Creep Deformation of Materials
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Importance of studying creep

Hello everyone, my name is Srikant, I will take you through this NPTEL course on Creep Deformation of Materials, so creep is a very interesting topic of mechanical metallurgy pertaining to especially high temperature deformation in the presence of a load or stress and over the next few classes or lectures. I will take you through the following topics on creep.

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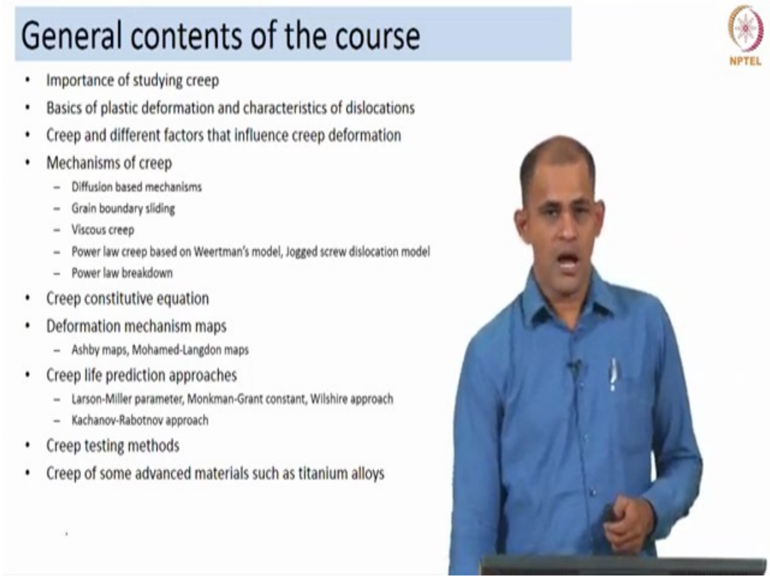

In the first lecture, I am going to introduce you to the importance of studying creep, so why studying creep deformation is important, how is it relevant for a metallurgist or for that matter an engineer or a scientist and how does it affect us in our day to day life. Since, creep is a mechanism of plastic deformation, so in one of the classes, I will introduce you to some basics of plastic deformation.

Especially with a focus on characteristics of dislocations because plastic deformation involves dislocations and creep along with point defects such as vacancies, the line defects dislocations have an important role to play, following that we will deep dive more into creep where we will talk about; what is creep, what does a creep curve look like, what are the different factors that influence creep and what are the different mechanisms that scientist and researchers have proposed to explain creep.

Just to elaborate a little bit, the mechanisms of creep that have been discussed so far over several decades of work are diffusion based mechanisms, grain boundary sliding, viscous creep and some power law creep based mechanisms which are essentially dislocation based such as the ones proposed by Weertman or the jogged screw dislocation model proposed by Nix and coworkers.

We would also talk about when does the power law break down and under what conditions of stress, temperature or other features would the power law break down and then what is the governing equation for creep, so this is an equation known as the Bird-Mukherjee-Dorn Equation which is known as the creep constitutive equation, so we are also going to talk about the importance of this equation.

Following that, we are going to talk about deformation mechanism maps; like a map does, a map basically guides us through different locations, similarly a deformation mechanism map will guide you through different stress temperature windows to understand if one mechanism of creep will be dominant over another mechanism, so the original deformation maps, mechanism maps were proposed by Ashby and subsequently there was another version of the deformation mechanism map that was proposed where Mohamed and Langdon, so we will be discussing both these maps and I will tell you how these maps are constructed.

Of course, the whole objective of learning creep is to know, how long a material or a component is going to survive in a real life application, what is the kind of service life that we can expect from a component during use in any engineering application, so learning about the different mechanisms of creep, learning the equations of creep, etc. gives us the ability to predict the life of a component under creep conditions and this is what some of the different researchers have done for example, the Larson-Miller parameter is one such parameter that helps you to estimate or predict the life of a component under creep conditions.

Similarly, there are other approaches such as the Monkman-Grant approach or the Wilshire approach which also help you in understanding the creep life of any material, there are other approaches also known as continuum damage based approaches such as the Kachanov-Rabotnov approach which would also help you in predicting the life of a component so that is also something that we will discuss in this course.

And of course, when we talk of creep, what is the best way of determining the creep behavior of a material, how do you test a material for creep and that is what we will cover under creep testing methods, I will introduce you to conventional creep testing methods and also to some small scale creep testing methods such as impression creep testing methods and finally we will conclude the course by giving you some real life examples of creep behavior of say titanium alloys.

Titanium alloy is an important technological material used in the aerospace industry as well as in other places, how have people developed titanium alloy so that it can be used say as a creep resistant material in the aerospace industry so somethings like that I will talk about that in the last section on creep of titanium alloys.

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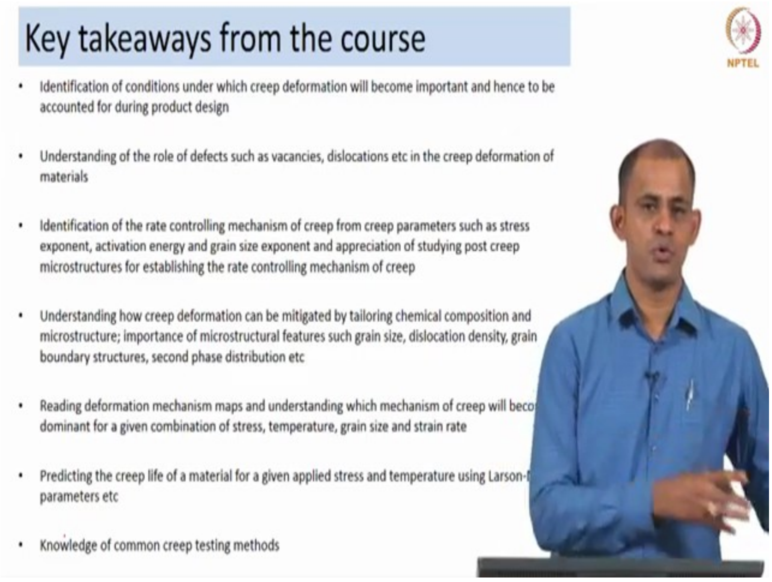

So after you have attended the course this is what I believe you would learn. So in this slide, I am talking about the key takeaways from this course, so on successful completion of the course including doing the assignments you will be in a position to identify the conditions under which creep deformation will become important, so once you understand the conditions you will know whether you have to account for creep for any product or any material that you are designing.

Similarly, completing the course you will gain an appreciation of the role of defects, point defects such as vacancies or line defects such as dislocations, what is the kind of role these defects play in the creep deformation of materials and once you understand that you will be in a better position to account for them and you will be in a better position to decide whether you should have more of these defects or you should have less of these defects while accounting for creep.

Similarly, having gone through the different mechanisms of creep, you will know which of these mechanisms will be rate controlling or will be dominant during creep deformation of materials, so this you will learn, this you will be able to do by looking at the creep parameters, so when you look at the creep constitutive equation that I will introduce in the coming lectures, you will know that there are different parameters such as stress exponent, activation energy, grains size exponent and knowledge of these parameters will give you insights into the rate controlling mechanism of creep.

You will also gain an appreciation of the importance of studying post creep microstructures, so knowledge of the parameters will tell you which mechanism of creep is operating, but you also need some more experimental evidence to validate your conclusions based on the parameters, so that validation can be obtained by studying post creep microstructures either by employing a scanning electron microscope or a transmission electron microscope.

This course will also help you in understanding how you can reduce or mitigate creep deformation so what kind of chemical compositional changes or chemistry that you should use for your alloy or what kind of microstructural features should your alloy or material bear, microstructural features such as grain size, dislocation density, grain boundary structure, etc. what kind of combination of chemical composition and microstructural features should your material have so that it can be considered creep resistant such that it will not experience high amount of creep in service.

You will also be able to read deformation mechanisms map at the conclusion of this course and understand from this maps which mechanism of creep will become dominant for a certain combination of stress, temperature, grain size and strain rate and like I mentioned in the previous slide, you will also be able to predict the life of a material, the creep life of a material for a given set of conditions and finally you will gain knowledge of common creep testing methods. So this is what you will learn on successful completion of the course.

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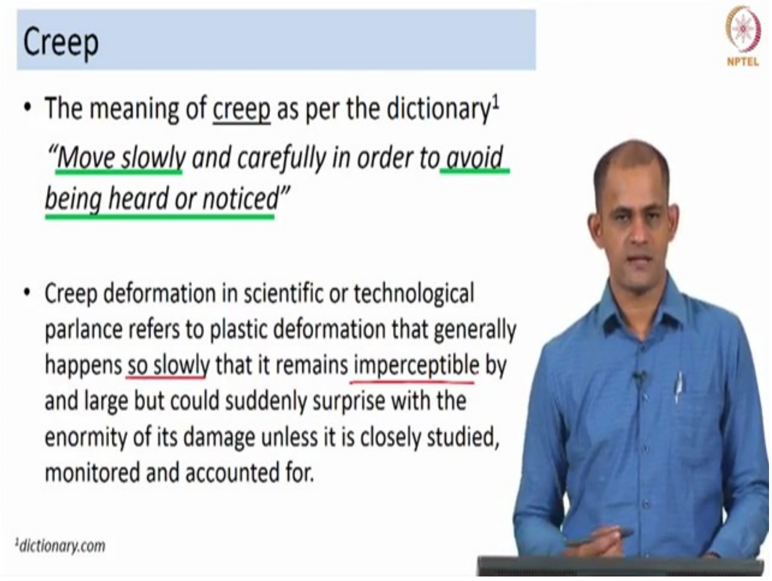

A brief introduction of creep and the significance of studying creep, so the meaning of creep as per the English dictionary is as follows, creep is basically an action of moving slowly and carefully in order to avoid being heard or noticed. Well this is what people studying English literature would think of creep but for us engineers or scientists, creep very interestingly indicates the same.

So in a very generic fashion if I have to define creep, I would say creep refers to plastic deformation that generally happens so slowly that it remains imperceptible by and large, but could suddenly surprise you with the enormity of its damage unless it is closely studied, monitored and accounted for. So you can clearly see the kind of analogy that one can draw with the English dictionary definition of creep.

So creep is going to happen slowly, move slowly and so slowly so there is a correlation there and because it happens slowly it is not dynamic enough such that you will not know that deformation is occurring by creep but creep plays an important role because the damage that happens in the wake of creep could be enormous and hence it is necessary to study it closely and account for it, when you design a product.

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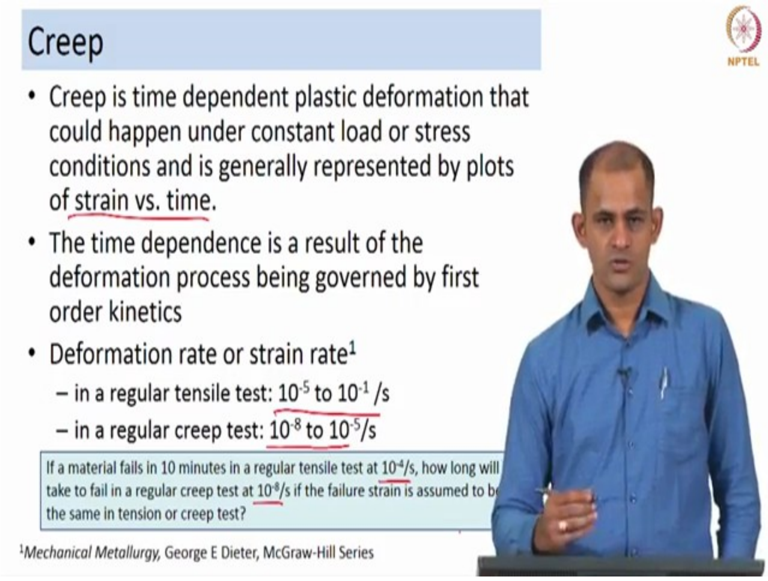

In scientific terms, creep is time dependent plastic deformation that generally happens under constant load or stress and creep is represented by plots of strain versus time, of course when we talk of plastic deformation we usually think of stress strain curves but here in creep the plastic deformation is represented by strain versus time curves, so how is creep different from plastic deformation that we understand from stress - strain curves.

Of course, the time dependence is something that is important about creep and the time dependence is a result of the deformation process being governed by first order reaction rate kinetics but then the deformation rate here is significantly lower compared to what an engineer would observe in a regular tensile test or a compression test, so if you are doing a regular tensile test using a dog-bone sample, the kind of strain rates or deformation rates that you will apply will be in the range of 10 to the power minus 5 to 10 to the power minus 1 per second.

But in a regular creep test the deformation rates are on an average 3 to 4 orders of magnitude lower than what you experience in a regular tensile test, so the deformation rates are in the range of 10 to the power minus 8 to 10 to the power minus 5 per second, now how does this influence the time part of your test, so just to give you an example, let's say a material fails in 10 minutes in a regular tension test at a strain rate of 10 to the power minus 4 per second.

Now how long will it take for the same sample to fail in a regular creep test which is being carried out at deformation rates of the order of 10 to the power minus 8 per second, assuming that the strain to failure in the tension test as well as in the creep test is the same. So if you do this problem you will find it very interesting because the time taken in creep is at least 3 to 4 orders of magnitude higher than what is necessary in a tension test.

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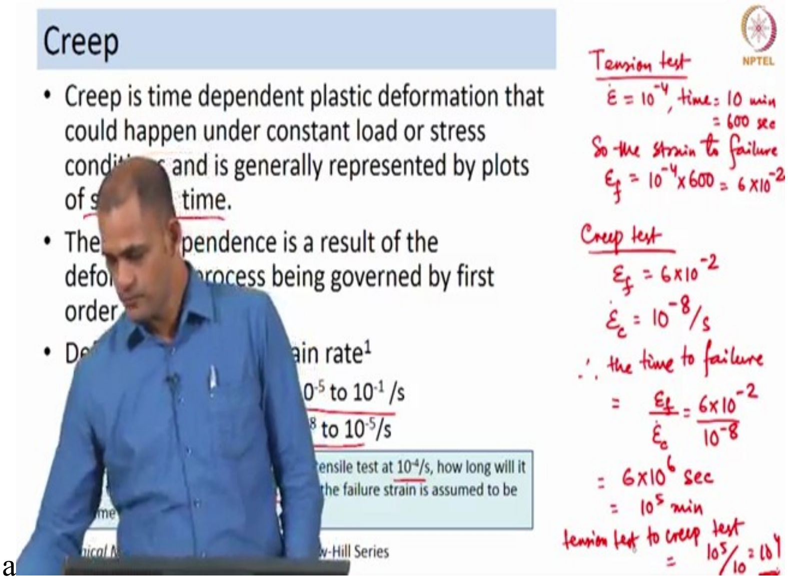

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So just to solve this problem:

<u>Tension test</u>

The strain rate of deformation is given by $\dot{\varepsilon} = 10^{-4}$

The time taken to failure, t = 10 min = 600 sec

The strain to failure, $\varepsilon_f = 600 \times 10^{-4} = 6 \times 10^{-2}$

So since the condition that we have stated is that,

The strain to failure is the same in both tension and the creep test.

Let's look at,

<u>Creep test</u>

The strain to failure, $\varepsilon_f = 600 \times 10^{-4} = 6 \times 10^{-2}$

The deformation rate in creep,

Let's say, $\dot{\varepsilon}_c = 10^{-8}$ /sec

Therefore, the time to failure in the creep test will be

$$\frac{\varepsilon_f}{\dot{\varepsilon}_c} = \frac{6 \times 10^{-4}}{10^{-8}} = 6 \times 10^4 sec = 10^5 min$$

So, it is clear that if you compare

The tension test to creep test: $\frac{10^5}{10} = 10^4$

times higher time for the material to fail, so why am I doing this or why am I telling you this is the tension test is a lot more dynamic compared to the creep test and because the creep test happens so slow you will not notice that the material is deforming and deforming towards failure.

And so it is very easy to ignore the creep test but ignoring the creep deformation will be at our own peril and that I will tell you by giving you a few examples in the following few slides. So, I said ignoring creep will be at our own risk and why is that, creep as a plastic deformation phenomena has been observed to be important in a variety of industries.

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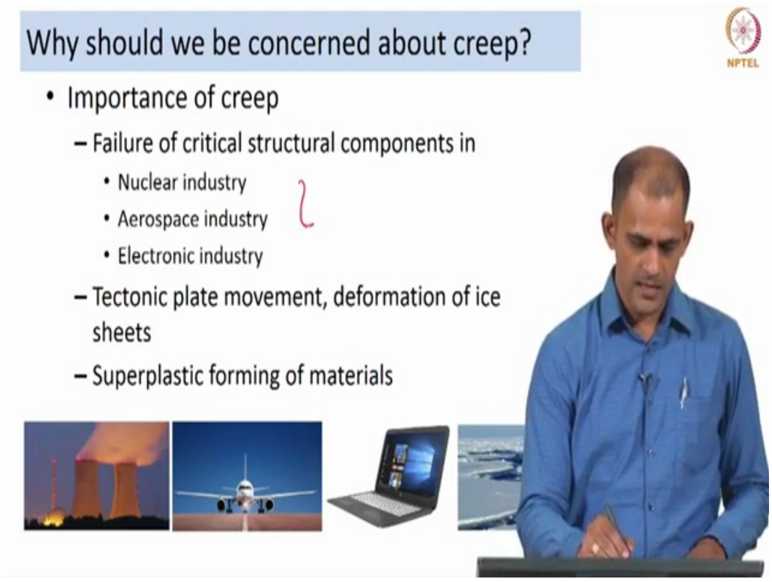

The nuclear industry, the aerospace industry, electronic industry, in each of this industries the components have been found to experience deformation governed by creep mechanisms and we all know the significance and the importance of the nuclear industry as well as the aerospace industry and the kind of impact these industries can have on our day to day to life and the hazards they pose if failures happen in a catastrophic fashion, of course electronic industry, laptops we use them day in day out and we would not like our laptop to fail suddenly and causing us financial losses.

So certainly there is a need to account for creep in each of this examples even if we move away from these industries there are other places where creep is actively playing a role, the tectonic plate movements happening within the earth's crust have been observed to be governed by creep mechanisms and creep deformation, similarly the deformation of ice sheets or glaciers in our Artic or Antarctic region or in Greenland for example, each of these sheets and the glaciers have a role to play in the climate that we are experiencing and we definitely do not want these to fail in a rapid fashion.

And again people have observed that creep mechanisms have a role to play there; even outside of these examples if we go into the manufacturing sector people have successfully employed super plastic forming for making a variety of components and super plasticity has its roots in concepts of creep so grain boundary sliding as an example is known to play an important role in super plastic forming.

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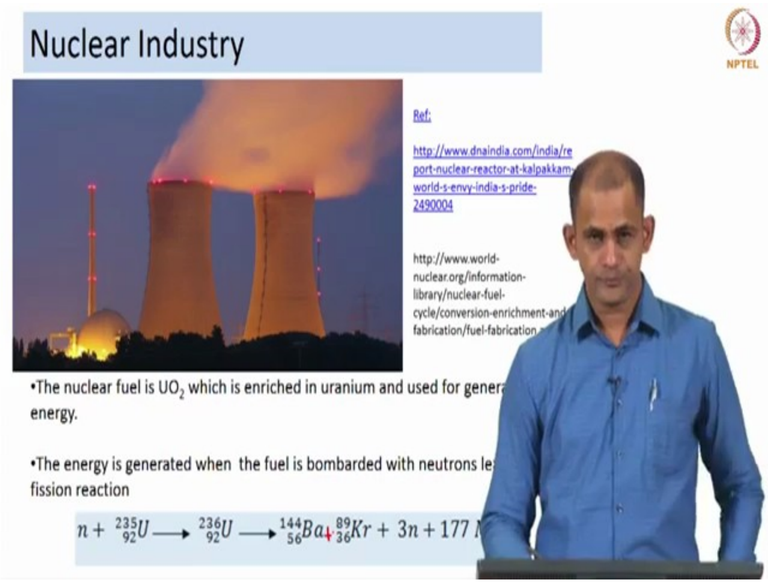

I will give you a few more details about each of these cases especially the industrial aspect as well as the tectonic plate movement aspect. Coming to the nuclear industry, the nuclear industry as we all know is an important source of energy and of course it has its own risks which we are made aware of time and now and then through some accidents whether involving say a tsunami in Japan, the Fukushima Reactor and the kind of issues that people faced in its aftermath.

In the nuclear industry the nuclear fuel is Uranium dioxide which is generally enriched in Uranium 235 and this fuel is used for the generation of energy, the energy is generated in the following fashion so this is an example of fission reaction where a neutron comes in contact with the Uranium 235 and creates an unstable isotope of Uranium which eventually decomposes into Barium plus Krypton and releasing some more neutrons and a high amount of energy.

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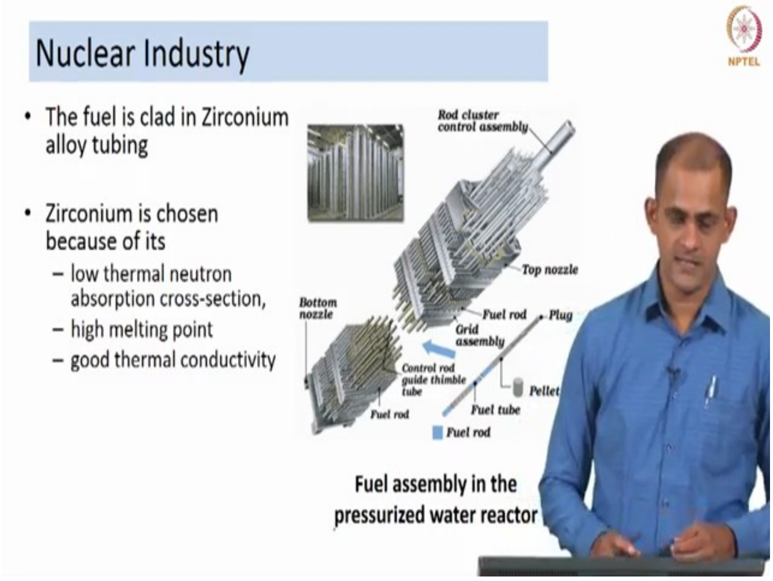

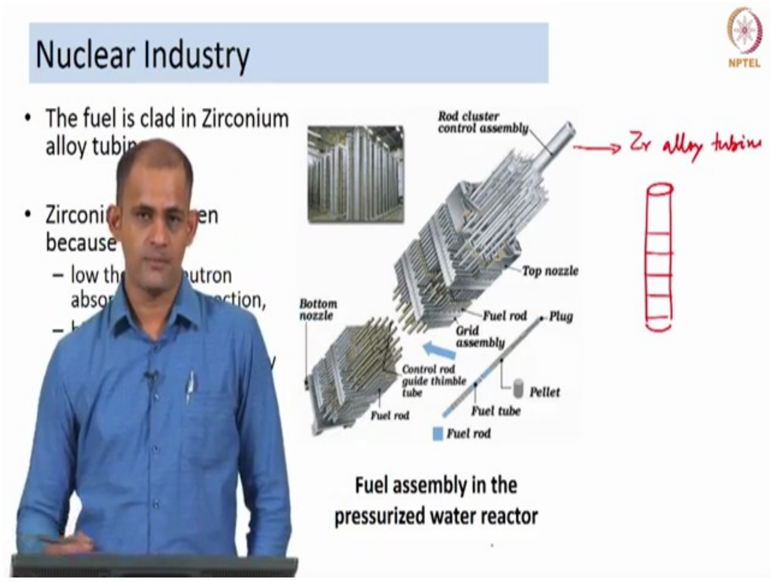

So in the nuclear industry the fuel which is in the pellets usually loaded into Zirconium alloy tubing, so imagine a tube of Zirconium alloy and pellets of the fuel loaded into this tube, these pellets the uranium dioxide pellets are releasing a lot of energy and since they are releasing neutrons, there is some amount of damage that the material can experience.

Of course before I go and talk about the kind of damage introduced, I would like to tell you why Zirconium is used as a material in the nuclear industry that is because of its low thermal neutron absorption cross-section, its high melting point as well as good thermal conductivity and this picture is basically showing you an assembly of Zirconium alloy tubing which is where the fuel is loaded in, as an example, I am talking about the pressurized water reactor.

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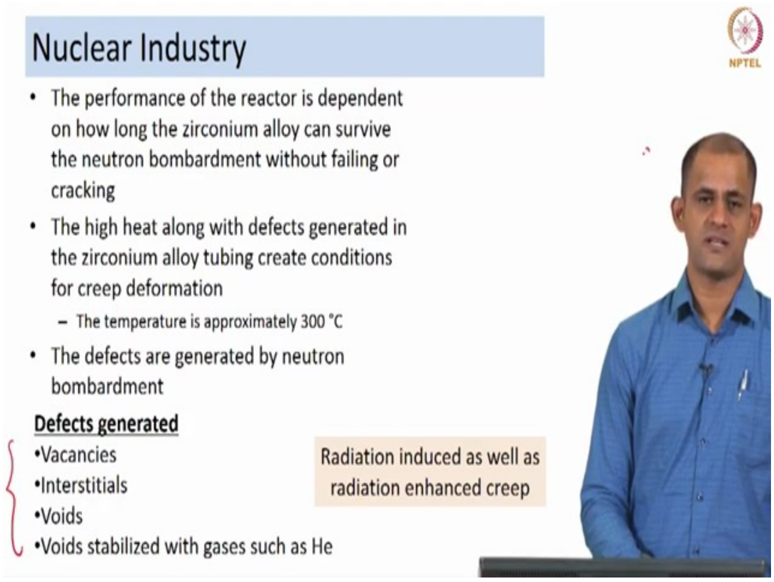

Now, I said the Zirconium alloy tubing is undergoing some damage and to tell you the performance of the reactor is actually dependent on how long the Zirconium alloy can survive the neutron bombardment without failing or cracking, so there is fuel loaded in the Zirconium alloy tubing and fuel is releasing neutrons as well as a lot of energy and the neutrons are bombarding the Zirconium material and creating a lot of defects.

So the defects that are generally generated are listed here, so you have vacancies, you have interstitials, you have voids, you also have some voids stabilized with gases such as helium and then you have high heat generated because of the energy released and the heat creates temperature in the range of approximately 300 degree centigrade, so under these conditions of temperature as well as defects created in the material people have observed that you have radiation induced as well as radiation enhanced creep in Zirconium alloy tubing.

And like I said earlier, creep is a mechanism of plastic deformation which can lead to failure of a material, it is important that the Zirconium alloy tubing survives these conditions and provides us performance as long as we desire, ideally it should survive these conditions till the fuel is no more useful to us .

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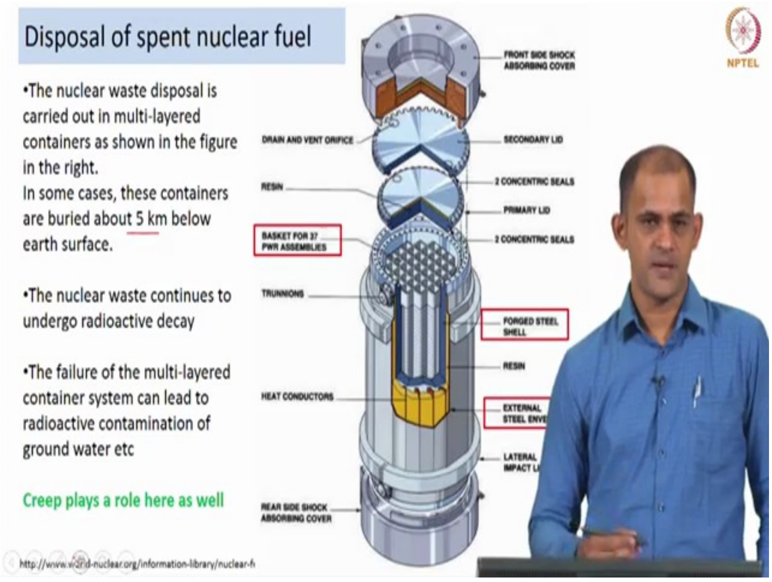

So since there is a radioactive reaction going on, the nuclear fuel continues to decay so much so that after a few years of usage it will not be as efficient as we want it to be and at that point of time it is now important to dispose the nuclear fuel, the disposal of nuclear fuel cannot happen like general trash. Specialized technologies have been developed in order to dispose nuclear fuel because of the obvious reason that it poses several environmental hazards as well as hazards to human health.

So the disposal of nuclear fuel is carried out in the same Zirconium alloy tubing. So the tubing is removed from the reactor and then this tubing is covered in the following setups, so you have these elaborate setup where the Zirconium alloy tubing is first enclosed by some steel envelopes and then some amount of concrete is used and this setup, this entire configuration is buried under earth about 5 kilometer below the earth's surface.

Of course we cannot stand and worry is what if the Zirconium alloy tubing fails or cracks allowing the neutron, allowing the radioactive fuel to come in contact with the steel and what if the steel also gives away leading to leakage of the radioactive waste and it coming in contact with our ground water so there are several scary possibilities, the basic point is we want the alloy as well as the steel to survive these conditions of heat as well as pressure.

And so you want the multilayered container system to be able to survive all these for as long as possible and one of the things people, researchers have observed is creep deformation plays an important role here and hence must be accounted for, so this was telling you the significance of creep in the nuclear industry.

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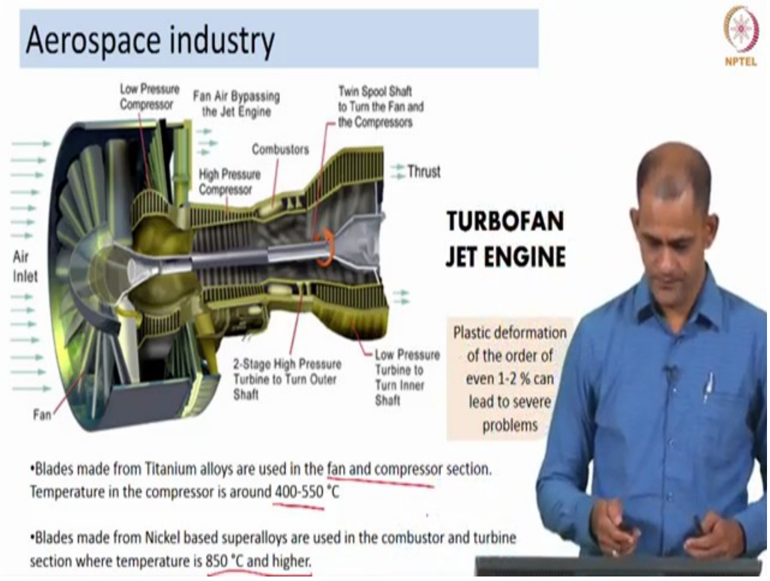

Another example is the aerospace industry, so in the aerospace industry you have gas turbine engines and we have other kind of engines as well as for example here I am showing you a turbo fan jet engine and the turbo fan jet engine uses air, the air comes in, comes in contact with the fan which accelerates it further then it goes into a compressor and then to a combustor where the because of its contact with fuel the air is further accelerated and it generates high pressure in the turbine region and eventually creates a sufficient amount of thrust for the engine to work and propel the aero plane or the jet engine forward or the jet plane forward.

When the air comes in contact at high speeds and it creates some amount of frictional heat so in the different regions of the jet engine there are conditions of heat as well as pressure created and for example in the compressor region the temperature created is in the range of 400 to 550 degree centigrade where as in the combustor as well as in the turbine region the temperatures can be significantly higher, in fact it's way above 850 degree centigrade but engineers by using certain type of thermal barrier coatings as well as cooling channels, ensure that the temperature is in the range of 850 degree centigrade and maybe around 1000 degree centigrade.

Because there are conditions of high temperature as well as pressure, creep deformation again plays a role and material such as titanium alloys are used in the fan and the compression section whereas nickel based super alloys are used in the combustor and turbine section and in each of the case what has been observed is, it is important that the plastic deformation created because of these conditions of temperature and pressure is not high because people have observed plastic deformation of the order of even 1 to 2 percent can lead to severe problems such that the engine could develop problems and worst case scenario is the engine stopping midair leading to a crash of the air craft.

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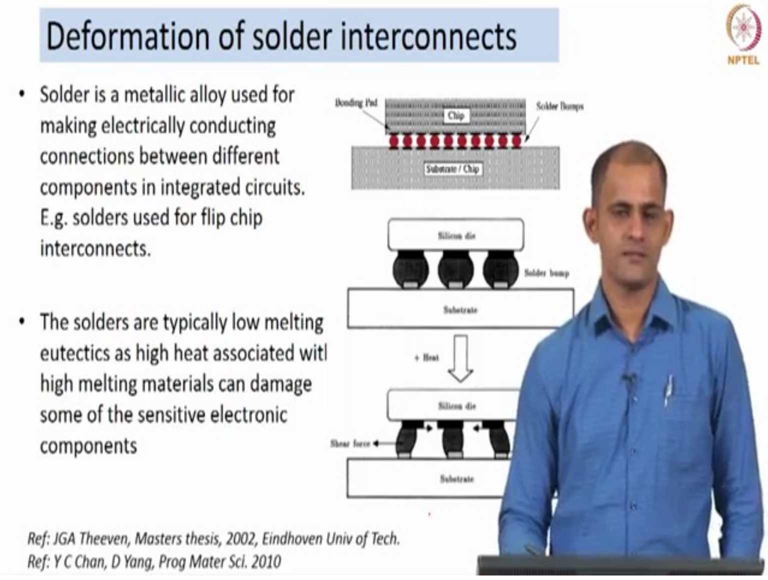

So it's important to monitor the creep deformation in these materials so that we know the useful life of the engine; another example is the electronic industry as I mentioned earlier, so the electronic industry uses solders as an interconnect material, now solder is a metallic alloy which is used for making electrically conducting connections between different components in integrated circuits, so it is basically like a joining material which completes the circuit as an example solders are used for the flip chip interconnects.

These solders are generally low melting eutectics because if you use a material which is high melting which has a high melting point then you have to provide a lot of heat to melt it for joining the different parts in the printed circuit board but one of the issues with electronics is if the heat generated is high then it can damage some of the sensitive electronic components that is why engineers have gone for low melting eutectics.

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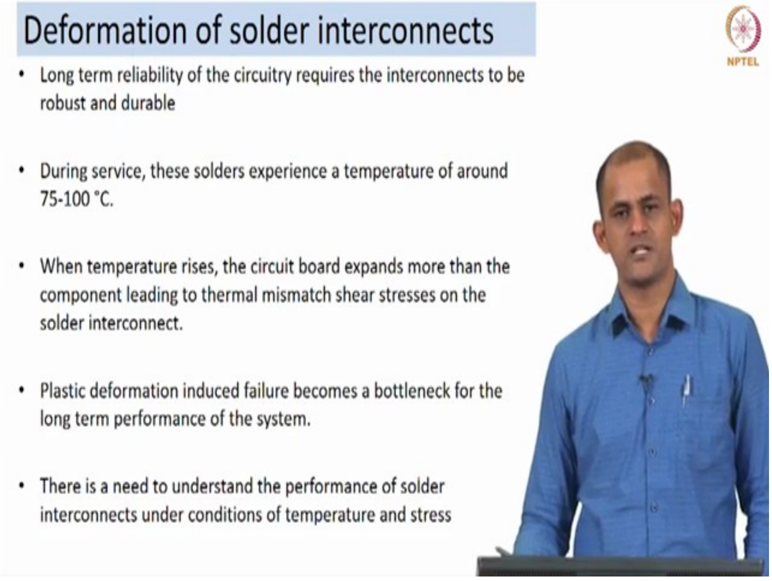

An example of a low melting eutectics is the tin silver eutectics so it is tin 3.58 percent silver and this is known to have a melting point of around 220 degree centigrade, now the life of the circuit board is dependent on the life of the solder interconnects and that's why creep plays a role to tell you how creep comes into play, so every time your laptop is working or computer or for that matter or any other electronic product is working, there is going to be some thermal mismatch stresses generated between the different parts making up the circuit.

And because these different parts are in contact with each other through the solders, these solders invariably are going to experience some of these mismatch stresses, so the thermal expansion co-efficient being different between the different components leads to thermal mismatch stresses and the solder interconnects experience these thermal mismatch stresses and because of that there is a chance that they will undergo plastic deformation and in the long run fail.

So the long term reliability of the circuitry requires the interconnects to be robust and durable during service, I mean while you are using your laptop as an example, the solders could experience temperatures in the range of around 75 to 100 degree centigrade and like I mentioned earlier when temperature rises the circuit board expands more than the component leading to thermal mismatch shear stresses on the solder interconnect.

And because of this plastic deformation induced failure becomes a bottle neck for the long term performance of the system. Hence there is a need to understand the performance of solder interconnects under conditions of stress and temperature and this is where again creep plays a role and must be accounted for.

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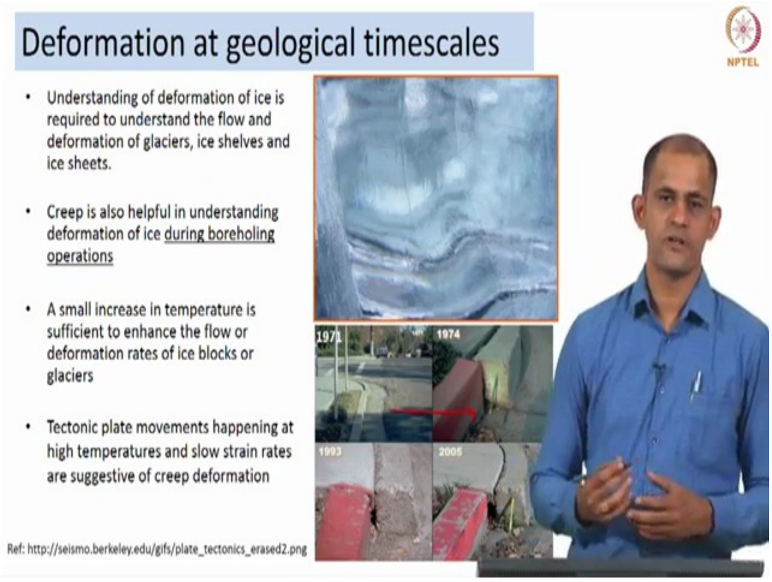

Another example where creep plays a role I mentioned about tectonic plate movements as well as deformation in ice sheets so geologists have noticed that the deformation of ice is governed by creep mechanisms, the deformation and flow of glaciers, ice shelves and ice sheets is very crucial especially so in today's times where global warming is a factor that we cannot ignore and from several years of work people have noticed that the deformation of these icy materials can be predicted by using creep equations.

Another area where creep equations are also useful is during bore holing of the icy sheets for cold ocean oil drilling operations require drilling of these icy sheets and while the drilling operation is in progress the ice sometimes flows back to close the hole and the flow of ice is again governed by creep equations.

So there is a need to account for creep or understand creep in these materials so that we can predict the life of these sheets and we can predict how long these sheets will be in contact before they break away exposing the sea underneath and probably contributing towards climate change, again another example like I mentioned is the tectonic plate movements and the tectonic plate movements are probably one of the reason why we experience earthquakes.

And the tectonic plate movements happen because as we go into the earth's core the temperature rises significantly and there is a temperature gradient because in the ocean bed the crust in contact with the ocean bed is at a slightly lower temperature compared to the crust in contact with the land or directly in contact with the mantle so there is some amount of stress build up happening because of the difference in temperature and this leads to stress generation and some of this stress is of shear nature is in the stress has a shear character.

And this leads to deformation which is again governed by creep mechanisms, just to give you an example the deformation can happen over several decades so here is an example of a pavement in California which has gradually experienced shear deformation as you can see one of the pavement part has moved significantly away from the other part, so the detachment of the pavement has happened because of this plate movements.

And like I said since there is a few decades involved in the movement again so the rate of deformation is very slow and again the rate of deformation is governed by creep mechanisms, so I have now given you at least 3, 4 different examples where creep is playing a role and this must tell you why creep must be accounted for because in each of the examples the end result is important and if we do not account for creep then this creep can lead to failure of a critical performance.

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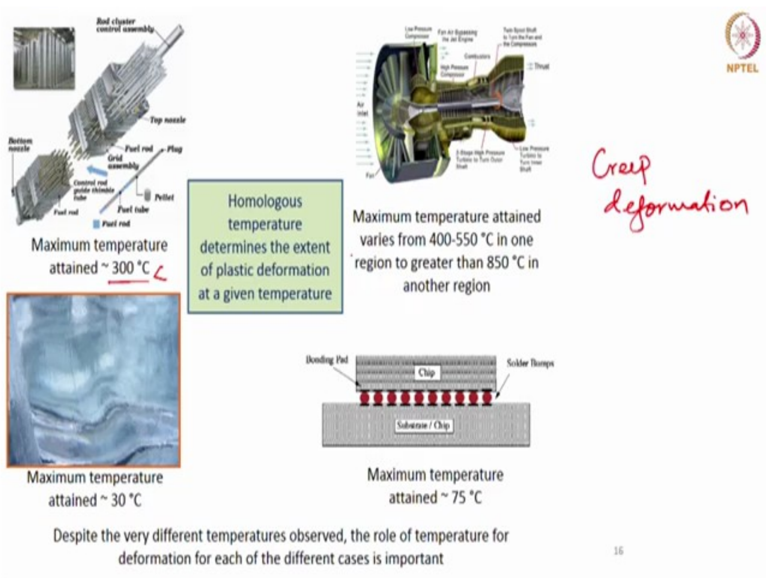

But I would like to draw your attention to something very interesting, in each of the application the temperature that the component or the material is experiencing is significantly different for example, I mentioned in the nuclear reactor, the Zirconium alloy tubing experiences a temperature around 300 degree centigrade, of course I said creep is happening in the turbo engine, turbo fan jet engine, the temperatures could vary from somewhere in the range of 400 to 550 degree centigrade in the compressor to as high as 850 or higher in the turbine and combustor region and again I said creep must be accounted for.

In contrast to that if you go to the glaciers or ice caps or ice sheets, a temperature of even 30 degree centigrade is sufficient to accelerate creep deformation leading to breakage of this sheets, so here the temperature is very low when we compare that what Zirconium alloy experiences or what titanium alloys and nickel based super alloys experience in a jet engine.

Even though the temperatures are so widely different in each case I have mentioned creep deformation is important and why is that? That is because of a concept called homologous temperature, so homologous temperature is actually what determines the extent of plastic deformation at a given temperature.

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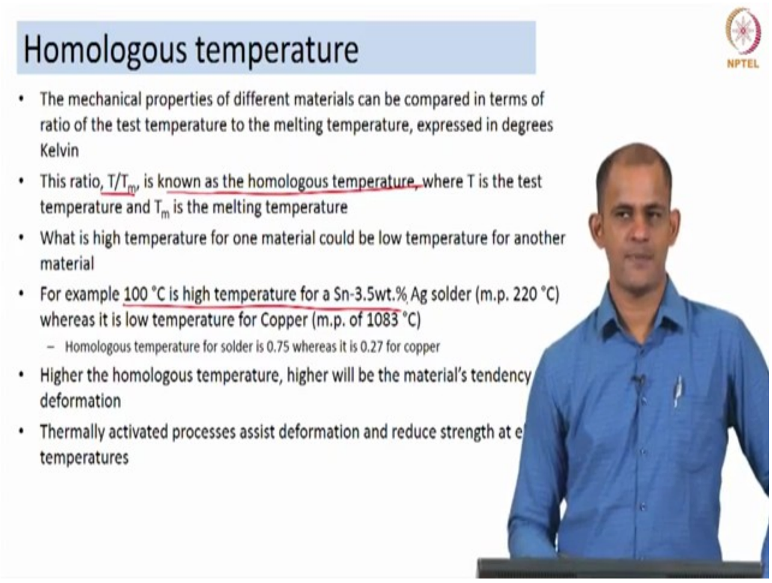

So just to elaborate a little bit about homologous temperature, the mechanical properties of different materials can be compared in terms of the ratio of the test temperature to the melting temperature expressed in degrees kelvin, so if you look at the ratio of the test temperature to the melting point of the material, this ratio is known as the homologous temperature and the homologous temperature is what will determine whether a material is going to experience plastic deformation by creep or high temperature plastic deformation.

So when I say high temperature deformation, what is high temperature for one material could actually be low temperature for another material based on this ratio for example, 100 degree centigrade is high temperature for a solder, for a Sn-3.5 wt.% Ag solder, the melting point is 220 degree centigrade and for this material 100 degree centigrade is very high whereas it could be considered as a slightly low temperature for copper which has a melting point of 1083 degree centigrade.

That is because the homologous temperature for solder is around 0.75 whereas it is 0.27 for copper, similarly if you look at ice, the melting point of ice is probably 0 degree centigrade or a couple of degree centigrade above 0 degree centigrade so if the ambient temperature is around 30 degree centigrade that will be very high temperature for ice to survive so which means the material is going to deform very rapidly as the temperature increases.

So the bottom line is if the homologous temperature is high then the plastic deformation is going to accelerate, so higher the homologous temperature, higher will be the material's tendency for deformation and hence if you have to decide whether high temperature plastic deformation is going to be significant for a material, the first that you should do is calculate the homologous temperature and if it is typically greater than 0.4 times of the melting point then you should start accounting for creep.

So the importance of temperature and other factors such as stress and all that is what I will cover in the next lecture I will especially talk about how some of the deformation processes are activated by the presence of temperature and how it assists deformation and before I go into that I will first take you through some basics of plastic deformation.