Experimental Stress Analysis
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Lecture - 30
Strain Gauge Alloys, Carriers and Adhesives

In the last class, we had discussed what is the strain sensitivity of a strain gauge because earlier we looked at strain sensitivity of a conductor then when we saw when we have to make a strain gauge you have to make it as a loop so you have a finite area, you have a grid pattern and once you make it as a grid, the grid is sensitive to strain along the axial direction as well as strain along the transverse direction.

Then we moved on to discuss how do you measure the small changes in resistance caused by application of stress on the actual specimen, which is translated as strain and sensed by the strain gauge and you measure it by a Wheatstone bridge. Then we said if you have to find out state of strain on a free surface, I need 3 strain gauges and we also saw while you make metal foil strain gauges these 3 strain gauges can be pre-aligned and available in 1 backing that is advantage.

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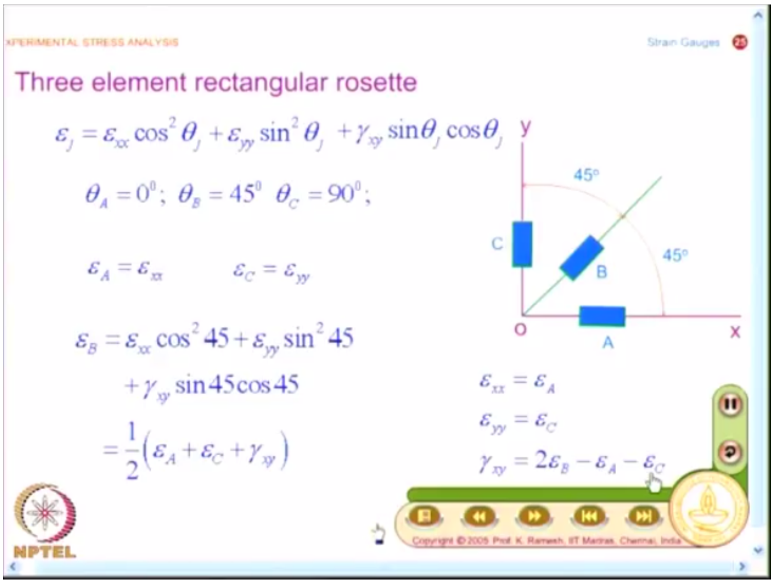

And one of the simplest rosettes we saw was a 3 element rectangular rosette and I said rosette analysis becomes extremely simple if you recall your famous strain transformation law, which is given as follows and I have also asked you to work out by noting the readings of strain gauge A, strain gauge B and strain gauge C. How do we get the strain components epsilon xx, epsilon yy and gamma xy?

And when you have the strain gauge at 45 degrees whatever the strain measured by the strain gauge B is related to gamma xy, epsilon C and epsilon A and when you solve these 3 equations, which is straight forward I get epsilon xx as epsilon A, epsilon yy as epsilon C and the shear strain gamma xy as 2 epsilon B-epsilon A-epsilon C.

And you will have to note down though I said in general there would be a small sensitivity in the transverse direction in the rosette analysis, which we have seen we have not accounted for the transfer sensitivity effects. The moment I do it, the equations become complex and you also have such equations available. We will see those equations later.

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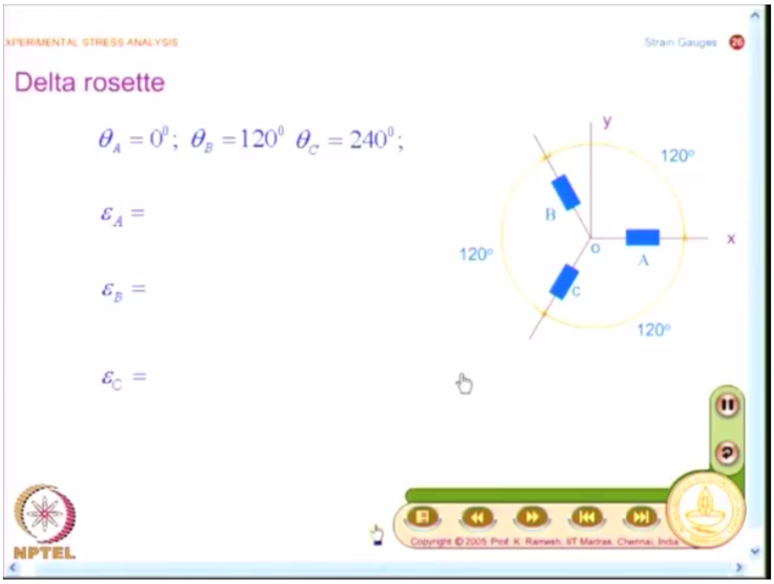

And another popular rosette is a delta rosette and in this you have strain gauges aligned at 120 degree each and what you have here is theta A is 0 degree, theta B is 120 degrees, theta C is 240 degrees and I am not going to work this out. You plug in these values and find out what is the entire relationship between epsilon A, epsilon x, epsilon y, gamma xy, write for 3 values of theta, solve them and get the expressions for epsilon x, epsilon y and gamma xy.

Now we move on to look at various aspects of the strain gauge system. I start from the strain gauge foil. What is the alloys that are used? Then we go to the carrier. Then we look at the adhesive. See we have earlier looked at what is hysteresis? What is zero shift? And you would find selection of the appropriate alloy, selection of the backing as well as selection of the adhesive.

They all influence the performance characteristics of a strain gauge. So depending on the kind of problem you handle you need to make a selection. Normally, one does selection of a strain gauge, design of a strain gauge you do not do it unless it is warranted you have several standard strain gauges available from a manufacturer and in order to select the strain gauge what these parameters are?

How they influence? You need to have an understanding slightly descriptive in nature and I said this information is also equally important.

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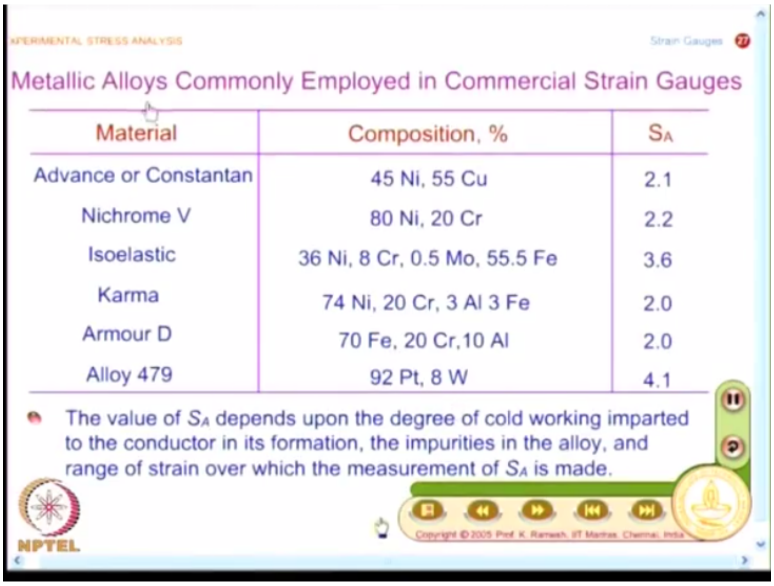

And we start with the metallic alloys and we had already seen Advance or Constantan was the most commonly used strain gauge alloy and this is a composition of 45% nickel and 55% copper and your strain sensitivity of the conductor is 2.1. Then you have a list Nichrome V, Isoelastic, Karma, Armour D and Alloy 479 and these are for various applications.

So you need to know the basic difference between some of these alloys why a particular alloy is chosen for a particular application. You have reasons given by knowing the properties of these alloys, the salient properties from strain gauge instrumentation point of view whatever that is important we will look at and when you look at the strain sensitivity of the conductor, it depends upon the degree of cold working important to the conductor in its formation.

The impurities in the alloy and range of strain over which the measurement of SA is to be made. So what you will have to look at is the strain sensitivity is a function of cold working and impurities, which is advantageously used later when you want to develop self-temperature compensated gauges, you play with these 2 parameters and modify your strain gauge properties, so that you have a self-temperature compensation possible.

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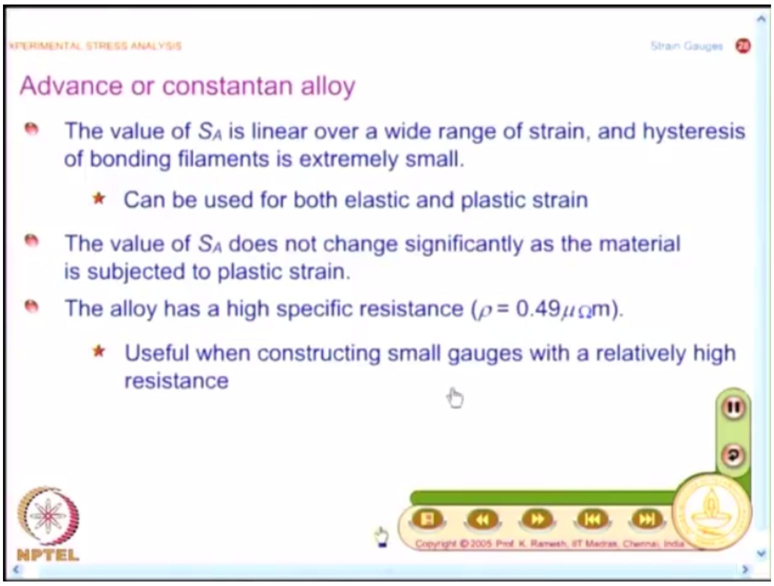

We have already seen in some detail what are all the properties of Advance or Constantan alloy and we will have a quick look at this and what you find here is the value of SA is linear over a wide range of strain and hysteresis is extremely small so that is an advantage. We have to avoid hysteresis in our measurement either minimize or avoid and what you find in the case of Advance or Constantan is the hysteresis is extremely small.

So it is very useful and we have already seen because SA is close to 2 can be used for both elastic and plastic strain and we have also noted that Advance has a very high specific resistance and what is the advantage of this? This is useful when constructing small gauges with a relatively high resistance.

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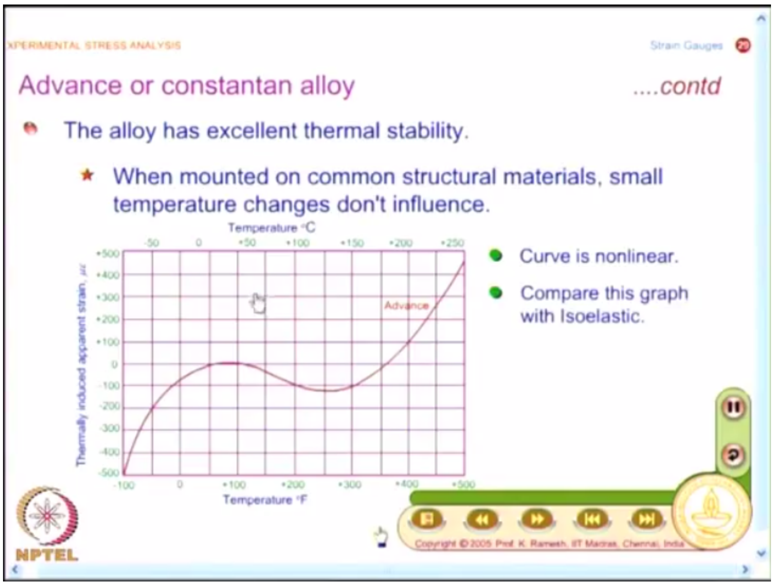

And another aspect what you will look at is what is its thermal stability? And I have already mentioned that it is a relative term. In comparison to other strain gauge alloys, it has better thermal stability and from engineering point of view you know you find the thermal response is highly non-linear. So what you have here is you have a temperature in Fahrenheit on this axis, temperature as centigrade on this axis.

And you have thermally induced apparent strain in microstrain. So what you find is the curve is non-linear. The moment I compare this with Isoelastic you will find this is far better. If you look only this graph, you will only say it is highly non-linear and if you look at in this region, which is more like a room temperature application you find that it is almost horizontal so that is where you have an adjective that it has excellent thermal stability.

At room temperature application, the thermally induced apparent strain for small changes of temperature is almost close to 0, but if I want to use it for higher temperature then I have to be careful in accounting for this thermal influence.

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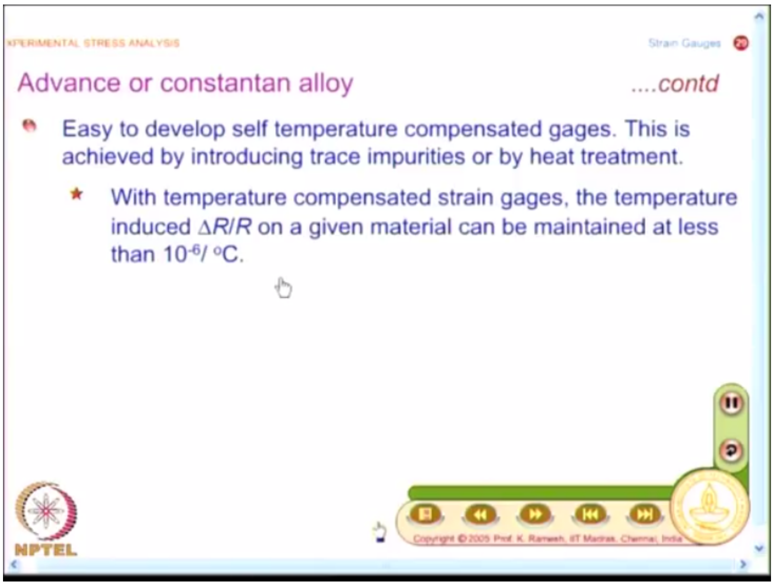

And I have already mentioned that the SA is controlled by the cold working of the material as well as impurities and you use this advantageously to develop self-temperature compensated gauges. For the time being, you note down that you can make self-temperature compensated gauges. Once we discuss about thermal influence, we will look at what is the meaning of temperature compensation and what is self-temperature compensation.

We will look at those details later. Right now you find that Advance or Constantan is good for making self-temperature compensated gauges and what you find here is if you are able to get a self-temperature compensated gauges, the temperature induced delta R/R can be as small as 1 microstrain per degree centigrade.

It is a very great achievement when you see Isoelastic you will find a small change in temperature will have a very high value of apparent strain you know you have to be very careful about that.

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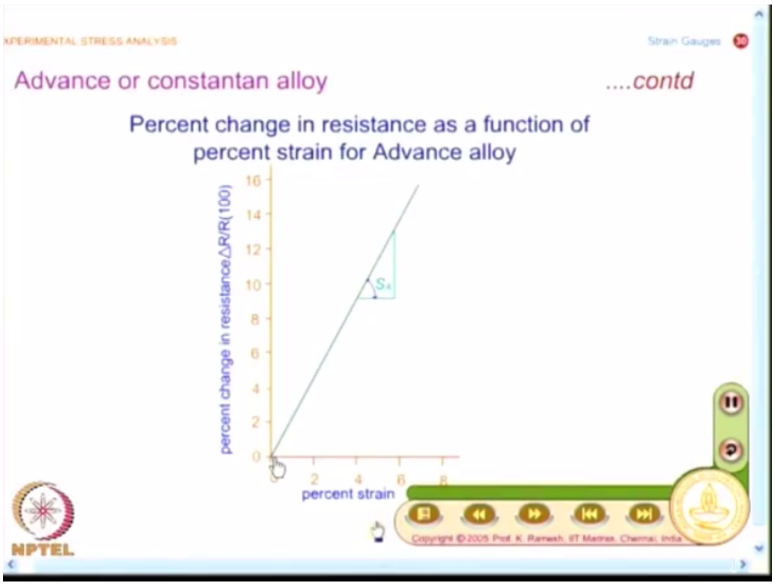

And we have been looking that Constantan is good for going from elastic to plastic strain and you have a graph between strain and percentage change in resistance on the y axis. So what you find here is the graph is linear from 0 to 8% and we have already noted when it reaches 0.2%, the material has become plastic and if you look at in initial stages of engineering development, people focus more on worrying about plastic deformation.

Now with advancements in fracture mechanics people worry about normal strains you know they are not worried about excessive plastic deformation because now we have optimized to the extent we want to make the maximum amount of the material and we also bring in inherent flaws so now the strain measurement domain is different.

But when you are looking at the technology it is useful for both elastic and plastic regions that is the key point here so it varies from 0 to 8%.

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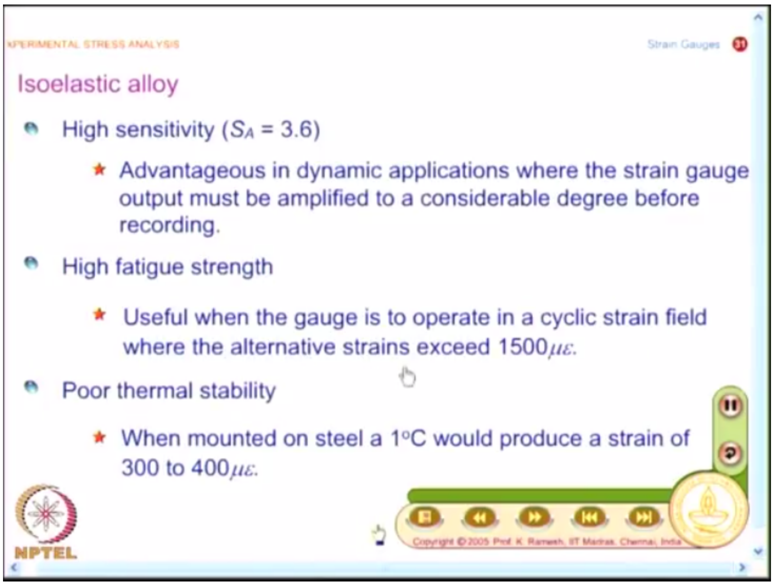

The first advantage of Isoelastic is it is high sensitivity, SA is 3.6 and another advantage is it has a high fatigue strength so if I have high sensitivity what is the advantage? When I go for dynamic applications where the strain gauge output must be amplified to a considerable degree before recording a high value of SA helps so I have a better signal and if you look at engineering you know one of the most important type of loading in the field is fatigue loading.

And if I have the fatigue strains exceed 1500 microstrain, use of Isoelastic alloy is recommended because this has high fatigue strength and such applications are very important you know you have applications where you have to certify for good fatigue life and should have high fatigue strength and so on so forth. One of the disadvantages of Isoelastic alloy is poor thermal stability.

If you mount it on steel, you would find a 1 degree centigrade change would produce a strain of 300 to 400 microstrain. It is very, very high. You know just now we saw in advance if I do self-temperature compensation per degree centigrade you will have a change of 1 microstrain where is 1 microstrain and where is 300 to 400 microstrain. The curve is almost asymptotic; we will have a look at it.

But the requirement here is when I go for dynamic applications, when I go for high fatigue strength, you go in for Isoelastic alloy. So each of this base material has an advantage and a disadvantage. Advance is more of a general purpose material. Isoelastic alloy is for special applications.

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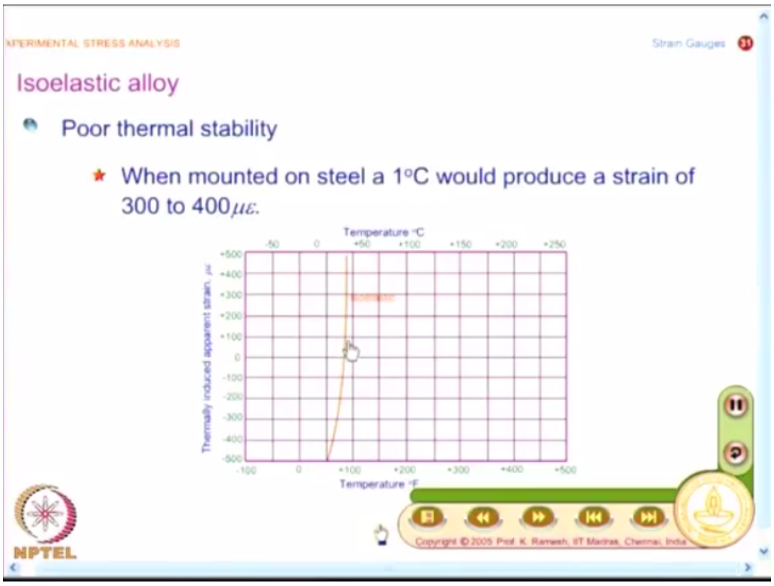

And this is what you see. The graph is you do not have to draw this you can draw in the same graph the Isoelastic also. It is almost asymptotic so a very small change in temperature will have a very high change in apparent strain. Strain introduced because of thermal effect is much larger in comparison to what is the strain that you are going to measure. So you have to be very careful. So disadvantage of Isoelastic alloy is its poor thermal stability.

Because it is poor in temperature effects, the general recommendation is it is useful for dynamic applications where temperature is stable because these dynamic phenomena are very, very fast so even before you wink your eye the phenomena is over. So in such fast applications Isoelastic alloy is advantageous. So that is what the advantage of using Isoelastic alloy and then we move on to the next material which is the Karma alloy.

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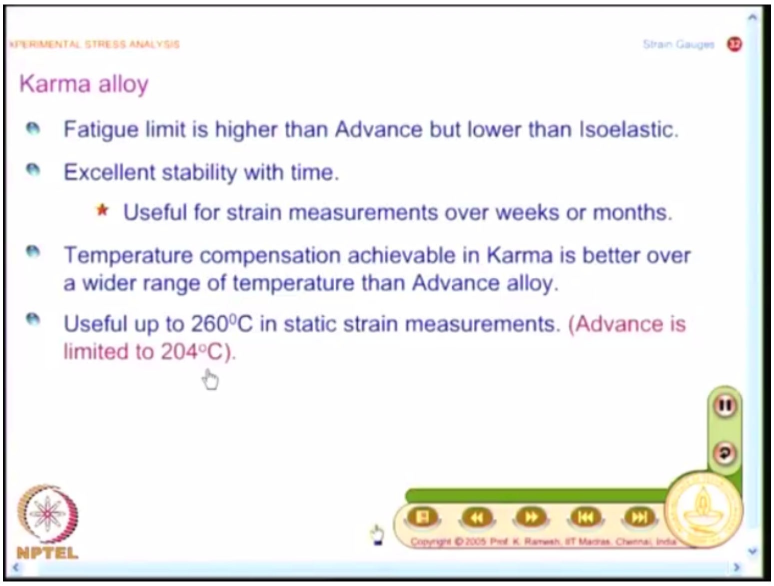

The moment you come to Karma alloy, the basic characteristic is it has excellent stability with time. See I have also said in strain gauge instrumentation; you have applications where you may need to monitor the strain for long durations of time. You may be wanting to monitor a bridge, how it is performing over the several months and these are all called in situ applications where you put it on the actual structure.

And do a health monitoring of the structure and the advantage of Karma alloy is its excellent stability with time and what you find here is temperature compensation achievable in Karma alloy is better over a wide range of temperature than Advance alloy and if you look at the fatigue limit, Karma alloy is in between Advance and Isoelastic.

You know some of this information is required for you to reason out why you choose a particular strain gauge alloy for a given application. In order to familiarize with that yourself with strain gauge selection you need this background and you also find that Karma alloy can be used up to 260 degree centigrade in static strain measurements so it is slightly a shade better than Advance.

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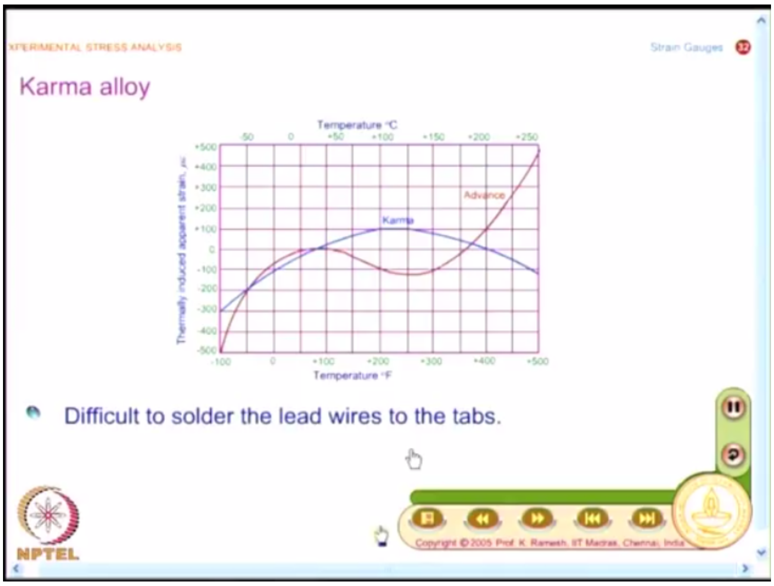

Advance is limited to 204 degree centigrade. See all this information helps you to arrive at how do you go for selecting a particular alloy for a given application and now you have a comparison between Advance and Karma. Both are non-linear and what we saw was at room temperature your Advance is good, at room temperature Karma is not good, but I have to do some kind of temperature compensation.

But the temperature compensation if I adopt, it can be done for a wide range than what you have in Advance and for every alloy there is an advantage and there is a disadvantage. The moment you have a strain gauge made of Karma alloy, it is difficult to solder the lead wires to the tabs. So what the manufacturer does is he also sells lead wire connected strain gauges. So he would solder it in the manufacturing shop itself and then give it to you.

So you have such strain gauges are also available so that makes your life lot more simpler.

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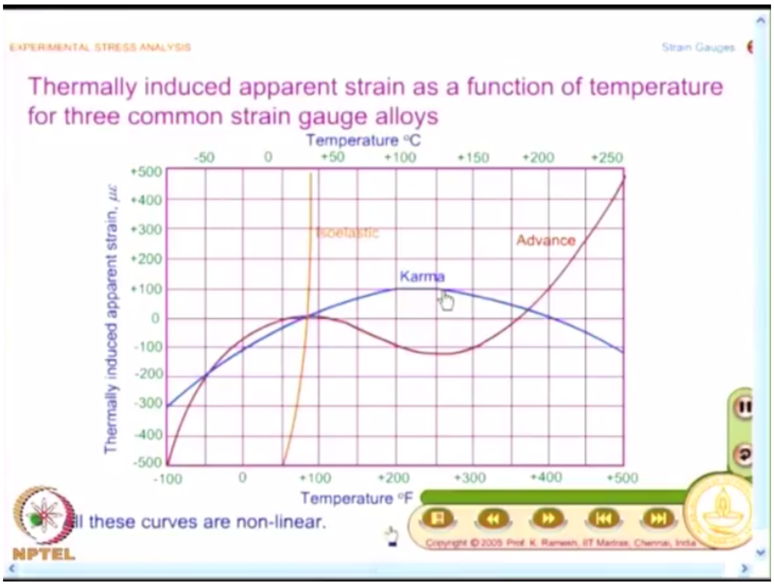

And here the reputation of the graphs wherein you have in 1 graph you have the thermally induced apparent strain for Isoelastic alloy, Karma alloy as well as Advance and your first observation is all these individual graphs are highly non-linear and your adjective excellent thermal stability is really a relative terminology. So for room temperature application, Advance is good.

For dynamic application, Isoelastic is selected. For in situ measurements, you go for Karma alloy for long periods of time.

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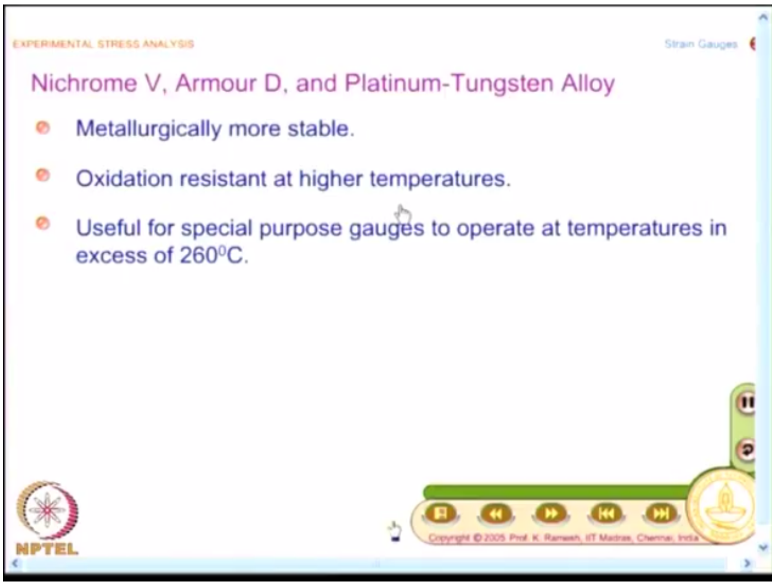

Then you have the special alloys Nichrome V, Armour D and Platinum-Tungsten alloy. If you look at these are suitable for high temperature applications in excess of 260 degree centigrade where metallurgically more stable at high temperature and also oxidation resistant at high temperatures. See measurement of strain at high temperature is becoming an important issue.

You have requirement in that you also have a requirement at very low temperatures. When you have cryogenic engines, you need to make measurements on structures which are at very low temperature. Many applications you have at room temperature fine, but you also have special applications both at high temperature and at low temperatures.

So now what we have looked at is we have looked at first the various alloys available for the fabrication of the strain gauge grid, but this grid needs to be supported by a carrier.

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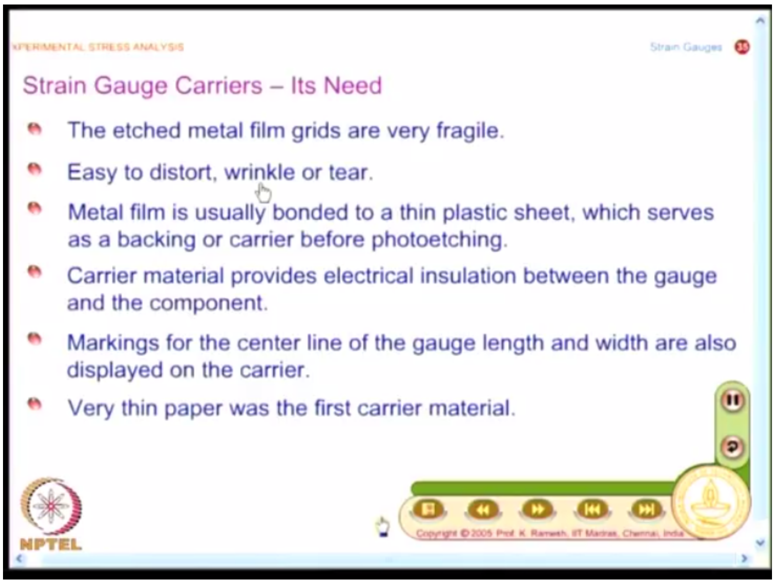

And we will look at why you need these carriers. Though we use a metal film, they are very, very thin and are very fragile. So they are easy to distort and you need to have a supportive backing and what you find is metal film is usually bonded to a thin plastic sheet, which serves as a backing before photoetching and what is the role of the carrier material? It provides electrical insulation between the gauge and the component.

And we have already noted you have markings for the center line of the gauge length and width are also displayed on the carrier. We have already looked at because when you are doing any strain gauge instrumentation alignment of the strain gauge at the point of interest is very crucial because even small misalignment you will be measuring a different component of strain.

So alignment is very important so you need to have alignment markings and these alignment markings are very clearly put on the carrier material and if you look at very thin paper was a first carrier material. Now paper is replaced but if you look at the earliest strain gauges they had a paper and you have a quite a variety of them available now for different applications.

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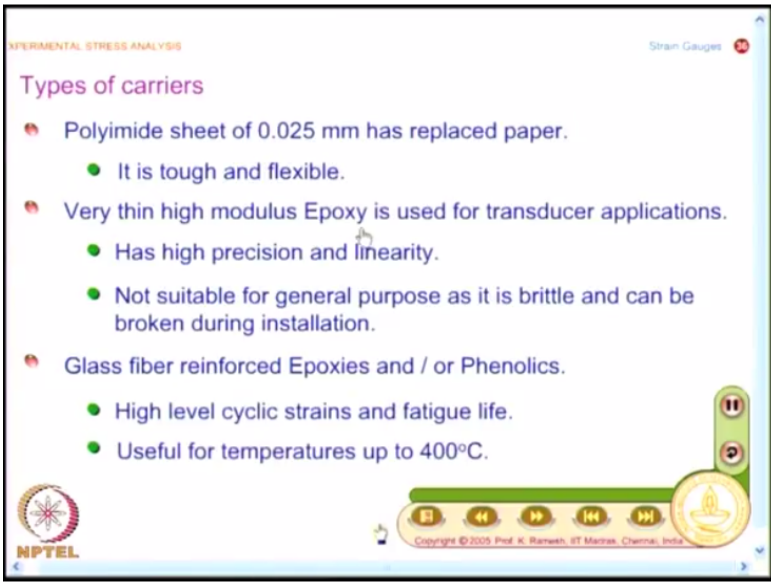

So I have types of carriers, polyimide sheet of 0.025 millimeter as replaced paper and you also have carrier made of thin high modulus epoxy, which is used for transducer applications. See special applications require special preparations and what is the advantage of epoxy carrier? It has high precision and linearity and for general purpose it is not suitable. Why it is not suitable?

Because epoxy is brittle and if you do not know how to handle it properly, it can be broken during installation. See I said general purpose strain gauge you use a 3 millimeter gauge length, Advance or Constantan alloy with a polyimide backing. This is the most general strain gauge available for variety of common applications and polyimide being a plastic, it is easy to handle.

The moment I go for transducer application; I need to have the strain gauge working for very long length of time. So I need a good backing and a good adhesive to bond and since the accuracy involved in transducer application is very high, you need to go for better carrier and better material and the person also will be trained to handle it. So he will know how to handle the epoxy carrier and bond it.

In a general purpose application, you do not expect that and it is also expensive. See any special requirement you have it is expensive. We have seen simple epoxy being used you also have situations where you need to go in for glass fiber reinforced epoxies and phenolic carriers and we will take 1 example later how the choice of the carrier and the material for making the strain gauge has an influence on stability?

These are not trivial things though it is a list of facts sometimes boring you need to know them and it is also surprising you have a polyimide sheet, you have an epoxy and you also have glass fiber reinforced epoxy. So that means it is for high level cyclic strains and fatigue life. You go in for very special carrier and this is useful for temperature up to 400 degree centigrade.

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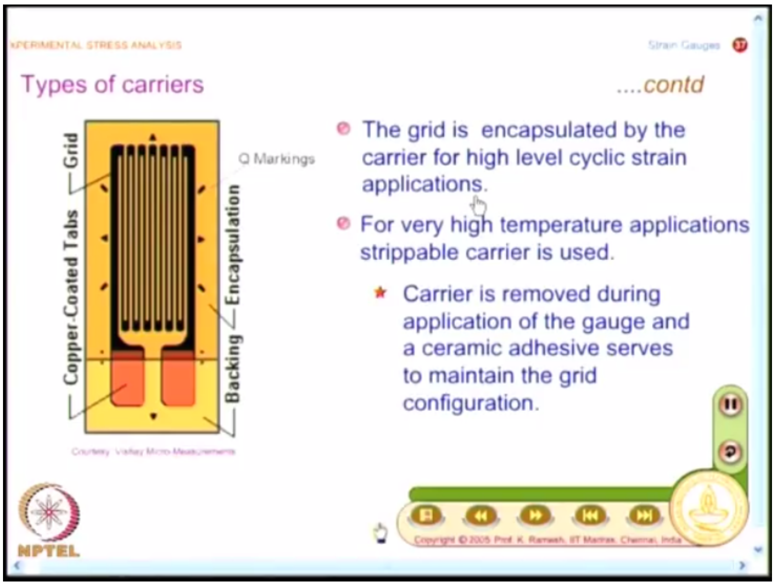

And you know in the earlier class, we have also noted when we looked at the strain gauge, it had an encapsulation and why do you do this encapsulation? The grid is encapsulated by the carrier for high level cyclic strain applications. So it provides more firmness to the metal foil. When I have a fatigue repeated loading, it gives more firmness to the metal foil because it is very thin.

And it is going to be expensive and you will also have to worry about heat dissipation because you are enclosing by a film. We are preventing the natural convection to take place very easily. That is why I said in strain gauge instrumentation keep looking at how you handle thermal effects. So when I go for encapsulation, I must make special provision for dissipating the heat also.

So you use this for high level cyclic strain application, ensure that undue thermal strains are not developed and if I go for very high temperature applications, none of the carriers what we have discussed there useful. I cannot use plastic, I cannot use epoxy, I cannot use glass reinforced plastic. I have to go for ceramic adhesive, which serves to maintain the grid configuration.

So when I talk of very high temperature application, you have to take special steps in bonding the strain gauge and also selecting high temperature strain gauge material. We will see that a little while later.

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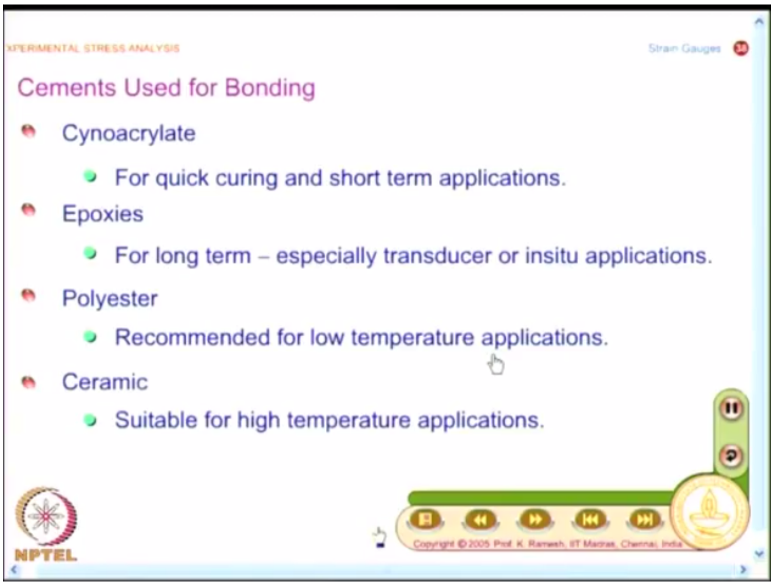

Now what we have looked at is we have looked at the strain gauge material then we looked at the backing. Now we will look at what are the adhesives? You have a variety of them and some of these adhesives are meant for quick application and you know anything fast has a short life. You go to the fast food restaurant and you get the food fast your dietician say that this food is not good for your health.

If you have a food which is cooked very slowly, it is good for your health. Same thing you will see in strain gauge application also. I have cyanoacrylate cement. It cures within seconds but good for short term applications. Suppose I want to make a transducer; I cannot use cyanoacrylate to bond the strain gauge to a transducer. For transducer application, I need to go for epoxies.

This is for long term and if you look at epoxy will take at least 24 hours to cure whereas cyanoacrylate cures within seconds and you have polyester which is similar to epoxy in many of the characteristics and polyester cement is recommended for low temperature applications. I said you have cryogenic engines and you have low temperature requirement for such applications it is better to go for polyester cement.

And I said you also have very high temperature and you need to go for ceramic cements, which will also replace the backing because the backing made of plastic or epoxy, they will all evaporate at that temperature. So you need to have a ceramic backing and we will see some of the details of the cements in some detail in the slides to follow.

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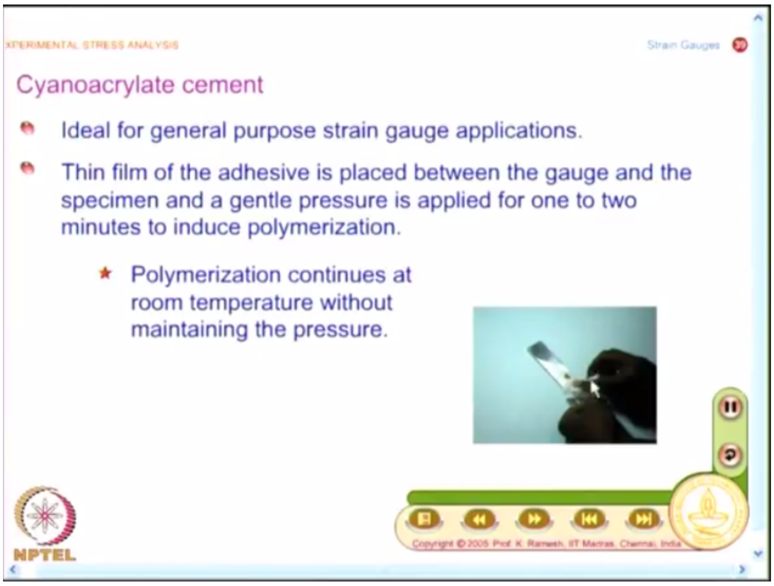

So for general purpose strain gauge applications, you go for a cyanoacrylate cement and we also have a look at this animation.

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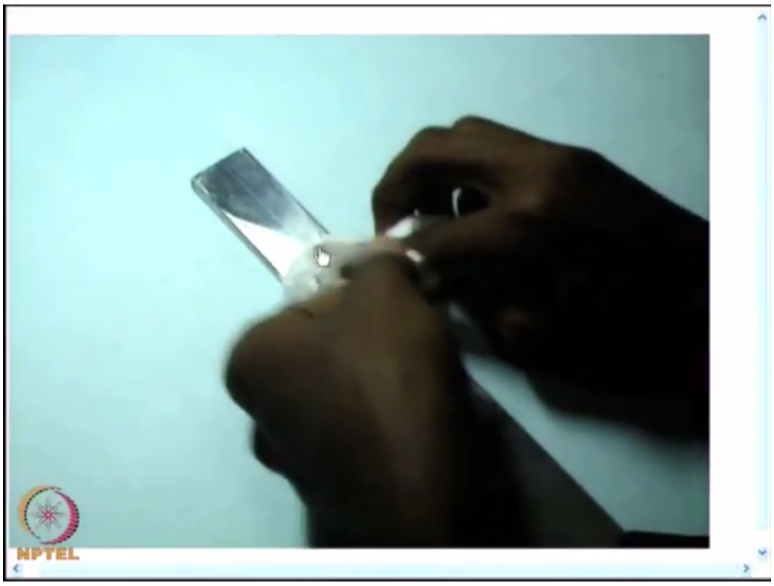

And what you find here is we have a strain gauge on the selefon tape, you had that M-bond adhesive here and you finally press it by a thumb and keep it for a minute or 2, your curing is done as simple as that. So what you find is thin film of the adhesive is placed between the gauge and the specimen and a gentle pressure is applied for 1 to 2 minutes to induce polymerization.

So strain gauge bonding is done so what you find is you have it go and press it and hold it for a minute or 2 your bonding is done but the polymerization continues at room temperature without maintaining the pressure. The moment the cyanoacrylate comes in contact with moisture that is available in the air that itself cures it.

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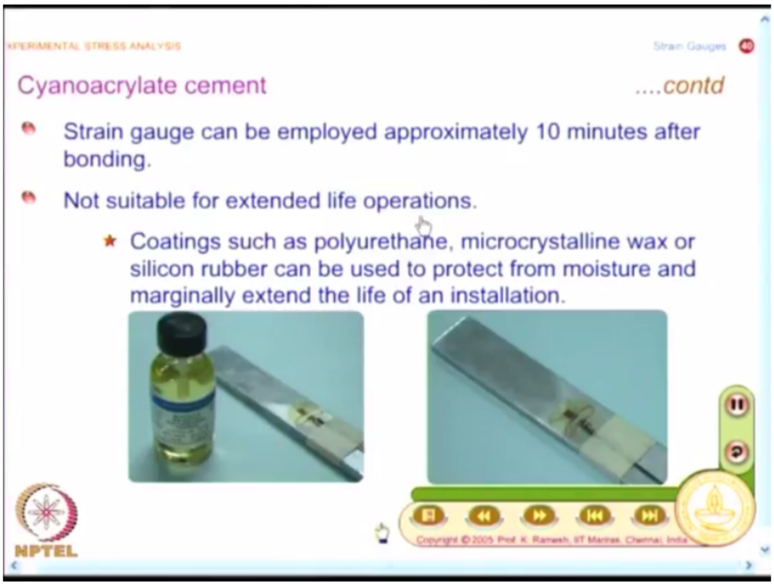

And what is the recommendation is once I use cyanoacrylate cement, strain gauge can be employed 10 minutes after bonding. That is the recommendation and definitely not suitable for extended life operations. See if I have to use a transducer, I will be using it repeatedly. I will have a load cell I will use it for few years and for such applications strain gauge need to be bonded by a more elaborate process.

Nevertheless, there are very many applications where you want quick results, general purpose, you just want at that point in time you find out what is the strain and you are not interested in monitoring the strain over a period of time. You just want to know for a design calculation what is the strain developed. If application is of that nature, cyanoacrylate is very, very advantageous and simple to use.

And after putting this cement, it is also recommended to put coating such as polyurethane or microcrystalline wax or silicon rubber can be used to protect from moisture and marginally extend the life of an installation. See the moisture has a very negative effect on strain gauge installation. You need to protect your strain gauge installation from the moisture the humidity whatever the humidity available can affect the strain gauge installation.

So you need to protect it only then the measurements will be reliable and what you see here the example is also good.

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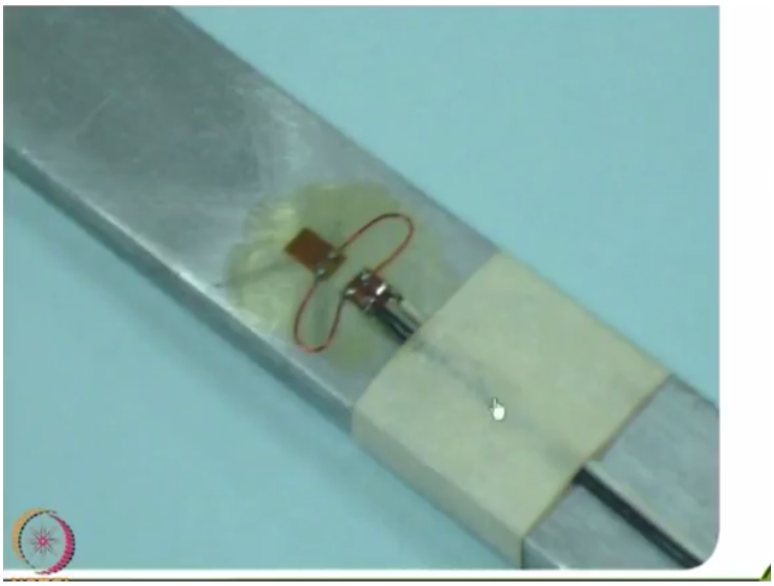

You have a nice strain gauge installation where I have a strain gauge. This was connected by a thin special type of wire and these are all the connectors you know it is easy for soldering and this is the lead wire and lead wire is also anchored so anything if you pull the lead wire that load will be taken care by this anchoring and it will not be sensed by the soldering contacts.

And what you see as light yellow what is put on the strain gauge is the polyurethane coating. So it prevents moisture absorption in the strain gauge system and it makes your measurement more meaningful.

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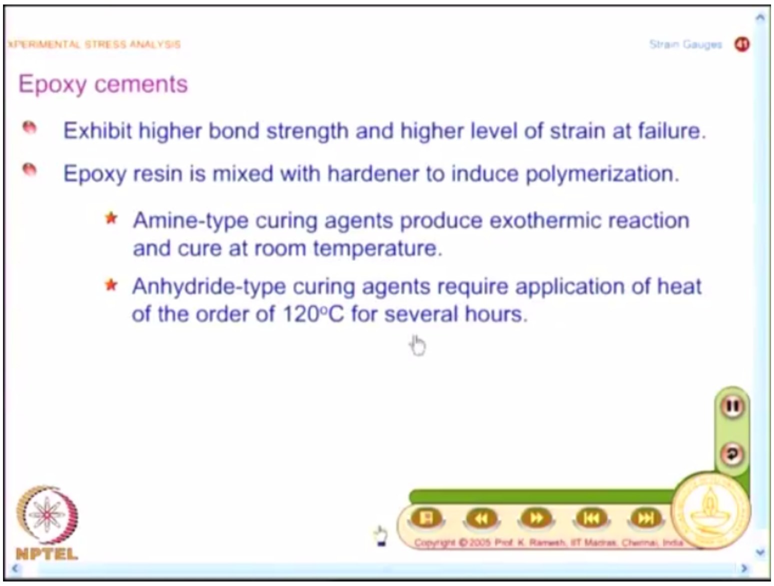

When we come to epoxy cements, the epoxy cements exhibit higher bond strength and higher level of strain at failure and it is a 2 component mixture. So I have an epoxy resin mixed with hardener to induce polymerization. On the other hand, when you look at cyanoacrylate you just take that cyanoacrylate, put it and then press it, press it for a minute your job is done. The moment you come to epoxy, the bonding procedure is very elaborate.

And you have 2 types of curing agents, amine-type curing agents, they produce exothermic reaction and cure at room temperature and in most of the transducer applications, they use Anhydride-type curing agents, which require application of heat of the order of 120 degree centigrade for several hours. Typically, 24 hours is what I have seen, not only this you also need to apply suitable clamping pressures.

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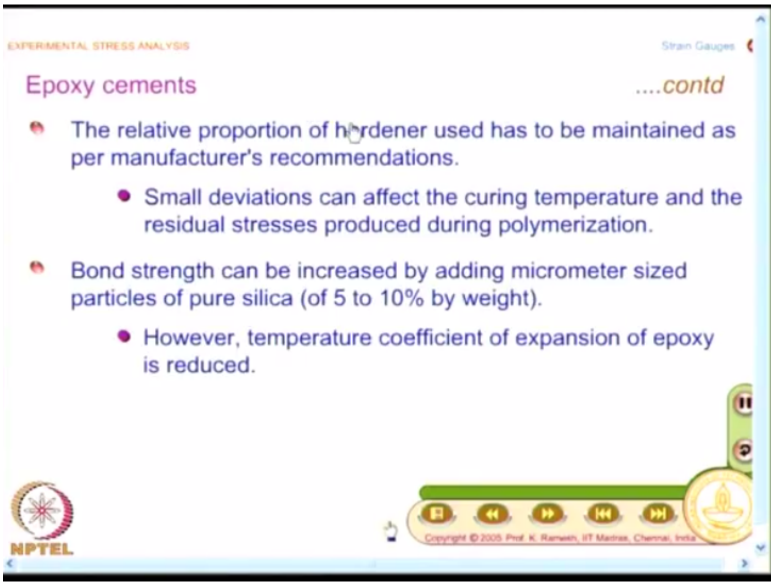

And you have to be very careful when you choose the hardener the proportion needs to be maintained properly. See in any one of this epoxy resin, you will have a resin and hardener 1:10 ratio, hardener will be only 1 10th of the resin and you have to mix this appropriately and there is also recommendation. If you change it even the curing its final properties everything will change.

So whatever the manufacturer gives the recommendation, you are expected to follow and what you find is the relative proportions of hardener has to be maintained as per manufacturer recommendations. Small deviations can affect the curing temperature and the residual stresses produce during polymerization and you know in certain applications in order to ensure that strain of the specimen is faithfully transferred to the strain gauge you may want to have a higher bond strength.

And this can be increased by adding micrometer size particles of pure silicon. It is about 5 to 10% by weight. This is done you have in photoelastic coating also you have that kind of adhesive so which permits smooth transfer of strain from the base material to the strain gauge. You need to have high bond strength for high strain applications better that strain transfer is done without loss.

But if I add this silica what happens? Temperature coefficient of expansion of epoxy is reduced so you have to pay attention on the thermal influence. So this is what I said in strain gauge instrumentation, you do one thing it is advantageous for doing one aspect, it introduces another problem. So you have to look at your recommendation holistically. Piecemeal you should not employ in any one of these recommendations.

So keep looking at if you want to have encapsulation go for encapsulation but also ensure that you provide dissipation of heat adequately taken care of. If dissipation of heat is not adequately taken care of at least provide another strain gauge and make a half brush and do temperature compensation. You have to do this in conjunction with your other decisions that you have to always keep a watch.

And thermal influence is a very great nuisance in strain gauge instrumentation. So what you find here is I go for increasing bond strength and I find the thermal coefficient of expansion of epoxy is reduced so this needs to be properly accounted for.

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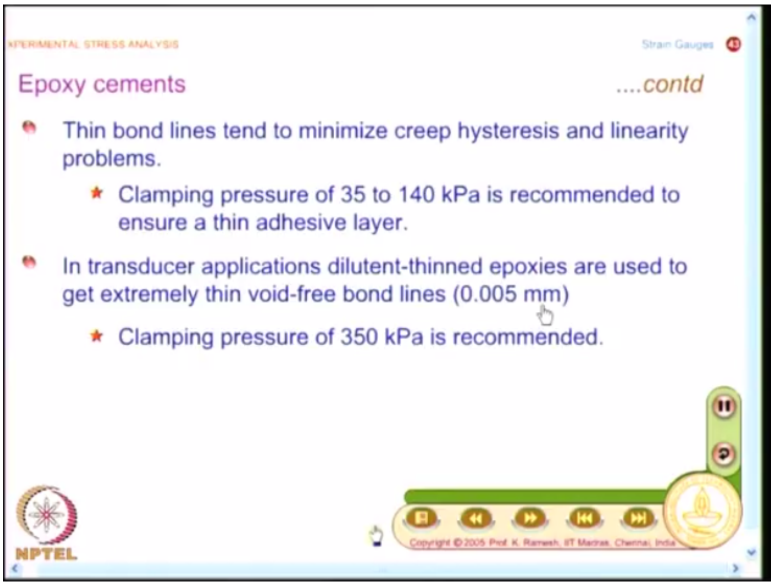

And you have to be very careful in arriving at very thin bond lines and why do you go for thin bond lines? This minimizes creep hysteresis and deviation from linearity and how do you ensure thin bond lines? You have to provide a clamping pressure of 35 to 140 kilopascal and if I go for transducer application, you are expected to make even thinner bond lines. So in order to make it thinner what they do is they add a dilutent to epoxy.

So that epoxy is very thick, it is very highly viscous so you add a dilutent, thin it and also apply a higher pressure. You want to apply a pressure of the order of 350 kPa is recommended and by doing this you get an extremely thin void-free bond lines of the order of

0.005 millimeter. See I have been saying that strain gauge technology is so well developed that you can measure 0.5 microstrain reliably now.

So when I want to do that I need to follow all these procedures. See when we looked at cyanoacrylate cement what was the advantage? You simply apply a thumb pressure that is good enough for curing the adhesive. The moment you come to epoxy, you find you need to go for higher temperatures and also you need to maintain appropriate clamping pressure and even the application of clamping pressure is simplified by the strain gauge manufacturers.

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So what you find is you have such special clips available. They are very hard, very hard to press you know very hard to press and you use this to clamp the strain gauge installation. You will have sort of a wood piece and then a gauze so that whatever the pressure that develop that is evenly transmitted to the strain gauge and you have this as available with a readymade spring whose stiffness is suitably adjusted to give the desired pressure.

And this is for applying some pressure and when I go for higher pressures, you also have bigger system. It is very hard to press you know really trying hard to press it. So you can imagine, I clamp it and put the whole thing in the furnace. So that you will maintain that pressure for polymerization to be complete. So it is very detailed you know strain gauge pasting is not a simple task.

A person need to be trained in strain gauge installation and only when you make the installation as good as possible, you are guaranteed of the final measurement so what you find is we want to have thin bond lines, you can also have extremely thin bond lines both are possible by increasing the pressure and also thinning the epoxies appropriately.

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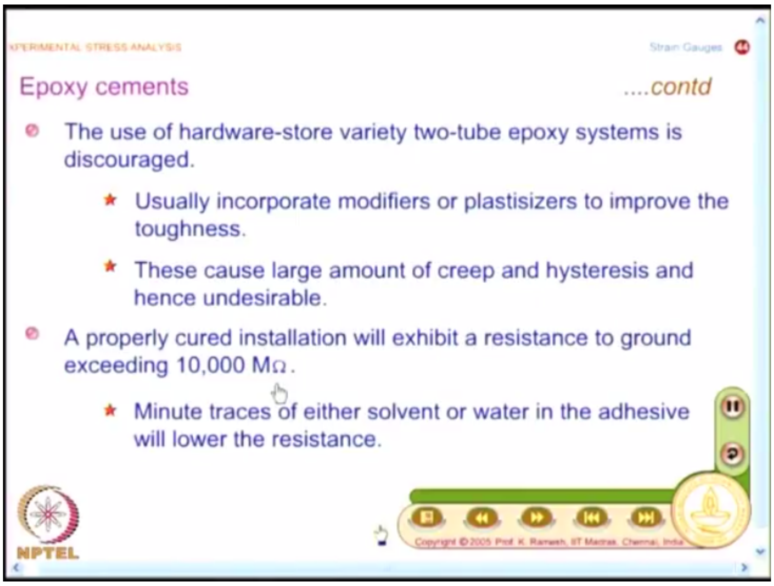

And another caution you know you cannot go I have read in the class that epoxies can be used you cannot go and buy M-seal and then say that is also an epoxy I have a putty why do not I mix together and then put it. You will have a thickness of may be 0.5 millimeter that is not good for your strain gauge instrumentation.

Because you know any of this hardware store variety two-tube epoxy systems incorporate modifiers or plasticizers to improve the toughness. They cause large amount of creep and hysteresis and hence undesirable. So the strain gauge manufacturer certifies a particular cement, whatever the cement that is available it is not good for because I said you do not want to have hysteresis problem in strain gauge installation.

And you cannot wake up after completing the strain gauge installation how to handle hysteresis. While you install the strain gauge itself, the selection of your adhesive, selection of your backing, selection of your strain gauge alloy everything contributes to the final performance of the strain gauge in a given environment. So you should know for which application you are selecting the strain gauge system.

So it is like a system, you have to worry about adhesive, backing as well as the alloy suitable for a given application and how do we ensure that the installation is properly cured? Because after installing the strain gauge, you must verify before you go for strain measurement whether the installation has been successful and the recommendation is if the adhesive is properly cured, a resistance to ground will exceed 10,000 mega ohms a very high resistance.

If the resistance is low, it is an indication that you have minute tracers of either solvent or water in the adhesive system. So this is a check after installing the strain gauge you also ensure before you make the measurement whether the resistance to ground is very high, it should be in order of 10 mega ohms and in fact you need special meters to measure this that is also supplied by the strain gauge manufacturer.

You cannot use it with your multimeter you cannot measure this. You have to have a special meter to measure this because this has to be measured with sufficient accuracy and that kind of meters are also available from strain gauge manufacturer.

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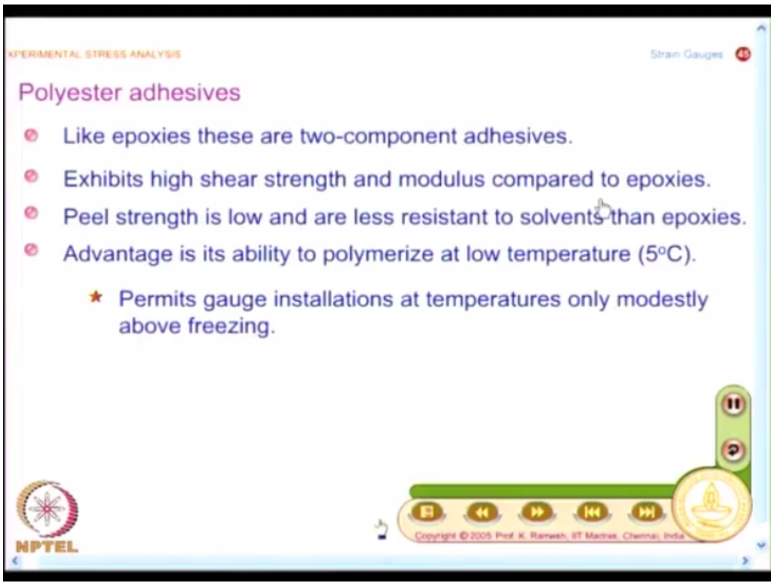

And you know polyester adhesives are very similar to epoxies. They are also 2 component adhesive and the advantage of polyester is its ability to polymerize at low temperature about 5 degrees centigrade. So it permits gauge installations at temperatures only modestly above freezing temperature and what you find is its peel strength is low and are less resistance to solvents than epoxies.

It exhibits higher shear strength and modulus compared to epoxies and it is very similar to epoxy adhesive, but it is useful for low temperature applications. So in this class, what we looked at was we looked strain gauge as a system; we looked at what are the various alloys that are used for making the strain gauge metal foil or the strain gauge grid. Then we looked at why you need a carrier, what are the different carriers available.

Then we looked at what are the different adhesives that you can use to bond the strain gauge and we have looked at selection of each one of this has an influence on the final performance. So if you want to go in for high fatigue strength, you go for selecting Isoelastic alloy. On the other hand, if you have to make measurement for long durations, you go for a Karma alloy. For room temperature application, Advance is good enough.

And if you want to go for the transducer application, you need to have very thin bond lines, so that repeatability is fully ensured because when you are going to use a transducer you will use it for load measurement for a very long time where it will be subjected to repeated loading and you want good stability and you need to maintain thin bond lines and we also saw to make thin bond lines we need to apply appropriate pressure.

And even the application of pressure is simplified by the train gauge manufacturer by supplying suitable clips. You do not have to hunt for how to apply the pressure, you just take the transducer and appropriately use this clips your job is done. You maintain that pressure and keep it at that temperature and allow the epoxy to cure completely. Thank you.