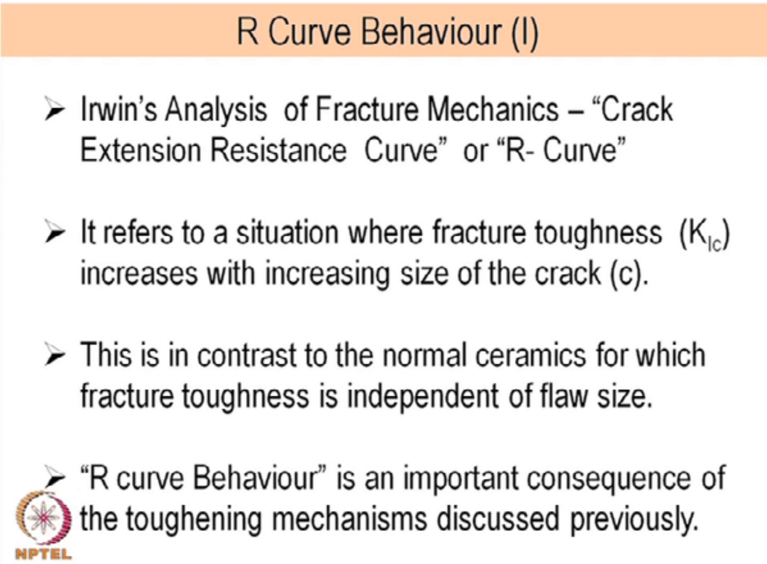
Advanced Ceramics for Strategic Applications
Prof. H. S. Maiti
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 45
Mechanical Properties of Ceramic Materials (Contd.)

Welcome today's topic is also the mechanical properties of ceramic materials, which we have been continuing for the last couple of lectures. In a earlier lecture, we have already discussed the different mechanisms of toughening ceramic materials whether it is by bivarient enforcement or whisker Reinforcement or simply by transformation toughening. Today, we look at its some of the implications of this transformation toughening or the toughening in general. And for that, we will discuss what we called the R curve behavior of ceramic materials in particular.

(Refer Slide Time: 01:01)

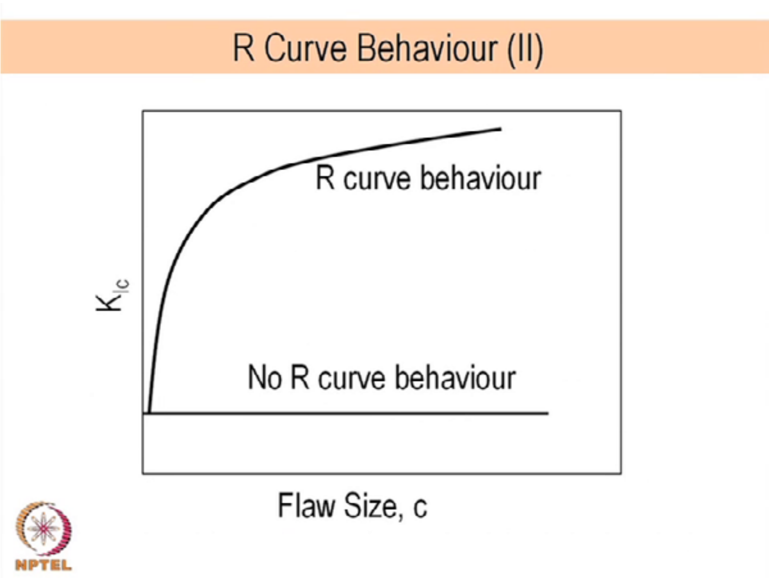


It comes from the Irwin's analysis of fracture mechanics, where he has calculated the, or postulated the crack extension resistance curve. So, there is a extension when the crack starts propagating a resistance is also created. And that is what the terms says crack extension resistant curve or simply the R curve, what are its implications or characteristics? It refers to a situation where fracture toughness K i c, which we have discussed earlier. We have defined fracture toughness; we have also discussed how to measure the fracture toughness of ceramic materials by different techniques.

So, this fracture toughness property of ceramic material increases with increasing size of the crack. So that is of the basic premises on which this R curve behavior has been discussed or will be discussed now. So, by toughening, we actually see that the toughness value and the fracture toughness value K i c as is increasing with increasing size of the crack. So, that is the primary characteristic of a R curve behavior so far as the mechanical property of ceramics is concerned. This is in contrast the normal ceramic material well, which are not toughen, which do not get toughened either by a bivariant reinforcement or crack reflection or transformation toughening.

So, normal ceramic material, do not have these characteristics. So, there K i c value, the fracture toughness is independent of flaw size that is the basic difference between the normal behavior of a ceramic material and R curve behavior of the ceramics, which had been and toughen by someone's. R curve behavior is an important consequence of the toughening mechanism discussed previously that we have just discuss. We have just mentioned that primarily this behavior is observed, where these ceramic materials have been toughened by some mechanisms, which we have discussed.

(Refer Slide Time: 03:57)



This is a typical behavior of R curve behavior or comparison of two different classes of ceramic material. One is a, the R curved materials having the R curve behavior and materials group which do not have that. If you plot K i c of these 2 groups of materials as a function of flaw size the c, which you have discussed in details earlier. So, for materials which do not so, the R curve behavior the K i c value is more or less independent of the flaw size. Whereas if you have a R curve behavior materials R curved materials which so, R curve the R curve is like this that the fracture toughness actually increases with the flaw size of course, it is does not increase continuously and initially increases. And then there's a kind of steady state is reached between the propagation of the cracks and the strengthening mechanism. So, at a certain stage it becomes more or less constant once again.

(Refer Slide Time: 05:21)

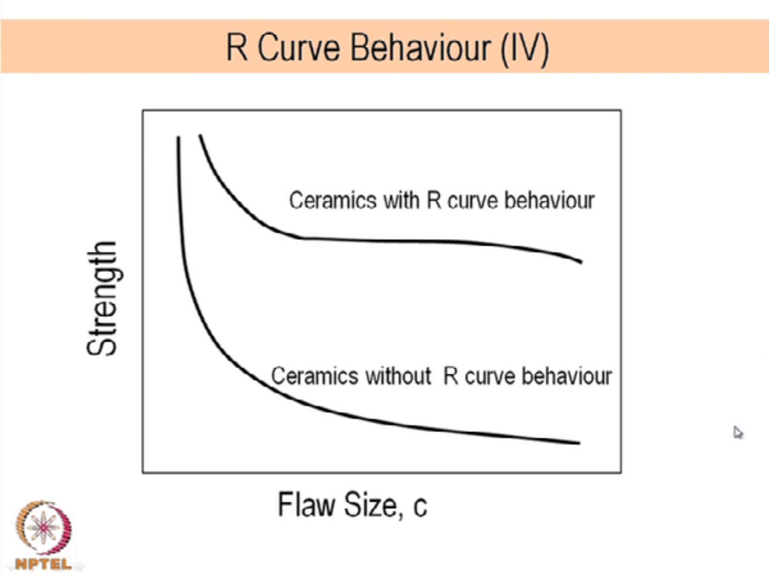
R Curve Behaviour (III)

- Crack Bridging and transformation toughening are the major causes of this behaiour.
- The crack closure stresses are imposed either by bridging ligaments or the transformed zone ahead of the crack tip.
- The fracture toughness, however, does not increase indefinitely, but reach more or less a constant value when a steady state is reached as the ligaments tend to break and pull out.

Well, some more observations on this crack bridging and transformation toughening are the major causes of this behavior, which we have just mention also. And the crack closure stresses are imposed either by bridging ligaments or the transformed zone ahead of the crack tip. If we remember, how exactly trans toughening takes place either by the transformation mechanism or transformation toughening. That means the materials ahead of the crack tip they get transformed and form a compressive load or compressive stress which does not allow the crack to further propagate.

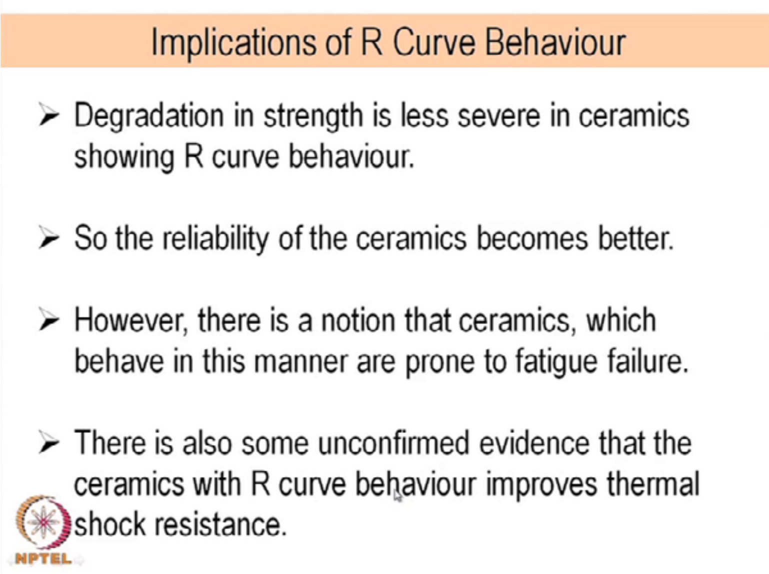
So, the energy is basically get absorbed by this transformation mechanism or transformation toughening. Similarly, if you have a large number of fibers in the, in the front of the crack tip then this fibers also act as a anchoring of these fibres and the crack cannot expand or cannot propagate in the in the forward direction. So, that is how the toughening is increased as the crack tries to propagate further. The fracture toughness however, does not increases as also I mention a few minutes back its does not increase indefinitely, but which more or less a constant value when a steady state is reached as the ligaments tend to break and pull out. So, after sometime of course, the stress builds up and the ligaments either gets or the fibers gets broken or it can be there is a debonding also takes place.

(Refer Slide Time: 07:34)



Compared to the K i c value the fracture toughness the strength, if you measure the strength of these materials, they have a different characteristics against flaw size or normal ceramics which do not. So, the R curve behavior the strength decrease strength decreases initially quite rapidly as the flaw size increases. And then at a larger flaw size more or less becomes constant that is the characteristics of normal ceramic materials without having the R curve behavior. However, if the materials having R curve behavior that means materials have been toughen already and K i c values is higher. We have a, a higher strength not only higher strength, but also the decrease is rather's low and comes to a constant value much a higher level of strength. So, strength increases by the toughening also, but as a flaw size. It does not the strength is the reverse of that K i c, K i c increases by the strength decreases.

(Refer Slide Time: 08:55)

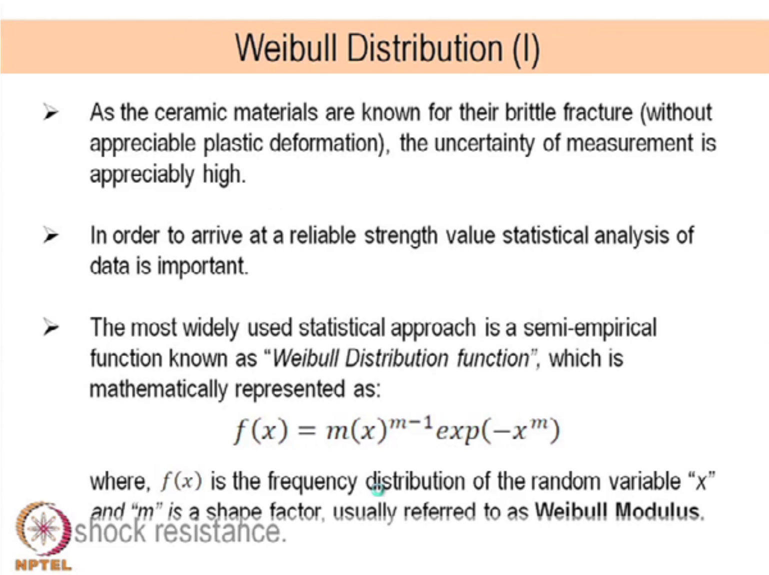


Implications of R curve behavior degrades degradation in strength is less severe in ceramics with R curve behavior as we have just observed in the earlier diagram. So, degradation as strengthen as it is the toughened. So, the degradation in strength is less severe in ceramics with R curve behavior that is one implication of R curve. So, the reliability of the ceramics also improves that means one of the major problems of ceramic materials its unreliability a, of the property are particularly mechanical property. Because of the fracture toughness if, because of the brittle character wants the crack propagates, it has a tendency to propagate at very fast rate almost a catastrophic failure takes place. So, it completely depends on what kind of cracks are already present there or whether we can arise those cracks by some means like toughening mechanisms and so on. So, there is a always at the reliability problems is there with ceramic materials and that is one of the major weaknesses of all ceramic materials in general.

However, once the toughening is done by one kind, one mechanism of the other reliability improves. And therefore, the toughening is also related to the R curve behavior. And therefore, R curve behavior on the materials showing R curve behavior are supposed to most reliable than the normal materials. However, there is a notion; there is a proposition or there has been some observations by researchers that the materials which show R curve behavior normally are prone to fatigue failure. Well, fatigue failure is basically cyclic lading, we will mention briefly about what is fatigue later on, but. So, for your discussing about the strength; strength certainly is becomes more reliable the material becomes less prone to fracture.

However, under normal stress condition, but if there is a fatigue loading or a cyclic loading, a kind of cyclic loading up the tensile load as well as compressive load one of the other. Then there may be possibility of failure or less a less reliable, it becomes particularly under fatigue loading. There is also a proposition or there is also some of observations that the materials which behave or. So, on R curve behavior improves the thermal shock resistance in general as you know the, because of the less thermal conductivity of ceramic materials and poor fracture mechanical properties materials, sell ceramic materials have less shock resistance. But the materials we have R curve behavior of toughened material do improve the thermal shock resistance, which is a kind of access and expect of this behavior a on this kind of improved material or properties with improved the materials with improve the properties.

(Refer Slide Time: 12:49)

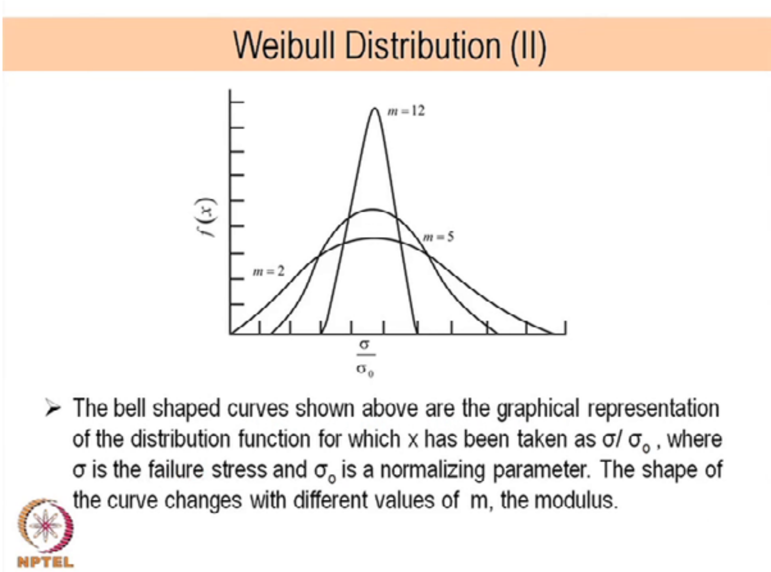


So that is all about our knowledge of R curve behavior materials and that as you have seen is quite closely related to the toughening toughens ceramics. Then we come to another aspect of mechanical behavior of ceramic material that is what we call the Weibull distribution. Now, as has been mentioned again and again that the reliability of the ceramic materials. So, for as the mechanical properties are concerned or quite pore and some material may fail suddenly the same material more or less prepaid in the same manner may not fell. So, it is difficult to predict the behavior in that manner.

So, in that context, a statistical distribution of these measurements have been proposed. And that is very important for ceramic materials where the reliability is an issue. As the ceramic materials are known for their brittle fracture, without appreciable plastic deformation that is the definition of brittle fracture. The uncertainty of measurement is appreciably high that is quite; obvious, in order to arrive at a reliable strength value is statistical analysis of data is very important. So, first of all we have mention earlier also that the number of data points, the number of measurements must be quite high. So that we can get a statistical average and reliable data and the most widely used statistical approach is a semi empirical function known as Weibull distribution function.

So, Weibull distribution function is a semi approved a empirical function which is normally used to de analyze the reliability of the data points and the reliability of the properties as such. This function which is a mathematically represented as f x equal to m x m minus 1, a exponential minus x to the power m. So, that is the function Weibull function where effects is a frequency distribution of random variables x and m is a safe factor usually referred to as Weibull modulus. So, in this function, in this function m is a very important parameter for our consideration. We will see how this via what is the consequence or what is the implications of this Weibull modulus.

(Refer Slide Time: 15:56)



If you plot this function as a function of a particular parameter stress parameter sigma by sigma 0, which is becomes x actually if you take this as x. So, f x by f x against x, x can be had been taken as sigma by sigma 0. So, this bell shaped curve in distribution curve can be seen and the distribution function for which x has been taken as the sigma by sigma 0 as I mention where sigma is a Ferro stress and sigma 0 is some normalizing parameter. So, sigma 0 is also a stress of under certain specific condition, we will see, what is that specific condition? So, it is a kind of normalized stress condition. So, we are plotting effects as a function of normalized stress, fracture failure stress, normalized failure stress actually.

So, if you take large number of samples to find out what is the failure strength of that particular sample and then plot that is a function of effects. So, it is a bell shape curve or a gosib distribution curve is obtained and the shape of the curve changes with the different values of n. So, depending on the either you can said depending on the shape of the curve the aim is to determined or for def four different value of m is shape changes. As you can see from this plot if aim is low it is more a broad peak with a broad, with a abroad peak, with a less defined peak, where as if m increase m value of m increases a much better defined peak and a narrow peak or half of these less in case of m having higher values so that is also a very important observation.

(Refer Slide Time: 18:11)

Weibull Distribution (III)

The survival probability i.e. the fraction of samples that would survive at a given stress level, may be expressed as:

$$S = \int_{x}^{\infty} f(x)dx$$

Replacing x by σ/σ_0 one gets

$$S = \int_{\frac{\sigma}{\sigma_0}}^{\infty} f\left(\frac{\sigma}{\sigma_0}\right) d\left(\frac{\sigma}{\sigma_0}\right)$$

$$\Longrightarrow \quad S = exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^{m}\right]$$

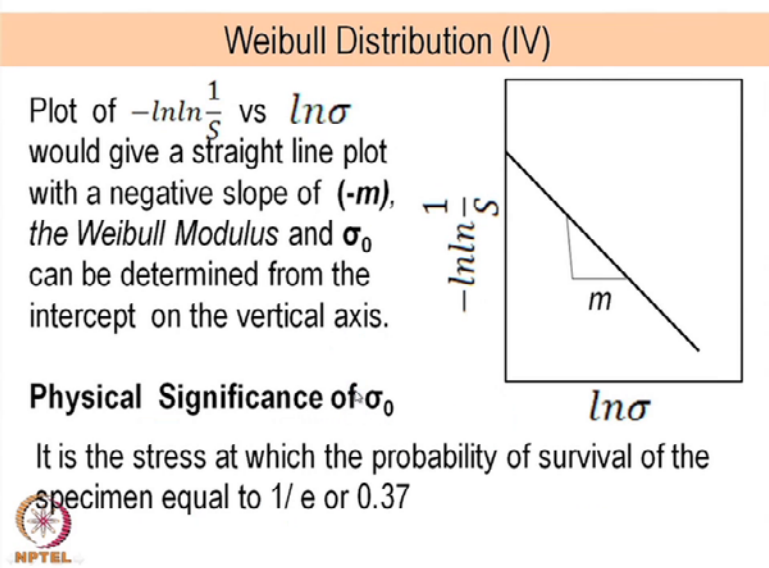
$$\Longrightarrow \quad lnln\frac{1}{S} = mln\frac{\sigma}{\sigma_0} = mln\sigma - mln\sigma_0$$

NPTEL

The survival probability that is the fraction of samples that would survive at a given stress level, we have said sigma is actually the failure stress. So, at that any particular level what is the survival either it will break or it will remain intact that is the condition. So, the survival probability can be defined by this function and the fraction of samples that would survive a typical given stress level may be expressed as this integration x to infinity f x d x. That is what we can say is the survival liability that means, basically it is the area under the curve area into the curve within a particular range in the particular range x to infinity replacing x by sigma by sigma 0, which you have done earlier.

So, you get S sigma by sigma 0 f sigma by sigma 0 d sigma by sigma 0. And by the integration you can get this solution that is exponential minus sigma by sigma 0 whole to the power m and a, that is the Weibull modulus here. And if you take a logarithm of that and in double logarithm and then taken inwards of this because there is a x here a minus here exponential minus. So, you will get a relationship like this m l n sigma by sigma 0 equal to m l n sigma minus m l n sigma not or sigma 0. So, this expression it becomes a linear relationship. So, if you plot this item against a l n sigma you will get a straight line.

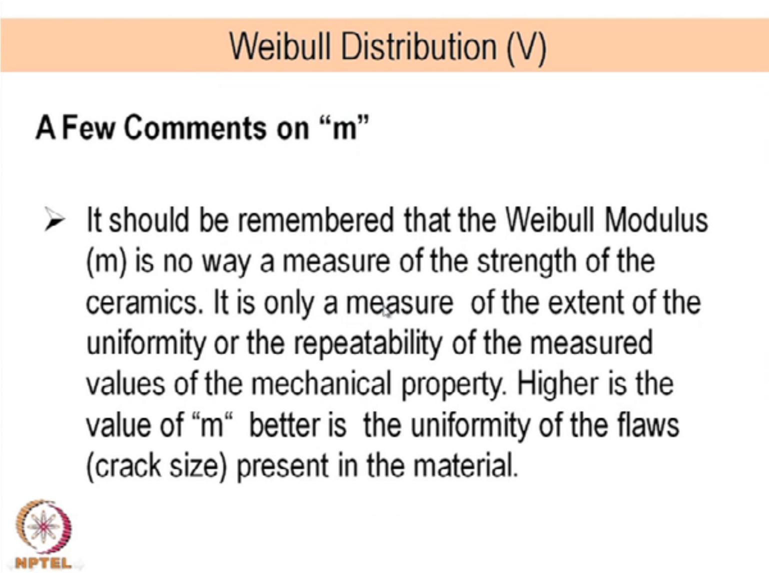
(Refer Slide Time: 20:36)



So, that is what have been shown here, this is the minus double logarithm of 1 by S as a function of l n sigma will get a negative straight line, the negative slope and that slope is actually equal to m m the Weibull modulus. So, the plot of minus l n l n 1 by S versus l n sigma would give a straight line. Straight line plot with a negative slope of minus n which is nothing but the Weibull modulus and sigma 0 can be obtain from the intercept of the vertical axis if you go back to this equation.

So, the sigma 0 here will be the intersect main l n sigma will be sigma 0 will be the intersect. So, from this intercepts one can calculate sigma 0 and from the slope; one can get the Weibull modulus and physical significance of sigma 0. It is the stress after the probability of survival of the specimen is equal to 1 by e or 0.37. So, sigma 0 actually a constant K constant with respect to those that particular experiment. So, it refers to the probability of survival of the specimens equal to. So, many specimens will survive at sigma 0 and with respect to that sigma we have to a major or you have to get ratio of that. So, the physical significance so, it is a constant value that in that manner and you can get what is that value.

(Refer Slide Time: 22:50)

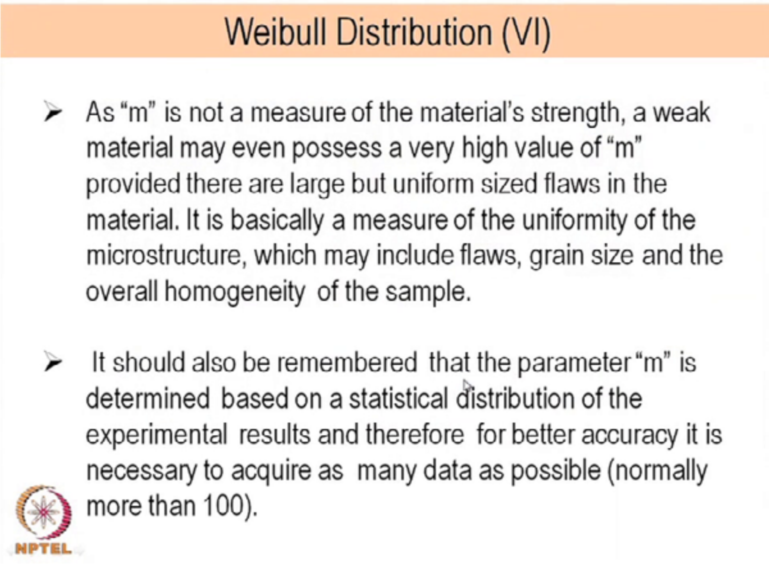


So, a few comments few comments on in the most important parameter out of this statistical analysis is the modulus or the Weibull modulus in it is should be remember that the Weibull modulus m is no way a measure of the strength. It is not a strength sigma is the actual strength or that the fracture strength with, with the difference samples and the modulus is not a strength here right unlike the modulus of rapture and. So, on modulus of rapture, which we have discussed earlier a more is certainly a actual strength of material. But m is not a major of the strength it is only a measure of the extent of the uniformity of the repeatability of the measured values of the mechanical property.

So, if the major property large number as you have mention when you are trying to get a reliable mechanical property data, you have to use a large number of samples large number of data points. And how reliable those data points that is actually is the major or m is the measure of that the higher is the value of m higher is the reliability factor. That means, high is the reproducibility between the samples or samples are more uniform or they have a uniform microstructure uniform grain size uniform virginity and so and so. So, it is always better to have higher m value. So that the measure not only measurements are more reliable, but the material will behave under service as a reliability. So, our objective must be to get as much a value of m, the Weibull modulus at possible for a particular set of data y. Higher is the value of m better is the uniformity of the flaws cracks size present in the material right.

So, because statistically particular material may have a large size differences sizes of flaws. And if the S a flaw size are different in any particular sample or a setup sample are; obviously, the measurement will be widespread are the values you will be widespread and young's modulus, a Weibull modulus and will be small or smaller value. Whereas if you have a better homogeneity, crack sizer uniforms, uniforms material, grain sizes are uniform or you have even chemical homogeneity phase distributions are uniform even when we are using a toughen material. If a tapping toughness is the uniformly distributed over this whole sample volume to sample then we will have a higher Weibull modulus. So, our approach must be to get as high Weibull modulus as possible.

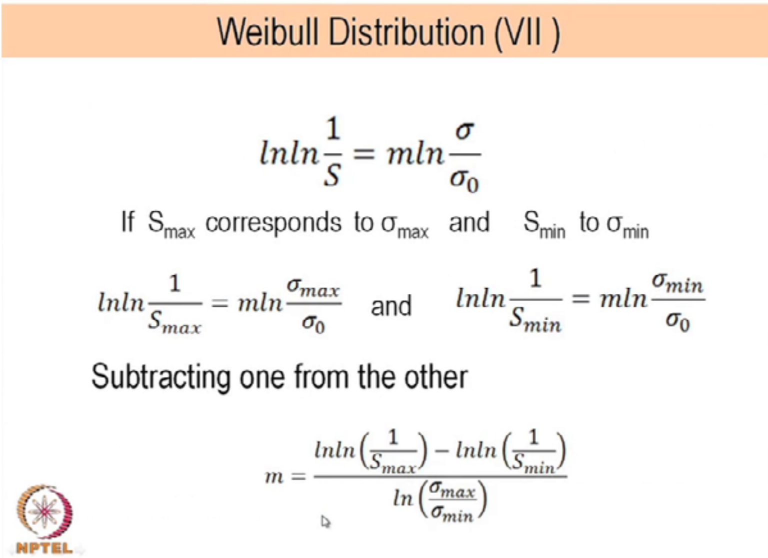
(Refer Slide Time: 26:22)



As m is not a measure of the material strength, a weak material may even possess a very high value of a as long as the variation of the property variation of strength is not large between the different measurements or between the different samples of the same a peace. So, a weak material may even posses a very high value of m provided there are large, but uniform size flaws in the material. It is basically a measure of the uniformity of the microstructure which may include flaws grain size and the overall homogeneity of this sample. So, it is the reliability of reproducibility of the measurements which actually gives higher value of modulus. It should also be remember that the parameter m is determined based on the statistical distribution of the experimental results.

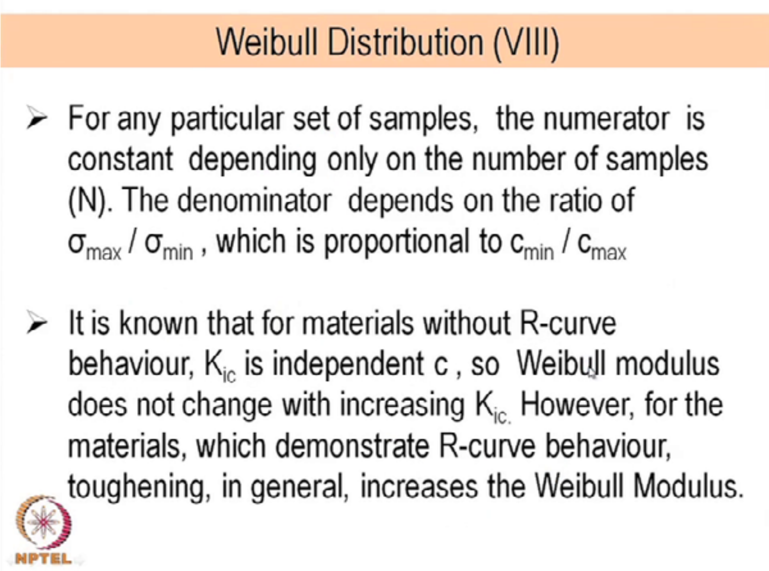
And therefore, a for better accuracy it is necessary to acquire as many data as possible a am a normal suggested figure is more than hundred. So, if you really want to measure the accurate ma property particular, the mechanical property of ceramic material, the number of points number measurements must be very large otherwise there will be less probability of the accuracy of the accuracy will be less. And you have problems in designing problems of designing for a particular component or engineering component out of the ceramic material, which we intend to do.

(Refer Slide Time: 28:21)



So, that is the implications of Weibull modulus, there is one more thing to this Weibull modulus and for which once again we use this equation, which we have seen earlier here. If the S max the probability corresponds to sigma max and S minimum minimum probability sigma minimum if that is the kind of situation. Then we can also write these equations directly from this l n l n 1 minus S max is m l n sigma max max by sigma 0 max by sigma 0. So, at highest sigma what is the probability and at minimum sigma what is the probability same thing? So, subtracting one from the other one can get actually m the value of m. So, the value of m actually if you know this probability value at highest sigma max and at sigma minimum, these are the 2 limits and then l n sigma max by sigma min. So, this is another expression of m the, which within a limit within a limit of sigma max on sigma min minimum sigma minimum and maximum sigma.

(Refer Slide Time: 30:00)

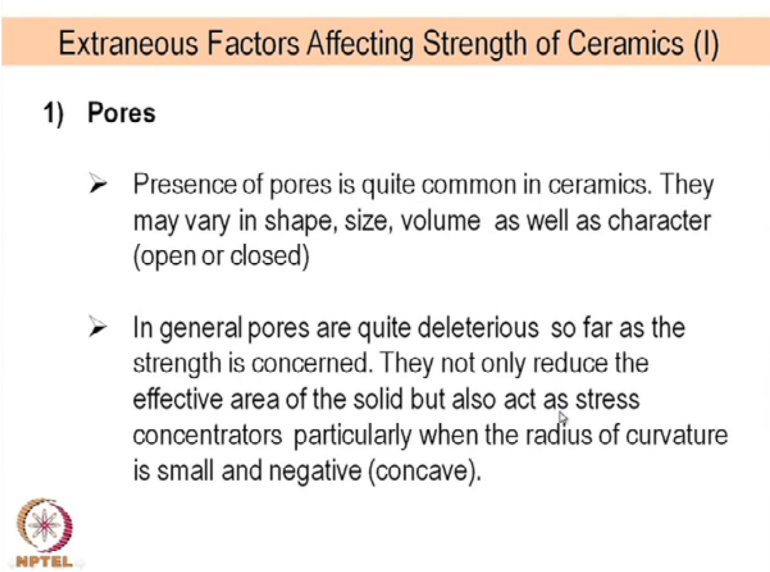


So, for any particular set of samples the parameter and the numerator is a constant numerator of that particular equation. This particular equation is a constant and depending only on the of course, the number of samples n and the denominator depends on the ratio of the sigma max to sigma min. This denominator depends on the sigma max and sigma min these are the best probability values, which is proportional to sigma min by sigma max is the reverse of, which means the, your strength. Or the fracture strength maximum fracture strength, what we are obtained corresponds to a crack length minimum, crack length when the minimum crack length is minimum that corresponds to the maximum fracture stress.

Whereas when the crack length is maximum, the minimum fracture stress is obtained that is, but; obvious, from our earlier discussion it is known that the materials with R curve behavior K i c a, this would be capital I not the small i. We can change here itself right coming back it is known that the materials with R curve behavior the K i c K i c is independent of c without a not with R curve without R curve a. So, Weibull modulus does not change with increasing K i c, once again this should be there is some mistakes. However, for the materials used a demonstrate R curve behavior that is toughening in general increases the Weibull modulus, which is quite expected. So, having the R curve behavior the modulus of Weibull modulus is going to be more and that is expected. Because you have the K i c is dependent on the sigma max and or the sigma not the sigma I am sorry a the c min or c max that is the crack length.

And therefore, and it is a have strength material the R curve behavior means it is a toughening material and toughening has a closer distant closure variation between sigma max and sigma min or sigma. The crack length of the maximum value and the mean value is much closer and therefore, we will have a higher young's modulus a Weibull modulus. So, a toughened material is expected to have a much better Weibull modulus. And therefore, whenever we are looking for a reliable material, reliable ceramic material for a certain structural applications, reliable structure ceramic material. It is better to always have a toughen material tougher material either by its transformation toughening or by some reinforcement of whiskers or many other different mechanisms which you have discussed.

(Refer Slide Time: 34:28)



Well that is all so, for as the Weibull concept of Weibull modulus is concerned, basically we want to say that the Weibull modulus must be high enough. So that the reliability of the data is much better and we have a better material to be used for the, a actual application's. So, that is also an indication how would that material; how reliable the material will be for any technological applications or structural applications? We will having discuss that latest try to look at some of the extraneous factors affecting the strength of ceramics, Because, because of the brittleness, because of the unreliability of most of the parameters mechanical engineering parameters are there are many different extraneous factors in addition to its basic structure, basic microstructure. And there are quite a few important parameters which also affect the strength of ceramics.

The first one is of course, pores ceramics well by almost by definition and the way it is been prepare, we start with a large pores large agglomeration of powders. And then we get sintered a in a cached the higher and higher density, but it is very difficult to get the theoretical density. And therefore, there is always some amount of pores the men a in any kind of ceramic material. So, pores as an important effect on the overall strength of the ceramics, the presence of pore is quite common in ceramics. They may vary in shape size volume as well as character some may be more spherical or circular in size more will angular in size. And they may be different shapes and sizes of pores available. And also, they can be open pores or closed pores, open pores means, it is a open to the surface or interconnected pores and close pores means it is closed within the within a single grain.

So, it is an isolated pores inside the grains. Mostly this error pores are, at the grain boundaries. But close pores or isolated pores and which can be within the grains. In general pores are quite deleterious so far as the strength is concerned. They not only reduce the effective area of the solid, but also act as stressed concentrates. So, although pores are nearly not cracks, but there are also a some amount of openness within the monolithic structure of the ceramics. And therefore, the pores not only reduce the overall area through the stress will be bone or the loaded bone. But also it can act some act some on the sudden and circumstances, it can also act as stress concentrators just like cracks. Particularly when the radius of the curvature of such pores at certain points is very small and concave in nature sure, it can act as a stressed concentrates and failure will lead to that or this will lead to the failure

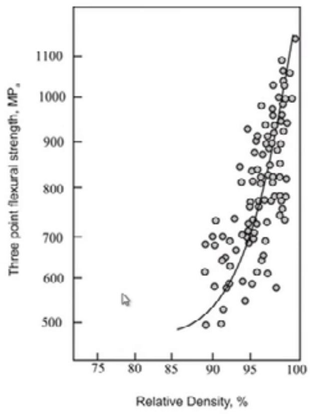
(Refer Slide Time: 38:29)

Extraneous Factors Affecting Strength of Ceramics (II)

Typical empirical relationship is as follows:

$$\sigma_p = \sigma_0 exp(-BP)$$

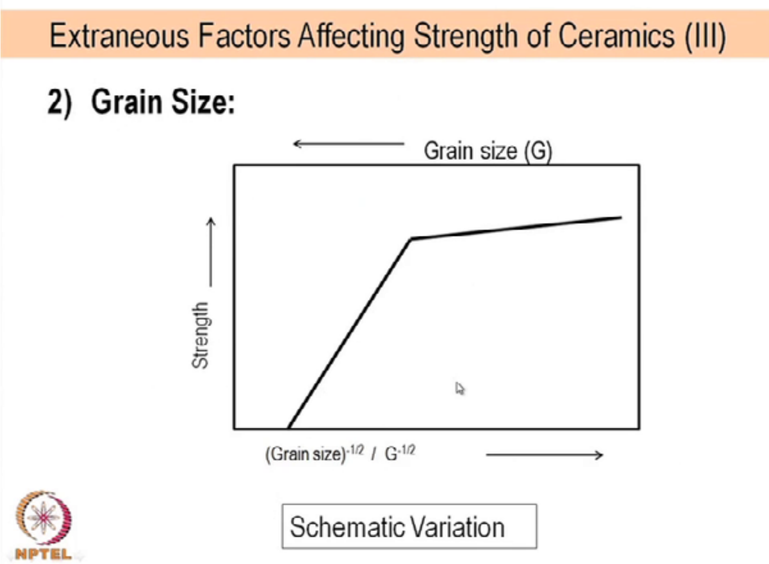
where, P, σ_p and σ_0 are the volume fraction porosity, the strength of the specimen with and without porosity respectively. B is a constant depending on the distribution and morphology of the pores.



Typical empirical relationship is follows as a function of pores is sigma P, the fra fracture failure stress of a the material with pores as P or subscript P. Then sigma 0 exponential minus B P P sigma P sigma 0 or volume fraction of the porosity P is the volume fraction of the porosity and the strength of the specimen with and without porosity. So, this is with porosity and with if there is no porosity that would have been the failure strength sigma 0, B is a constant depending on the distribution and the morphology of the pores. So, if you plot this as a relative density the inverse of porosity relative density then you get this kind of a plot once again there is a lot of scattered in the data you can see. But one can get more or less an exponential rise as a function of density that means, as the porosity decreases this is plot as a relative density.

So, inverse of porosity and do the fracture toughness of the flexible strength here of course, not fracture toughness it is just strength. The fractural strength bending strength a increases increases as a function of density higher is the density higher is the strength which is quite obvious. And it is not a linear increase that is also a remember that it is not a linear relationship is, but a exponential relationship. So, when the porosity is very high the strength is quite low, but as you approach higher and higher density or almost theoretical density it increases exponentially. So, that is e important observation that is an important criteria or important aspect of the mechanical behavior of pores materials. Of course, as you can see here the plot has been given only from 90 percent or 85 percent 85 percent to 90 percent a almost 99 percent shown. So, this relationship is valid basically valid at the a porosity higher than about 85 percent below that it may not be valid in that sense, because the other effects will coming.

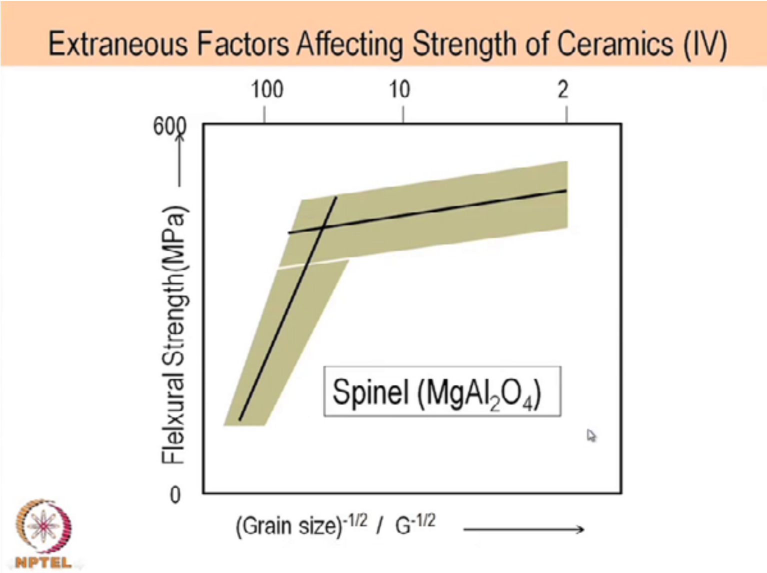
(Refer Slide Time: 41:35)



So, that is, was the effect of pore size or pore porosity they fraction. Here is another parameter grain size. Most of the ceramics of polycrystalline nature and grain sizes is certainly one of the parameters, which controls the strength of the ceramic material. In general, this is a kind of behavior there is a different kind of slope if you get if you plot strength as a function of look over grain size to the power half to a factor, which is called g factor. Or I think there is some is basically grain size now a, this is not a I think it there is a problem there it is basically G to the power of grain size.

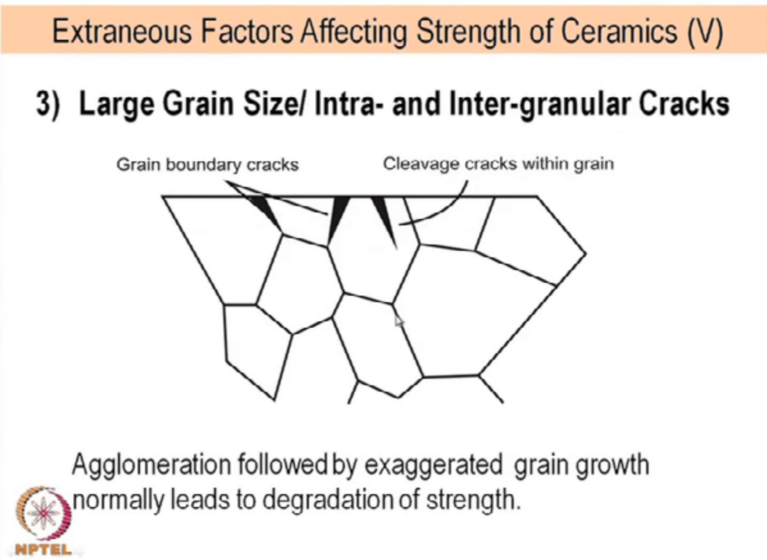
So, if you plot grain size to the power of route grain size as the grain size decreases in this direction actually and grain size in the top we can see increases in this direction the strength decreases. So, the final is the grain size final higher is the strength. So, that is the normal thing once you get you will find a basically, it is the inter granule fracture it is the inter granule fracture which controls the strength of the material. And therefore, final is the grain the crack sizes final and therefore, strength is also higher. So, that is a once again a kind of empirical situation so far as the effect of grain sizes is concerned.

(Refer Slide Time: 43:59)



That was a kind of theoretical curve, but in actual practice you get more or less the same behavior. This is for a particular material like spinal if you plot the flexible strength as a function of grain size once again, you will get as the grain size increases the strength decreases. And there is a two different slopes up to a certain value of grain size one slope. And then further that the further decrease. So, at a smaller grain size will get a lower slope, the variations is less whereas, the larger grain size the variation is much faster and you have a greater slope in this region. And of course, there is always scattered, the scattered is not exactly follow a straight line or a particular straight line.

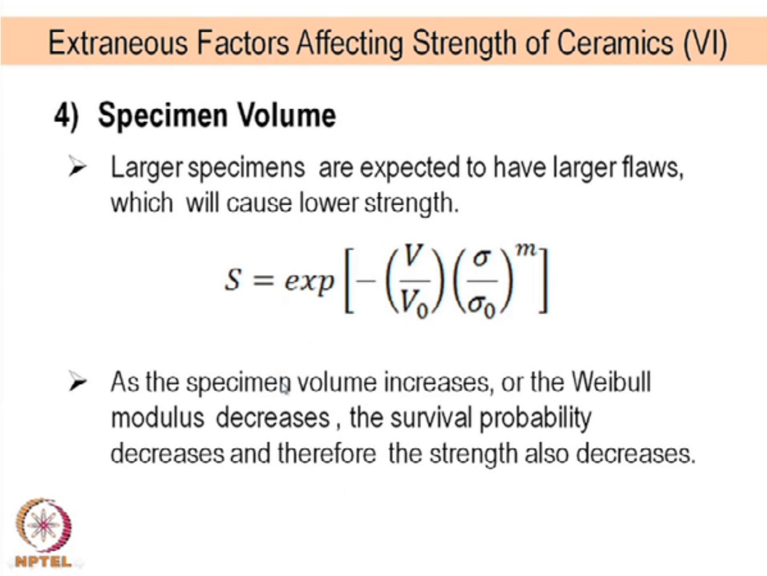
(Refer Slide Time: 45:12)



So, there is a the always a scattered around this particular behavior or particular line. This is why the larger grain size may have a lower strength, the large grain size or intra or intra inter granule cracks. The normal crack is inter granular, this is the grain boundary cracks along the grain boundaries or inter granule cracks whereas, if you have a large intra grain cracks or sometimes called cleavage cracks within the grain within the grains. So, this is possible when you have a large grain size. So that that is the one of the reason why a large grain size we have a weaker property or the strength will be less. The agglomeration followed by exaggerated grain growth normally leads to degradation of the strength, which we have seen earlier in our sintering discussion that at every high after sometime or after certain amount of densification.

If you continue to hit for a longer time, we will get an exaggerated grain growth very close to the melting point. And that exaggerated grain growth lead to a weaker material, because of this inter granular or cleavage cracks which is possible at higher grain sizes. So, this is one of the reason why higher grain size material will have a lower strength and smaller grain size will have a higher strength of course. So, called met in materials in met sorry metals and alloys you have also a very similar effect higher grain size material has a lower strength. And smaller grain size material have a stronger or the highest strength and that is also they are of course, it is not the cracks primary the it is a primary d is location movement of the dislocation which is important and one gets. So, called the all phase ratio, the all phase equation which is more or less the same what we have got here the grain size to the power half dependence.

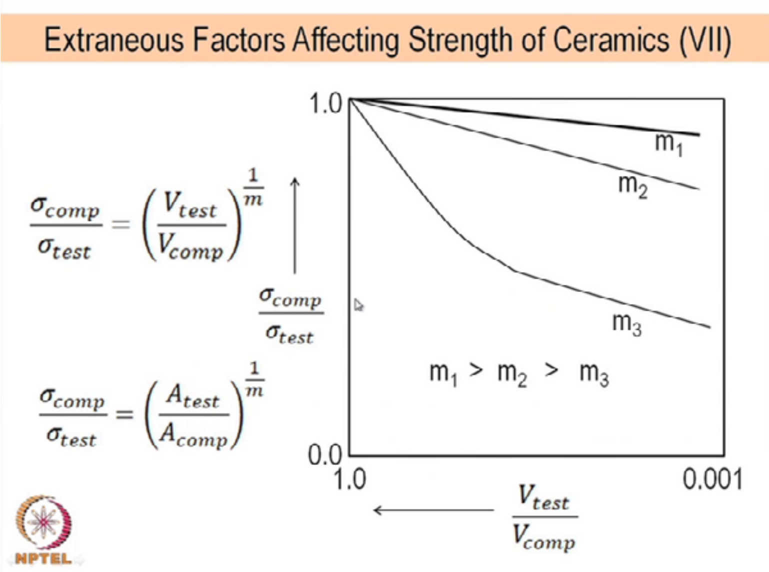
(Refer Slide Time: 47:47)



Now, here is another important aspect of ceramics, which is not always true for other materials other groups of materials like metals and alloys and. So, on the volume size the volume size sorry the volume is specimen size of the specimen volume. So, the larger specimens are expected to have larger flaws, which will cause lower strength. This is another very important aspect once again primarily, because the materials are brittle in nature. And it is the flaw size, which controls the strength of a material larger, if you have a pre existing larger flaws they will be much more prone to failure. And therefore, if you have a larger specimen sizes then that will have a lower strength, major strength with much lower compared to a have smaller world volume of the specimen from the same material.

So, this is what a empirical equation you can write the S is exponential V by V 0 sigma by sigma 0. Again the similar expression what we got in the Weibull modulus right this is the basically Weibull expression. As the specimen volume increases or the Weibull modulus decreases, the survival probability decreases and therefore, the strength also decreases. So, this is another aspect primarily because the materials and brittle incorrect and it is the crack size which controls the failure mechanisms. So, it is a some kind of the consequence of the Weibull modulus impact. So, specimen volume also has a role on the accuracy of the measurements or the representative measurement representative property, which we are measuring.

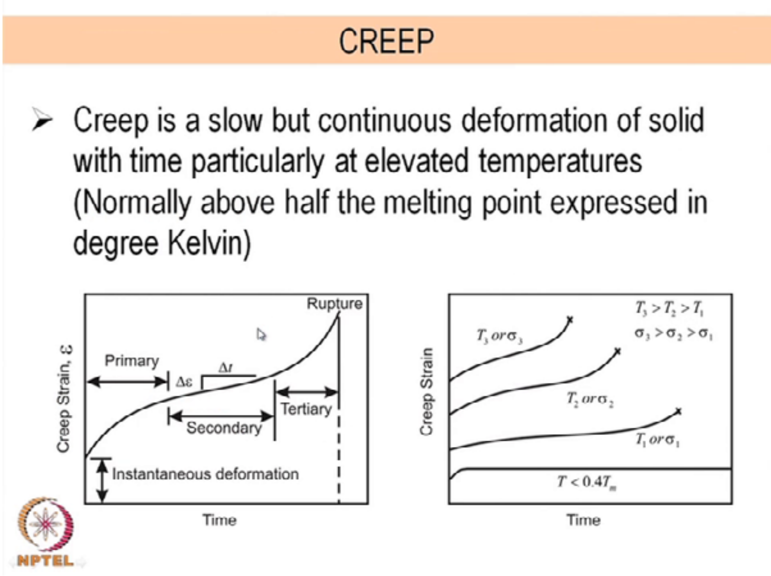
(Refer Slide Time: 50:07)



This can be shown here Weibull modulus and there are ratios of the component size to the test to specimen size that means, the actual size of the specimen which larger or out of that a small specimen is a small test specimens has been taken. So, the ratio of that ratio of, that actually gives you the volume ratio, volume of the test specimen to that of the actual size of the component. And that is this stress ratio is actually a function of volume ratio to the power of 1 by m m is once again the, the Weibull modulus. And then if you plot that as a function of the volume of the test specimen to that of the component, how much volume we have taken, taken out of the total component or total solid for the test purpose? That has a relationship like this the sigma, this particular relationship has been plotted here.

And you can see if the modulus of audio, the Weibull modulus is larger then you will get ratio very close to one throughout a respective of this test specimen a this volume ratio. Whereas if the modulus is low that means, the spread is more the spread is more and you have less representative measurement to carry out. So, volume also has a role role to play what is the volume of the test specimen you have taken compared to the component specimen right. So, it is difficult is difficult to get a representative sample if you are talking about a large component large component means you have to take a large size of the specimen so, to so that to get a representative property measurement.

(Refer Slide Time: 52:43)



Now, those are some of the aspects of different aspects of the measurement their reliability, and how to take care of the unreliability in terms of the, in terms of the Weibull modulus? And then the different factors, which controls the property, which has affects the property. Lastly we will take a few other properties that is one of them is creep; creep is a slow, but continues deformation of solid with time particularly at elevated temperature. So, for all the properties, we have taken there was no effect of time was not a parameter for our measurement or for our understanding the property. Here for the first time we are saying that with time, there is a change in the property or the changes expansion that is what we call the creep strain that has been fixed. From the young’s modulus, we have seen this stressed and diagrams and consider so far that if the stress is constant, strain is constraint.

But here even, even if it is stress is constant there is a strain strain increases strain is no longer constants it is a function of time. So, that is the continuous deformation or a time dependent strain, time dependent deformation is actually what we know as creep usually creep curve, this is a typical creep curve of the any material impact with the ceramics or metals or alloys. Of course, all this deformation will take place, we have already seen that for brittle solids there is no plastic deformation as set plastic deformation can take place only at elevated temperatures normally above half the melting point express in degree Kelvin. But for ceramics is very closer to its melting point there maybe plastic deformation, and even the stresses constant there will be some amount of deformation as a function of time. So, depending on the time we allow the stressed to be operative there will be a strain continuous rise in strength. And that is it typical creep curve, what is initially there will be a instantaneous deformation. And then the deformation is slow down or increased, not slow down the rate will the decrease. But there will be increase up slow then there will be almost a kind of constant value over it time period and then again there is a off turn.

So, these 3 regions can be termed as the instantaneous deformation then there is a primary creep up to this point when there is a faster rise then there is a slower in slowing down there is a slowing down all most the slope will go down. And then we have a once again a faster rate of strain on deformation and that is called tertiary. So, it is primary, secondary and tertiary. So, these are the three regions of a normal universicaly creep curve. And this of course, is dependent on temperature or stress we apply, because there is always a constant stress. What is happening the deformation is taking place under constant stress and that constant stress can be varied or the temperature can be varied.

So, the creep curve will also change, the nature of the crop curve will also change if the T is that is the temperature is less than 0.4 half T m the melting point. So, where creep is negligible? So, there is held any held any deformation as a function of primary increase in the formation as a function of times. So, there is constant trend if you increase the temperature or the overall stress on the reduce deformation is taking place then there will be a change in slope. And this will be the type of curve, which compared to this ultimately we are getting a very similar curve like this. And that is a kind of universal curve, which you will get only at the higher table higher temperature like T 3 here, T 3 is more than T 2 and T 1 still more than T 1 or at a higher sigma sigma this stress, which you apply sigma 3 or sigma 2 an sigma 1; so, sigma greater than sigma 2, which is also greater than sigma 1.

So, this is the behavior of any material and including ceramics and particularly at higher temperature. Well, this is what we call the power law creep the expression is sigma dot is sigma d T equal to a gamma into P to the power sigma to the power P. So, P is the creep law exponent with a value of about 1 to 10 varies is between 1 2 8 and gamma a temperature dependent constant. So, this is what we called the creep power law of creep power law creep or a steady state creep impact. This is a kind of steady state creep here the secondary creep a there are different mechanism of this creep a just simply finished this or this mechanism it seems the time is up just very quickly it is a diffusion creep one of the that is one of the mechanisms. And then you have two other mechanisms; one is a called viscous creep and this called dislocation creep. So, there is different mechanisms maybe will discuss little more about this I mechanisms in the next class. So.

Thank you very much for your attention.