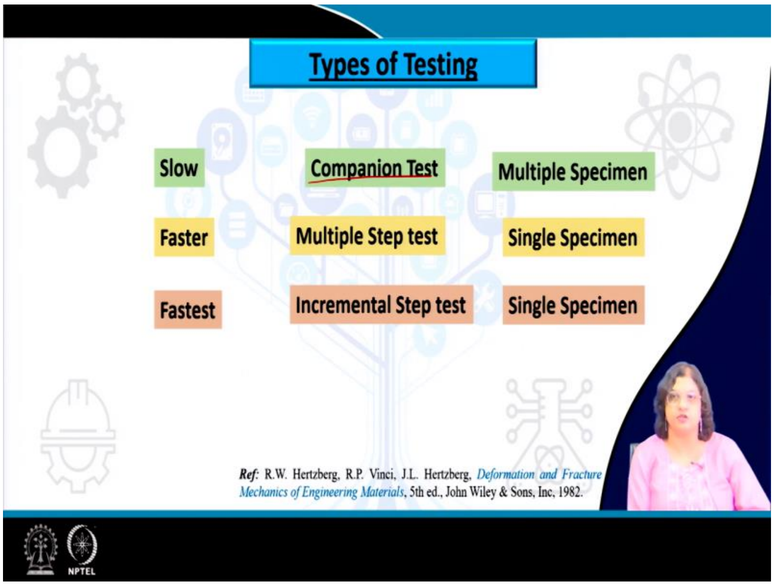

Now let us talk about the different modes of testing by which we can attain that. The first one which is a very simple method of doing that is known as the Companion Test in this we use several specimens all tested one by one at different strain amplitude and we can get the corresponding stabilized stress strain hysteresis loops for each of this particular strain amplitude and later on we can figure out the cyclic stress strain behavior from a series of such kind of testing.

So, this typically uses Multiple Specimen and as a result since it uses more number of specimens the overall results that we are getting is quite slow which means that to get one cyclic stress strain curve we need to use several specimens and certainly the result can be obtained only after doing some valid number of tests. So, that is a slower process.

A little bit faster process is Multiple Step Test in which for each specimen. So, we use a single specimen in this case and we used different blocks of loading having different stress amplitude for each of this block on the same specimen itself and we get the hysteresis loops for each of the strain blocks the stabilized hysteresis loop and from there we can determine the stress strain curve in the cyclic loading condition.

But the first test amongst all is also based on a Single Specimen which is known as Incremental Step Test method in which we apply different blocks of loading but within each block the strain amplitudes are being varied in an incremental fashion and in turn we are getting the stabilized hysteresis loops or stress strain curve for each of the different strain amplitude and from there we can determine the cyclic stress strain curve of a material. So, let us see one by one how we are attaining different kind of test.

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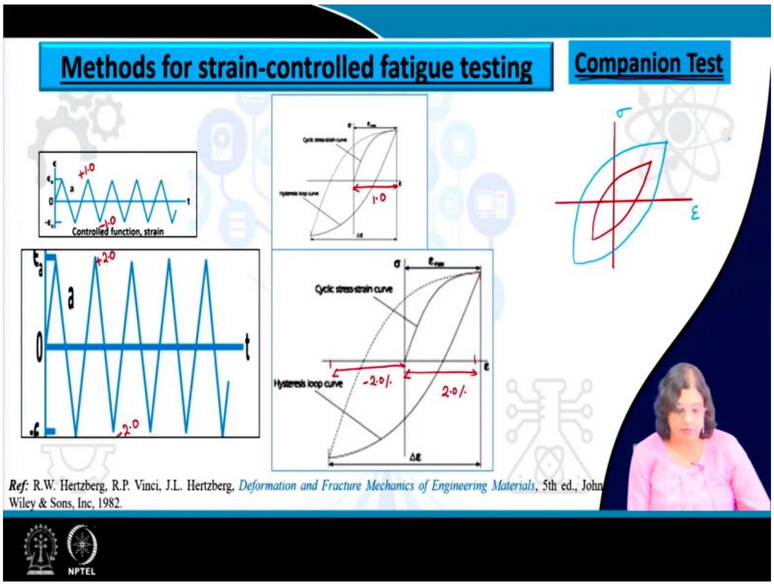

So, in the first case the companion test what we do for each particular specimen let us say we are applying strain versus time cycle of something like this when we are applying some arbitrary strain number I am giving. So, this is let us say 1 % of positive strain and minus 1 % of negative strain and this we are repeating for n number of cycles and after certain number of cycles after the initial hardening or softening phases has passed for several or maybe within some hundred number of cycles we are supposed to get some stabilized hysteresis stress strain behavior.

So, something that looks like this, on a similar fashion we can take a second specimen and on this we can apply a higher values of strain. So, let us say we are applying a strain value of 2 % and minus 2 % in this case. What should be the exact strain amplitude that depends on the behavior of the material the deformation capability of material and the yield strain of the material. The strain should be above the yield point of the material.

So, we should apply such kind of strain. So, these are just the numbers 1 % to 2 % that I am using here to illustrate the things. So, in this case since we are applying higher values of strain amplitude certainly the hysteresis loops will be much more bigger and wider in this case. So, we are getting a total strain something like 2 % in the positive direction and again minus 2 % in the negative direction. That is in comparison to what we have got here as 1 % and minus 1 % for the previous case.

Now, if we are plotting this together, what we can see is both the hysteresis loops in a single reference and what we can see here is let us say this is for the 1 % strain and so this could be for the 2 % strain. So, if we are plotting this for multiple number of specimen. So, we should be able to find out the overall cyclic stress strain behavior. So, this is quite straight forward simple yet it needs a number of specimens and this often is restricted by the availability of material as well as the time constraint.

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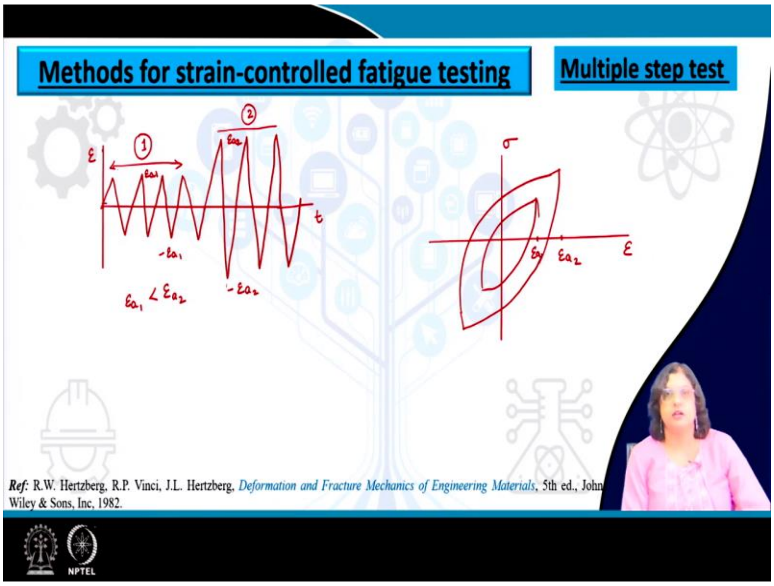

So, let us now focus to the next method. So, in the Multiple step test method what we do is we apply the strain versus time plot in several blocks. So, initially let us say we are applying some particular values of strain versus time for certain number of cycles to make it one block and next we can apply a different magnitude of strain amplitude again for certain number of cycles. So, that we attain the stabilized hysteresis loop.

So, let us say this is strain versus time and the first one here is having a positive and negative strain amplitude of ε_{a1} and minus ε_{a1} as well as the second block. So, let us name this as 1, this as 2, here we can see that the strain amplitude level is quite high compared to the previous one.

So, if we do that even for the single specimen we are supposed to get the hysteresis loops once again for both of this block separately something like this, this is for the condition 1 and this is for condition 2. So, this one here correspond to E_{a1} as well as this one here as E_{a2}. So, this is just the free hand representation which shows that if we are doing the test at some particular strain amplitude level for several number of cyclics we are expected to get the stabilized hysteresis stress strain behavior.

And if we get stabilized value we have seen this in the last lecture also that since the data points will be repeating the same values again and again. So, we are going to get a very strong signal, very strong points there which we can easily differentiate from the rest of the curve in the final stress strain behavior. So, that is how we can figure out the stabilized hysteresis stress strain behavior for each of this strain amplitude block and we should be able to figure this out.

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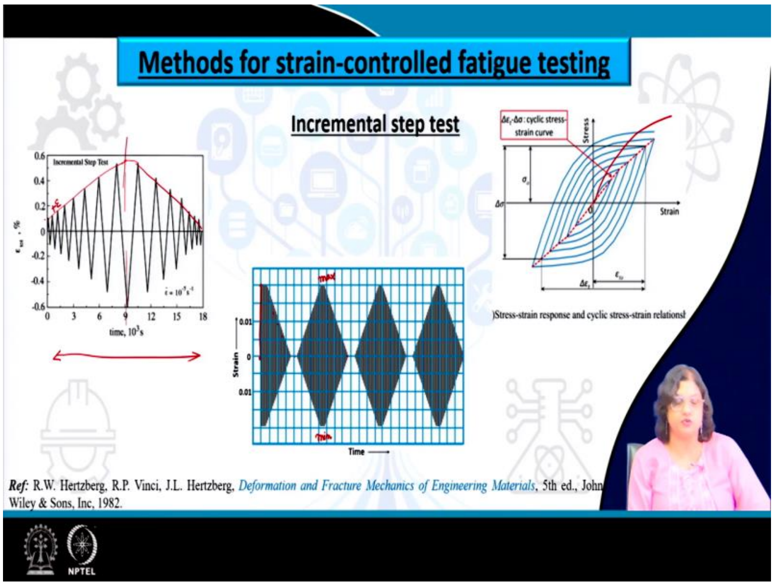

The next method which is the most commonly used one and the most smartest method is the incremental step test. So, what is done here is that for each single specimen we use a block of strain amplitude and each of this block contains consist of several steps. So, it starts with very low values of strain plus and minus and then it keeps on increasing. So, that is why the name is incremental. So, it keeps on increasing up to a certain level and then it gradually keeps on decreasing.

So, we get a this kind of rhombus kind of shape and we can find this out that how the cyclic deformation behavior of a material changes if we apply like this. Now, if we are doing this for one particular block nothing will happen to the specimen it is not supposed to break and we have to keep this, we have to repeat this kind of block sequence for several number of times.

So, that for each condition. So, each particular value of positive and the negative strain we should get the stabilized hysteresis loops. So, if we are successfully doing that we should be able to get the overall stress strain hysteresis loops for different stress amplitude different strain amplitude from one single specimen.

Now, this is not all, we are even smarter to use it one particular specimen to even understand the monotonic behavior versus the cyclic behavior just from one single test. So, let us see how we can do that what we actually do is we split it into half and we start the test from this half here. So, from zero we apply the maximum monotonic tensile stress or strain at the very first cycle itself and from there we keep on decreasing the strain amplitude at every cycle until it comes to zero or not actually zero it should have some positive value.

So, that it is not shifted from its position it is the position is still maintained and then we start the next block again starting from 0 with gradually increasing up to the maximum point and then gradually decreasing till the minimum point and then coming to almost 0 value please remember we are not going to full unloading rather a very finite, very small yet finite value of positive strain is typically applied. So, that the position is not lost.

So now, why do we do that, the reason is that if we are starting from 0 to the maximum strain amplitude value. So, that is nothing but a monotonic tensile test, that is the first cyclic and we are we are starting from 0 till the maximum value. So, whatever result stress strain response that we are getting for this particular cyclic that is actually the monotonic behavior of the material and if we keep on repeating such kind of block behavior for several number of blocks then we are going to get the stabilized stress strain hysteresis for each of this different strain amplitude level and eventually we get the curve something like this.

So, we get the monotonic curve also which could be somewhere here as well as the cyclic stress strain curve also and from there we can also understand not only the cyclic strain behavior but the difference between the monotonic and the cyclic strain behavior. So, that is the reason that incremental step test is often preferred than any other low cyclic fatigue test because we can use one single specimen, we can we actually require much lesser amount of time to complete the test.

So, which should not be very much expensive as well if you are thinking about the industrial perspective and along with that we should be also able to figure out the differences between the monotonic or quasi static testing versus repeated cyclic testing and all this can be understood from one single test.

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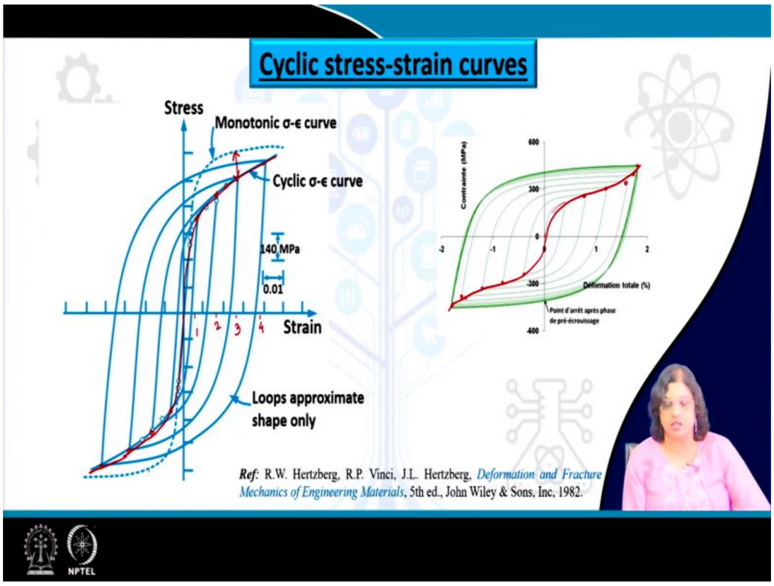

So, let us see how we are actually plotting the cyclic stress-strain curve. So, whichever way we are doing the test whether be it a companion test specimen or a multiple step test or incremental step test for each different strain amplitude we need to have stabilized hysteresis stress strain behavior. So, these are what is shown here and you can see this for each of these cases we can get the hysteresis loop.

So, this is for one particular value of strain, the second one is here. So, let us name this as 1 2 and 3 as well as 4 and if we are joining the locus of this hysteresis. So, for each of these cases then we should be able to find the cyclic stress-strain curve. So, cyclic stress-strain curve is determined if we are joining the origin with this locus of the tips then we should be able to find the cyclic stress-strain curve and along with that in case we are doing the incremental step test then we should also get the monotonic stress strain curve from the very first cycle itself.

So, that means that there has not been the specimen has not been cycled before that. So, that is the first test that we are doing. So, that signifies the monotonic behavior or the tensile behavior particularly the tensile one because when we are talking about the compressive section of that first cycle that means that we have already applied the tensile load and then we are moving to the compressive part.

So, that one is not any more monotonic one. So, this one here the compressive section is not any more monotonic but the tensile one is because that is the first cycle. So, this dashed line here signifies the dashed curve signifies the monotonic stress strain behavior and we can very well see that these two are not matching exactly. So, there are some differences between the monotonic and the cyclic behavior and we can find that out.

So, here is the experimental results of some material where you can see that the test has started from 0 and we are getting the hysteresis loops, hysteresis stress strain curve for several points and if we can simply join the locus of this we should be able to find out the cyclic stress-strain behavior of a material. So, that is how cyclic stress-strain of a material is determined

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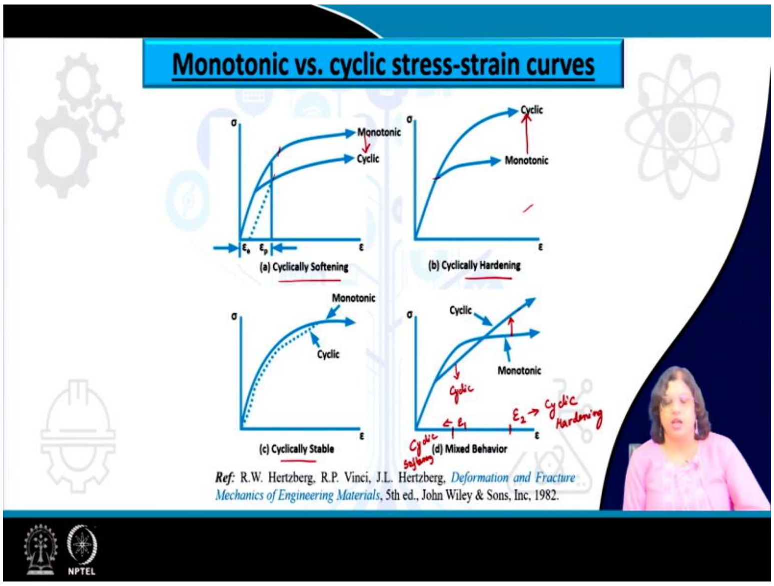

Now, as I mentioned that in case there is a difference between the monotonic and the cyclic part that could be apparent from the hardening or the softening behavior. So, hardening or softening behavior is simply what we have seen previously that if we are applying the same values of strain versus time at every cycle yet the stress response could be different it can either increase with time for certain number of cycles.

So, that is nothing but the hardening behavior in case the stress value decreases that means the softening behavior and when we are getting the stabilized relation actually that means that whatever hardening softening mechanisms were active that has come to a halt that has been stabilized and now we are getting the stress strain curve which is not going to change for any number of cycles until the defect or any kind of crack that has been initiated that can lead to total fracture.

So, if we are comparing that with the initial behavior or the tensile behavior or the monotonic behavior we can understand the difference between the two and we can figure out that whether the material is prone to undergo cyclic softening or cyclic hardening. So, here are the four examples shown and if we need to figure out that what is the cyclic stress value at any particular strain we can do so and we can also find out the difference.

So, the first one here signifies the monotonic curve being above the cyclic curve. That means that there is a reduction in the stress strain behavior or the stress values due to cyclic loading. So, that is nothing but cyclic softening that we have seen here. Now, often if we try to quantify this value that like up to what extent the cyclic softening is active we typically can do this based on the yield point behavior or 0.2 % offset strain.

So, based on 0.2 % offset strain we can figure out the yield point under monotonic loading and under cyclic loading and then the difference between the two can quote the extent of cyclic softening or hardening. The second one here shows the cyclic hardening behavior where we can see clearly that up to the elastic part there is not much of a difference but in the plastic part typically we see that the cyclic stress strain curve is above the monotonic one and in this case from the monotonic one we have a significant enhancement in the cyclic stress strain behavior so certainly this signifies the hardening.

In some cases, we have seen this in the last lecture also where the hysteresis stress strain behavior almost matches with the monotonic and the cyclic one and this is what is known as cyclically stable. So, that means that the stress strain variation is not going to change if we are doing the cyclic or the fluctuated loading and this is what is seen here in this diagram where the monotonic and the cyclic there are some differences but not those are very nominal and there is not a very distinct differences between the monotonic and the cyclic behavior.

And then there could be mixed behavior also when if we need to figure out that whether this material undergo cyclic softening or hardening we need to ask the other question that what kind of strain are we talking about if we are talking about a strain something like this you can see that the cyclic part here. So, this one is the cyclic stress strain curve.

So, for a strain value of this let us say ε_1 we see that the cyclic stress strain curve is beneath the or below the monotonic stress strain curve. So, here what we can see is cyclic softening but if we are talking about a higher value of strain let us say ε_2 then we can understand that in this case the cyclic stress strain curve is above the monotonic one and that means that this one shows such a value of strain actually shows cyclic hardening.

So, for such materials which undergo this kind of mix behavior it is very very important to appreciate that what kind of strain levels it is being will be used in service and based on that only we can determine the kind of stress strain behavior it may have under cyclic loading.

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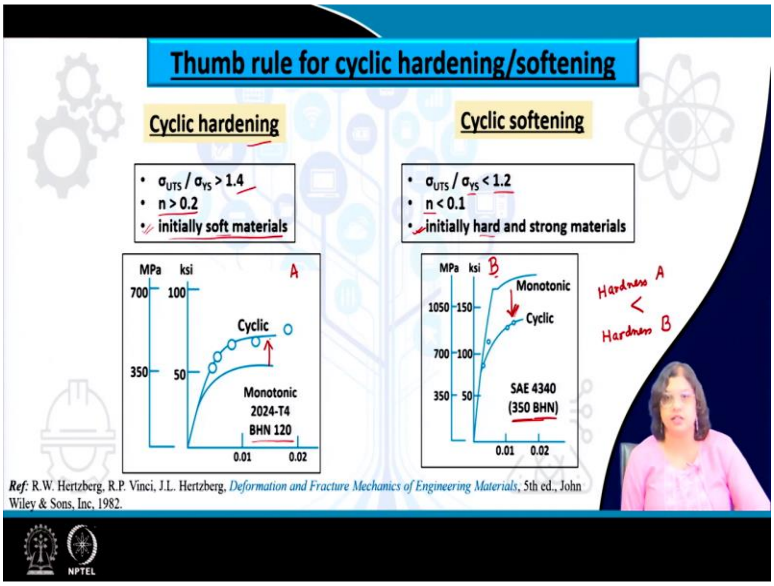

Now, that is not enough we understand that there could be hardening or softening just because of the cyclic loading but then our next target will be to find out if there is any way by which we can predict that in advance. So, there are some thumb rules based on which the cyclic hardening or softening behavior can be predicted even without doing the fatigue test that will certainly be very very helpful that will save the cost also that we do not need to do the test and we can have some idea that whether this material is supposed to undergo hardening or softening if we are repeating the test.

So, based on that understanding we can use it for certain application if we know that this is this one is prone to undergo cyclic loading. So, cyclic hardening can be seen in such material for which the ratio of the ultimate tensile strength to the yield strength of the material exceeds 1.4. So, in case the difference between the ultimate tensile strength and the yield strength is quite high. So, that means that the strain hardening exponent is also quite high.

So, that means that if n value strain hardening exponent is greater than 0.2 that kind of material can show cyclic hardening and most interestingly there is another clause the third clause which is very very interesting and important which says that initially soft material is bound to get hardened by cyclic loading.

On the other hand in case of cyclic softening whenever this ratio of ultimate tensile strength through the yield strength of the material is less than 1.2 such kind of material can show cyclic softening in other words in case the n value the work hardening exponent or the strain hardening exponent is less than 0.1 that kind of material is expected to show cyclic softening or again the very interesting and important point here is that the materials which are initially very hard and strong, initially means one which has not been cycled.

So, one that is not being cycled but still it is hard or soft that can be understood from the monotonic behavior of the material. So, that means that whichever material under monotonic loading is soft that is bound to get hardened after cyclic loading or the one which is hard initially that means under monotonic tensile loading that is giving us a good number of hardness that is supposed to get softened due to cyclic loading.

So, here are some example you can see here that for this particular material, this is the cyclic curve with the data points the circular data points as well as the beneath one is the monotonic one. So, obviously due to cyclic loading we have seen that there is some hardness. So, this comes under this category of cyclic hardening. Now, what we are seeing here is that the BHN number, BHN is the Brinell Hardness Number is 120. Now, in comparison there is another material for which this BHN number is 350. Brinell Hardness Number is 350. Obviously this specimen B and this one is A let us say.

So, specimen B has higher hardness. So, hardness of B is let me write it here. So, hardness of A is actually less than hardness of B and what we are seeing here is that for the case of B although it is initially harder it actually undergoes cyclic softening. So, this is one example of a particular material which we can which we have seen that if the hardness is lower which means softer materials it is prone to undergo cyclic hardening. On the other hand, a harder material is expected to undergo cyclic softening.

So, this makes it very very interesting but the question of course that comes to our mind is why what exactly is happening. So, let us understand this on the basis of the dislocation movement. Now, what happens in an initially soft material is that, that material is prone to undergo deformation that is why it is soft because its resistance to plastic deformation is not much.

Now, when we are repeatedly loading it, one which is prone to undergo easy deformation means that there are enough number of dislocations already if we are repeatedly loading it, loading it and unloading it and all then there will be more and more number of dislocations that will be generated and that due to this repeated loading and that too with changing of the direction that will lead to an entanglement of the dislocations and because of that due to cyclic loading they are supposed to get hardened.

On the other hand if we are having an initially hard and soft material means that there could be more number of dislocations but those dislocations are unable to move they are either interlocked or there is a pile up or something like that and in this case if we are repeatedly loading it we are actually providing more and more time for it for the dislocations to get rearranged since we are moving in the back and forth direction it will be easier for the dislocations to rearrange get away from this entanglement and that makes it quite easier to deform.

So, that is a reason that initially hard materials which have initially entangled dislocations now after cyclic loading has this rearrangement of dislocations which makes them easier to move and makes it softer under cyclic loading.

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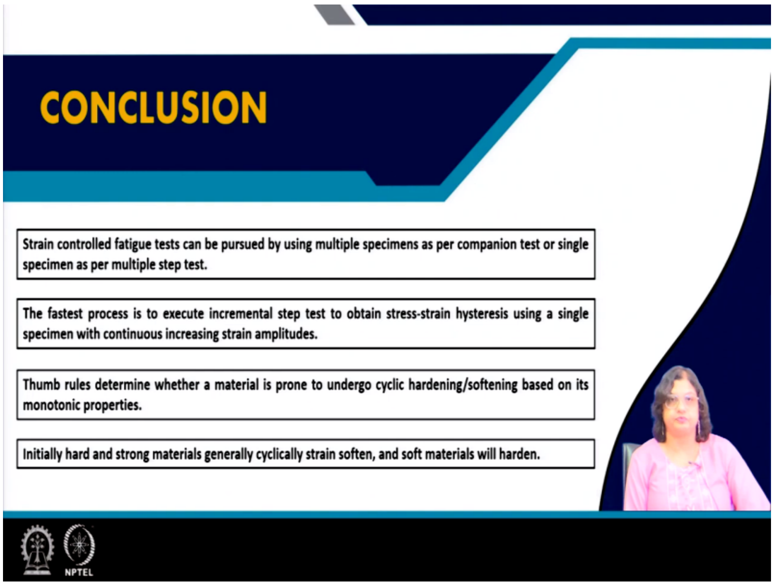

So, that is how the difference between hardness, cyclic hardening and cyclic softening can be understood and based on that let us conclude for this lecture as the following that. Strain controlled fatigue test can be pursued by using multiple specimens as per the companion test or even it can be done with single specimen as per the multiple step test but the fastest process of all is to execute incremental step test in which we apply the strain amplitude of varying dimension within a single block and we repeat this kind of block.

Now, the Thumb rules to determine whether a material is prone to undergo cyclic hardening or softening is related to its monotonic behavior it is dependent on the ratio of the ultimate tensile strength to the yield strength of the material as well as the work hardening exponent if the ratio of UTS to yield strength of the material is more than 1.4 as well as n value is greater than 0.2 that material is expected to undergo cyclic hardening.

On the other hand the one in which the ratio of the ultimate tensile strength to the yield strength is less than 1.2 as well as the n value is less than 0.1 that material is expected to undergo cyclic softening and what is the catchy point here is that initially hard and strong material the one which is quite harder in the monotonic testing that is expected to undergo cyclic softening and on the other hand initially soft material which has lesser resistance to permanent deformation that kind of material is expected to undergo hardening if we are repeating the deformation mode.

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So, these are some of the books that we have used for this lecture and thank you very much.