Advanced Design of Steel Structures
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Lecture - 09
FGM

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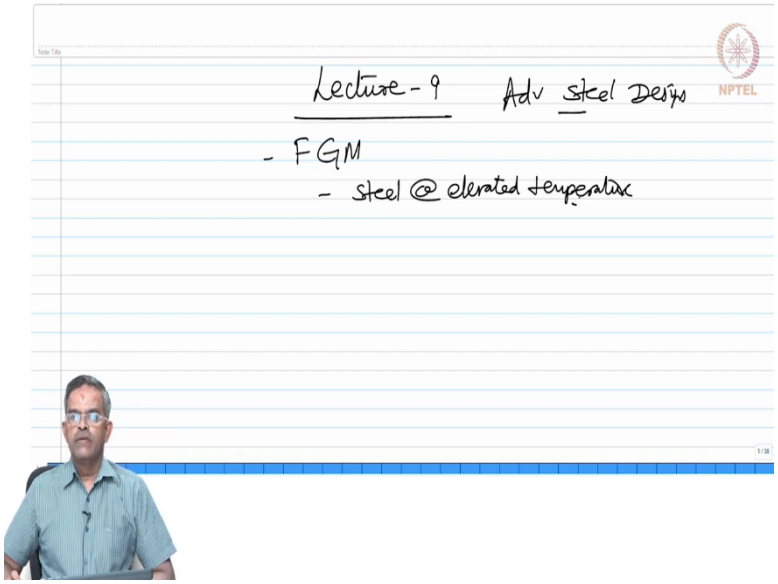

Friends welcome to the 9th lecture on Advanced Steel Design course. We have been talking about the material characteristics. In this lecture we will talk about functionally graded material and also we will discuss about steel at elevated temperatures.

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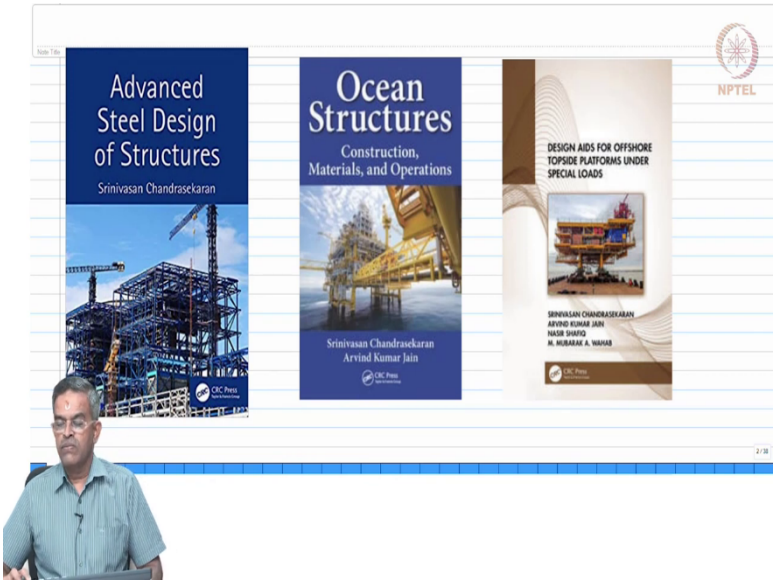

So, far friends a very good reference for the previous context of discussions we had can be seen from these textbooks as shown on the screen. Advanced Steel Design of Structures authored by me for CRC Press, Ocean Structures and Materials authored by me and Professor Arvind Kumar Jain for CRC press and a recent book published by CRC on Design Aids for Offshore Topside Platforms under Special Loads, which has got foreign authors as well in the textbook.

So, these books contain lot of information for additional and enhanced learning on the topics whatever we have. So, far discussed and I urge you to kindly go through them and improve your readability in a wide horizon apart from what we discussed in the classrooms during these lectures.

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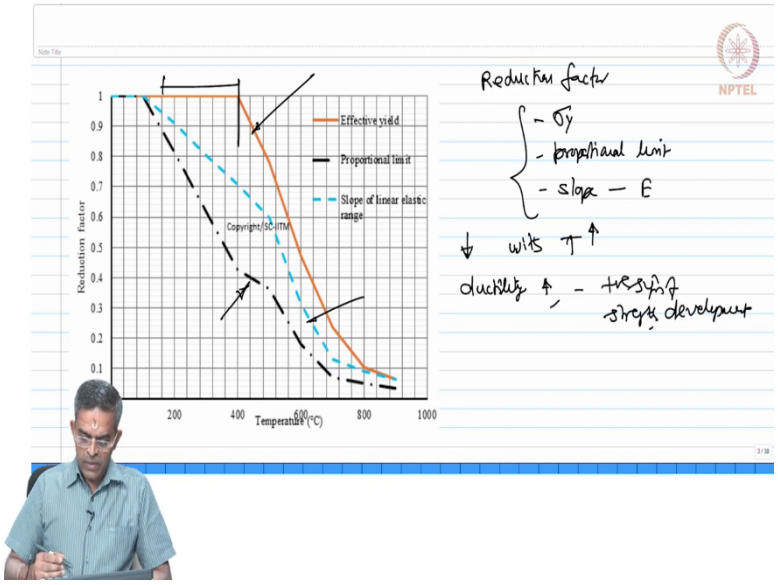

Having said this let us talk about steel property at a higher temperature. The figure what you see on the screen shows the reduction factor on different parameters of steel when the temperature is increased from about 200 degree centigrade to about 900. So, there is a reduction factor applicable to yield strength, proportionality limit and slope of the elastic range which will help you to compute the Young's modulus.

See effective yield is given by the crayon color, proportional limit is given by the black color and the slope of the linear elastic range of stress strain curve which is helpful to compute the modulus of elasticity is given by the blue color. One can see here from this figure from the plot the effective yield modulus of elasticity and yield strength decreases with increase in temperature. So, all of these properties decrease with increase in temperature.

However, ductility increases with the temperature to some extent you can see here to some extent. It is constant it is not influenced by the temperature which indicates a positive sign of strength development.

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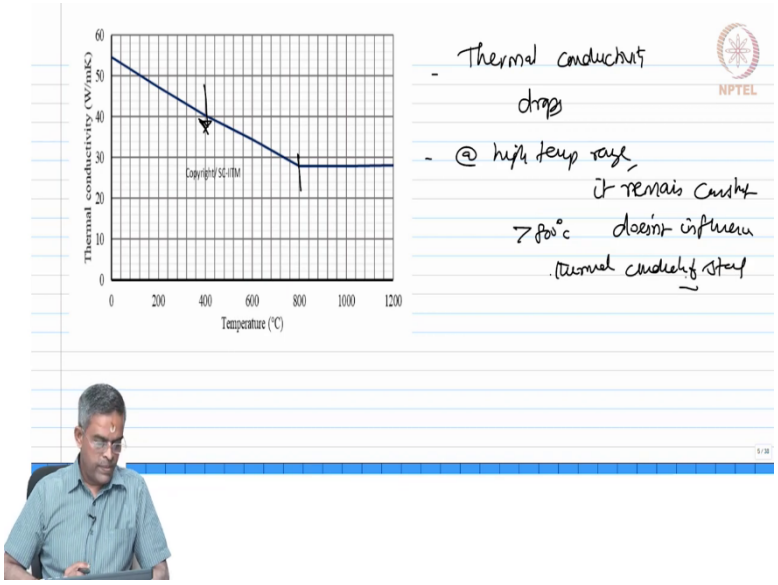

So, let us see the other properties of steel. This curve shows the variation of thermal conductivity which drops the thermal conductivity drops you can see here it drops with the increase in temperature. It is also see that up to 800 degree Celsius it drops then at higher temperature range it remains constant. So, temperature more than 800 degree centigrade approximately does not influence the thermal conductivity of steel.

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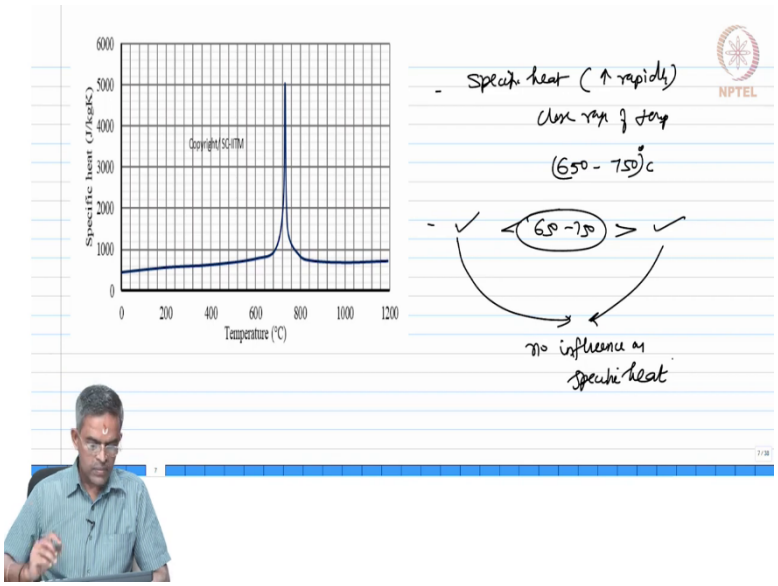

Similarly, if you look at the specific heat requirement, it gradually increases and the specific heat increases rapidly in the close range of temperature varying from 650 to about 750 degree

Celsius after which it remains more or less constant. That is temperature range between 650 to 750 it rises very steeply and the range below and after they have no influence on specific heat.

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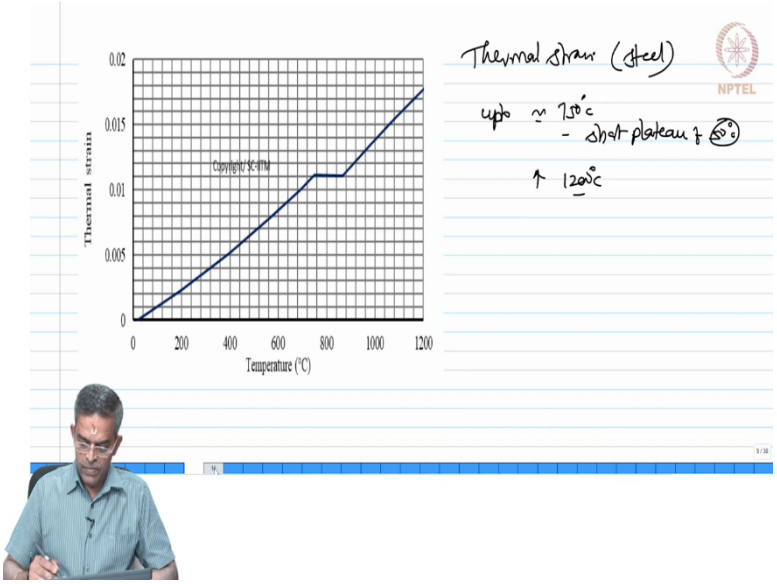

We can also see the curve which talks about thermal strain in steel which increases up to around 750, then remains constant for a short plateau of 50 degrees, then again increase up to 1200 degree Celsius. So, these are all very interesting behavior what we see as far as steel a construction material is concerned.

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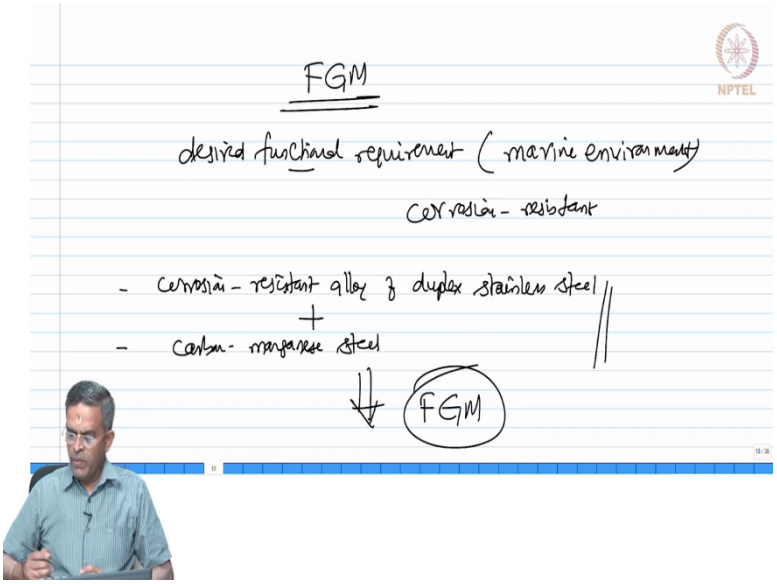

So, friends now we will talk about the new material which is recent and which is important for construction purposes which we say as functionally graded materials. The functionally graded materials or special kind of applications which are used or special kind of applications which are used for type of functional requirements. One of the desired functional requirement of steel in marine environment.

Let us say we will talk about marine environment because that is one of the vulnerable environment for corrosion. So, one of the desired functional requirements of steel to be used in marine environment should be corrosion resistant. Is it not? So, what actually people have been using so far is a corrosion resistant alloy of duplex stainless steel which has been used people also alternatively using carbon manganese steel.

So, now these have been used as individual materials for construction in marine environment. Let us quickly see how we can try to combine the best properties of these two and form a new material which is functionally graded material that is our objective now. Let us see that.

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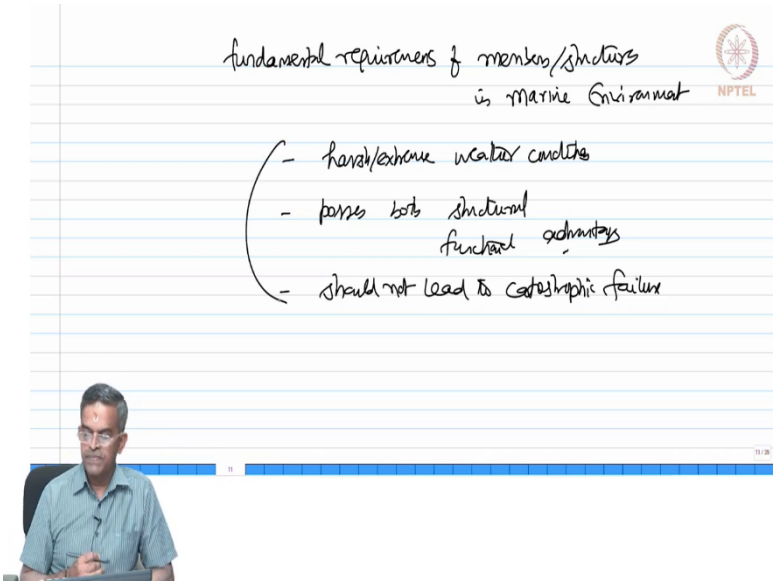

Before we understand to learn it further, let us ask a question what would be the fundamental objective of a design requirement of members in marine environment? The fundamental objective of design requirement could be that it should resist or structures in marine environment could be. It should resist harsh or extreme weather conditions it should posses both structural and functional advantages that is the idea. And most importantly as we recollect it should not lead to a catastrophic failure.

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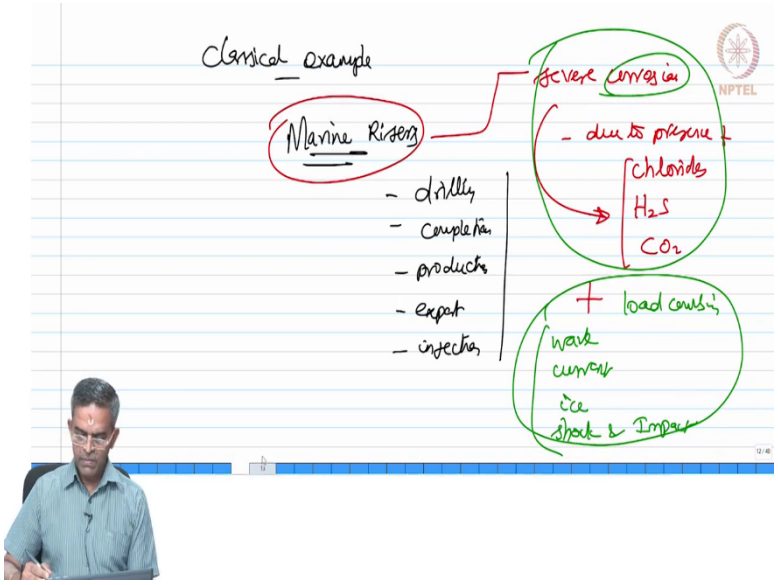

So, therefore, friends importantly when we talk about application of such conditions in marine environment. One classical example could be marine risers. Marine risers are actually used for various purposes in offshore structures for drilling, for completion, for production and export and for injection. These are various structural actions and functional requirements of elements of marine risers in offshore environment.

Now, what is the specific problem these risers have? These risers are subjected to severe corrosion. Why? Because due to the presence of chlorides hydrogen sulphide and carbon dioxide. This presence is felt as well as is encountered in the marine environment. Therefore, the marine risers are susceptible to this kind of environmental influence in addition to combination of loads that arise from wave, current, ice, shock and impact.

So, here I have taken a classical example where the loads are also very severe, the environment influence also very severe. Therefore, the design should focus on the functional requirement which is anti corrosive I do not want the metal to corrode forget about the design strength etcetera. Forget about giving corrosion allowance for the member.

Can you look into a material where the corrosion resistance is inhibited as a material property. Instead of using an existing steel or existing material and making it anti corrosive can I have a new material which is anti corrosive by itself that is innovation; that is advanced steel design we are talking about.

So, a recent research has been conducted in IIT Madras as a joint research between metallurgist, Professor and myself in Ocean Engineering Department. I would like to share some important information about that particular context of recent research development happened in IIT Madras for the benefit of the listeners of this course that is the advantage.

Friends in NPTEL courses where recent developments happening globally are presented for the knowledge sake for learning purposes an academic contributions through NPTEL platform. So, friends we are now looking forward for a new material which can have this combination.

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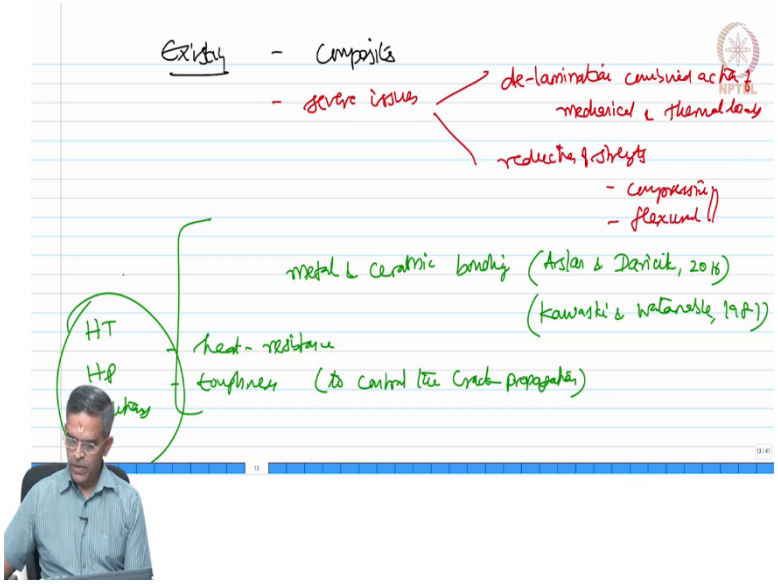

So, what is existing in the literature? What is now existing? Let us see that first before we develop a new material. The existing ones are focused on composites we have composite materials which are used as an alternate material for marine risers. But they have severe problems. One of the foremost severe issue is, delamination under the combined action of mechanical and thermal loads.

It also results in reduction of strength both in compressive and flexural perspectives and these are undesirable for marine risers because we need them in a larger perspective. People also investigated something related to the bonding which is done using metal and ceramic bonding Aslan and Daricik in 2016. Further Kawasaki and Watanabe into in 1987 gave this idea of improving the superiority of the material in terms of heat resistance.

Toughness because toughness is required to control the crack propagation or crack growth. And we are looking for this under high temperature, high pressure, conditions because marine risers are subjected to high temperature and high pressure conditions. So, under high pressure high temperature conditions composites are likely to have delamination therefore, we cannot use them. So, the alternate which is suggested in the literature could be the functionally graded materials.

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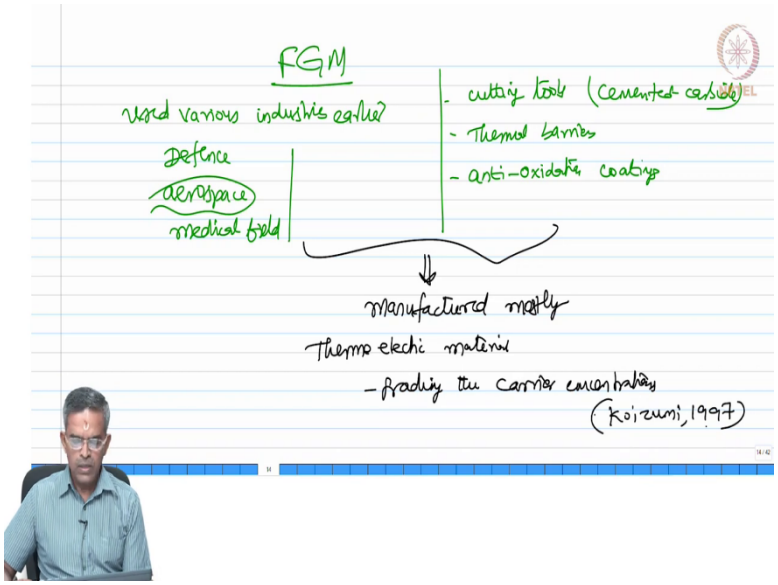

Let us see what are these functionally graded materials about. If you ask me the novelty of this material this has been used in various industries earlier it is not new. People have used this in defence, aerospace and in medical field. But you will; obviously, see the functional requirements of this material for different applications are different. In medical field people do not look for corrosion.

People look for durability in defence application, people look for strength in aerospace, people look for strength versus low weight strength ratio that is largest strength and lowest weight we are looking for the buoyant materials. So, the functional requirements of this applications are different, but people have been using this in these industries much earlier.

In addition, they have been also used as cutting tools in cemented carbide applications. They have been used as thermal barriers and they have been also used as anti-oxidation coatings. And if you look at the manufacturing process of these they have been manufactured mostly

using thermoelectric materials by grading the carrier concentrations as clearly pointed out in Koizumi 1997.

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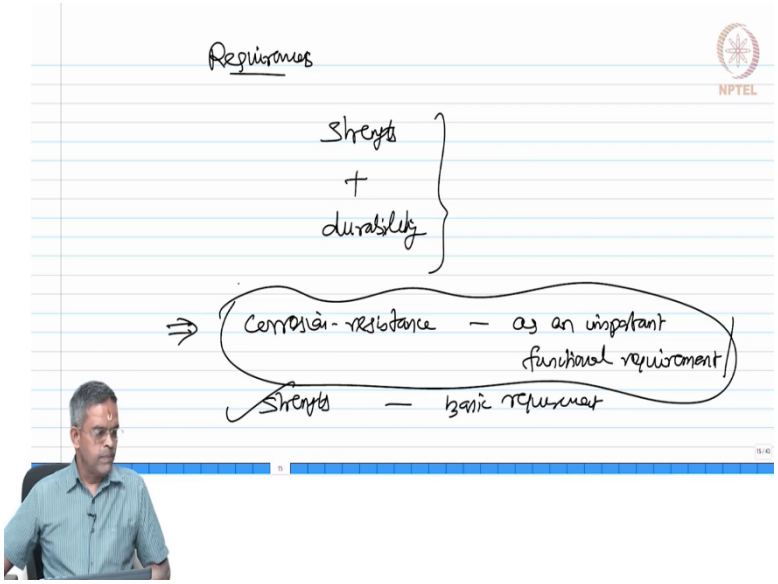

So, what we are now looking for is a material which has strength and durability. People have been using FGM for various applications and one of the primary requirement what we are now going to see is corrosion resistance as an important functional requirement. Of course, strength is a basic requirement for the member which is to be needed this cannot be compromised. In addition, we are looking for this is an additional requirement we have.

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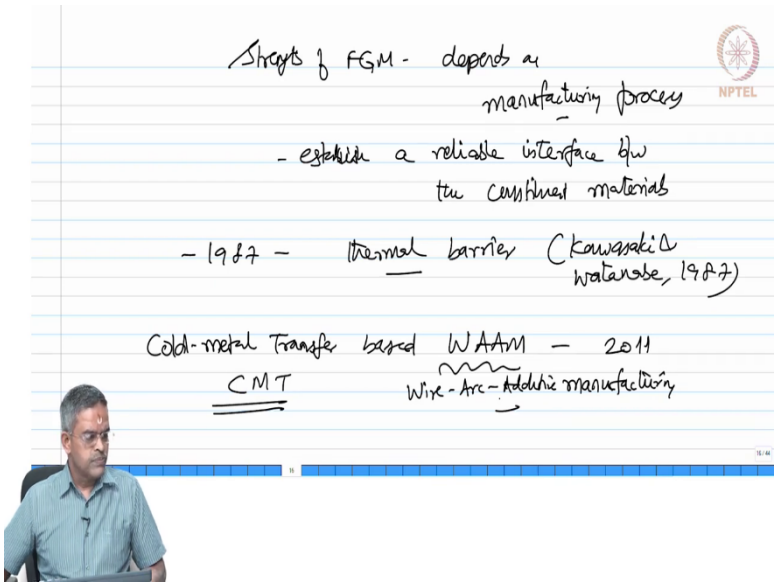

Now, interestingly the strength of FGM broadly depends on the manufacturing process. Because, you should be able to establish a reliable interface between the constituent materials. So, that you get a single material. The first application of FGM was tried in the year 1987; it was used as a thermal barrier not as a construction material. This was done by Kawasaki and Watanabe in the year 1987.

However, the cold metal transfer based WAAM Wire Arc Additive Manufacturing was brought to commercial use only in the year 2011. So, this is called CMT; Cold Metal Transfer this becomes the basis for wire arc additive manufacturing. This has been in commercial application only about just 10 years back. So, therefore, it is a recent development and we are investigating it for its suitability for special structures like marine risers.

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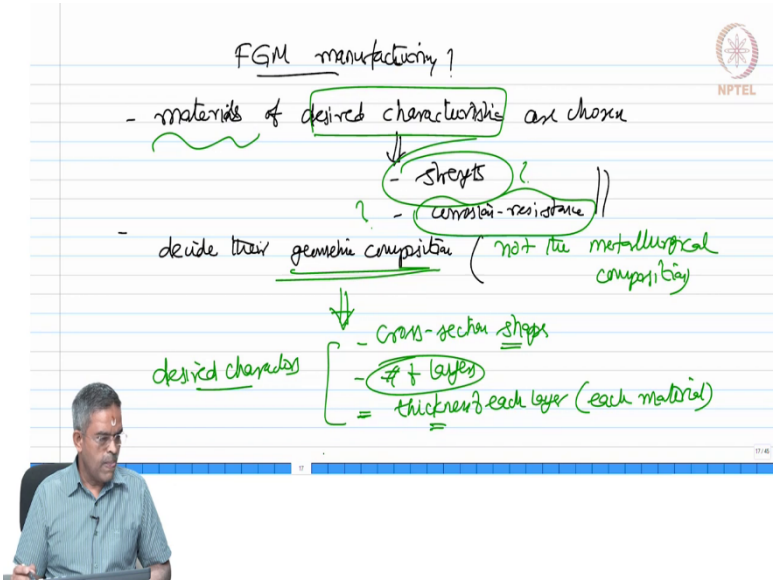

What do we do in FGM manufacturing? In FGM manufacturing materials of desired characteristics are chosen. What are the desired characteristics we need? We already said that we need the constant material should have strength and should have corrosion resistance. We are looking for essentially these two properties as functional requirements we choose this material then we decide their geometric composition.

Please note we are not talking about the metallurgical composition. We are talking about here the geometric composition friends please very careful about it. What do you understand by geometry composition? It means we have to decide about the cross sectional shape, the number of layers and of course, the thickness of each layer and each material.

So, in functionally graded material concept we pick up different materials of our choice having desired characteristics. And then we are going to unify join them fabricate them together using CMT based wire arc additive manufacturing technique. So, we decide during the time what should be the cross sectional shape, thickness and the number of layers to achieve the desired characteristics.

What are the desired characteristics we fixed earlier? What is the requirement of strength we need? What should be the corrosion resistance we want? So, we have to examine them right. So, we have to prefix them and examine them.

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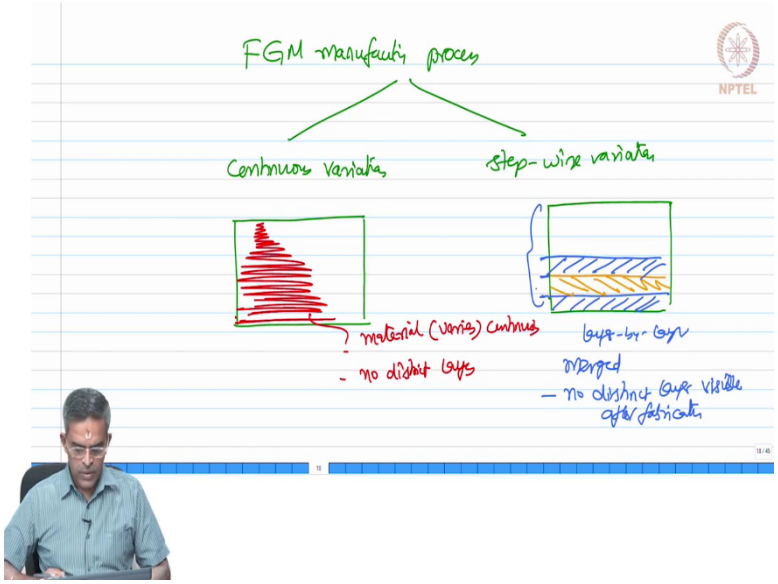

So, now if you look at a conventional FGM manufacturing process. They are manufactured by two ways; one is a continuous variation, the other one could be a stepwise variation. Now, what is the continuous variation? I look at a material this is my material boundary. So, the materials are varied continuously and there are no distinct boundaries. So, it varies continuously. So, the material varies continuously, no distinct layers.

The second could be a stepwise variation where what we do here is we keep on putting material layer by layer. So, we are doing layer by layer, but please note friends these layers, these boundaries will be merged. There will be no distinct layers visible after fabrication that is very important. It will look like a single material where the manufacturing is done in layers. So, that is the method of manufacturing FGM. One is called stepwise grading; other is called continuous grading.

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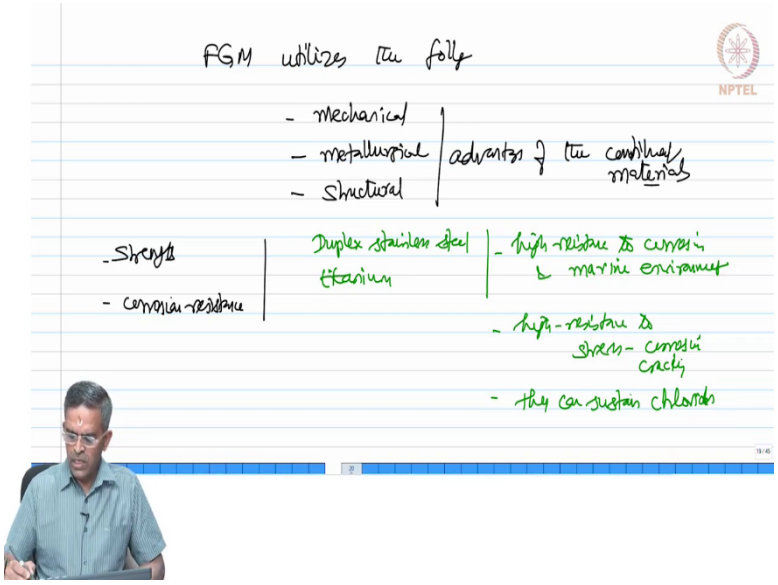

So, now FGM utilizes the following. What is the advantage if you manufacture FGM? It utilizes the following; it has the mechanical, the metallurgical and structural, advantages of the constituent material. Let us see what are those possible constant materials which can suit our functional requirement? What is our functional requirement? Our functional requirements are strength and corrosion resistance that is what we are looking at this moment as an example.

For this the material available are duplex stainless steel, titanium and carbon manganese steel where they show high resistance to corrosion an acidic environment. They also have high resistance to stress corrosion cracking. They also sustain chlorides in marine environment; those are present in marine environments and so on.

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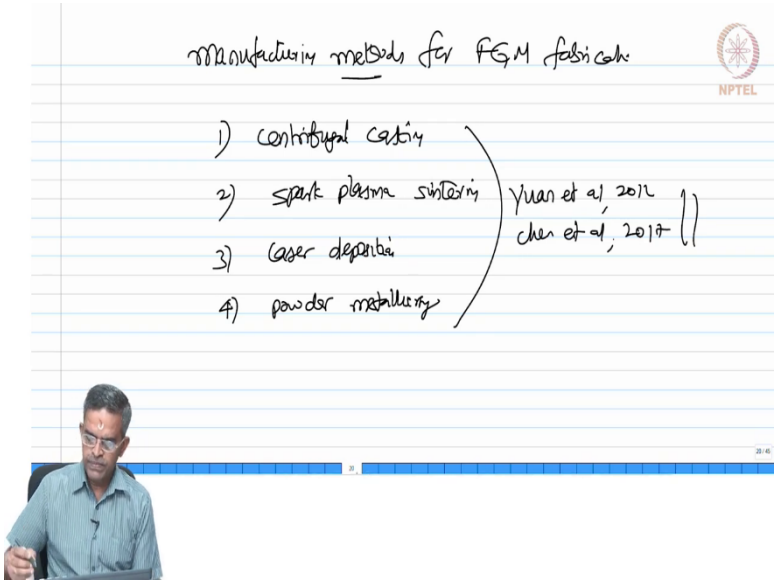

Now, let us ask a question what are the conventional manufacturing methods available in the literature for manufacturing FGM? There are many methods available in the literature centrifugal casting, spark plasma sintering, laser deposition and powder metallurgy. These are all of course, referred in literature very widely I am not discussing each one of them in detail.

For example, you can look at Yuan et al in 2012; we also look at Chen et al in 2017. These are for some cross references, but there are many things available please look into the list of references in the website of this course you will get this links.

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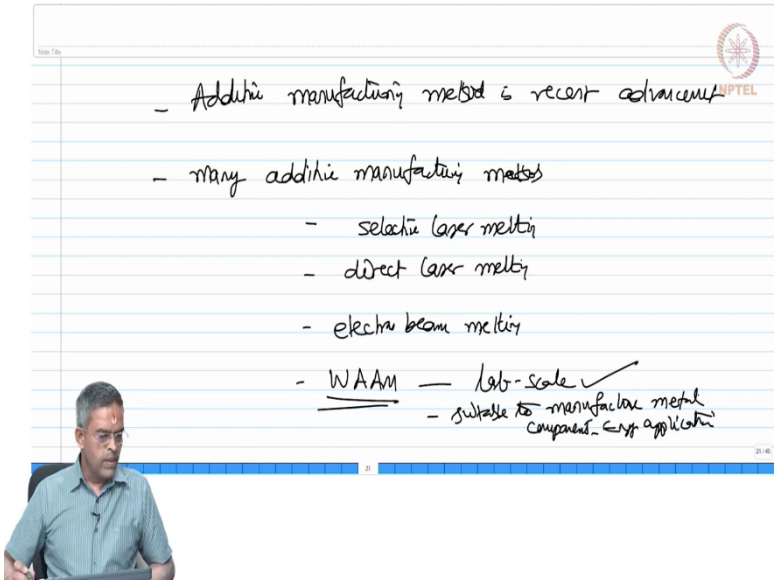

However, additive manufacturing technique is recent. There are many additive manufacturing methods, there are many additive manufacturing methods, selective laser melting, direct laser melting, electron beam melting and wire arc additive manufacturing. However, WAAM is very comfortable to use in lab scale and it has got one of the advanced techniques for manufacturing metal components for engineering applications. So, it is suitable to manufacture metal components for engineering applications.

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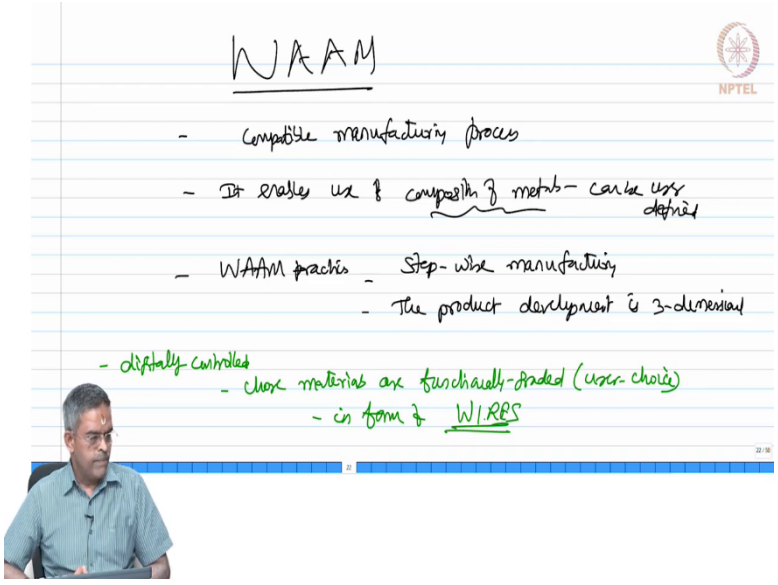

Let us now talk about WAAM. Let us talk about WAAM a bit, WAAM is a compatible manufacturing process. It enables use of composition of metals which can be user defined that is very interesting. You can define the composition to manufacture that combined product in WAAM process. So, WAAM practices stepwise manufacturing method. We have seen there are two methods of FGM continuous in stepwise WAAM adopts stepwise manufacturing, and the product development is 3 dimensional.

So, how does it do this manufacturing? The manufacturing process is digitally controlled wherein the chosen metals or I should say materials or functionally graded as per the user in the form of wires that is why it is called wire arc additive manufacturing. And these wires are interchanged these wires are interchanged during the deposition process.

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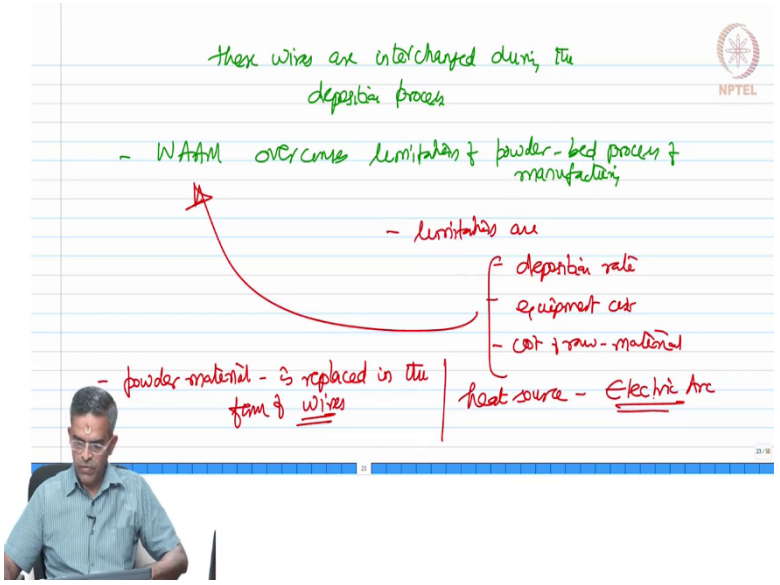

This method actually overcomes the limitations of powder bed process of manufacturing. The power bed process has got certain limitations; the limitations in powder bed manufacturing are deposition rate, equipment cost and cost of raw material. So, these factors are overcome in WAAM. So, in WAAM the powder material is replaced in the form of wires ok that is one physical difference you can see here. So, the heat source used for manufacturing for manufacturing is an electric arc that is the heat source we use for manufacturing.

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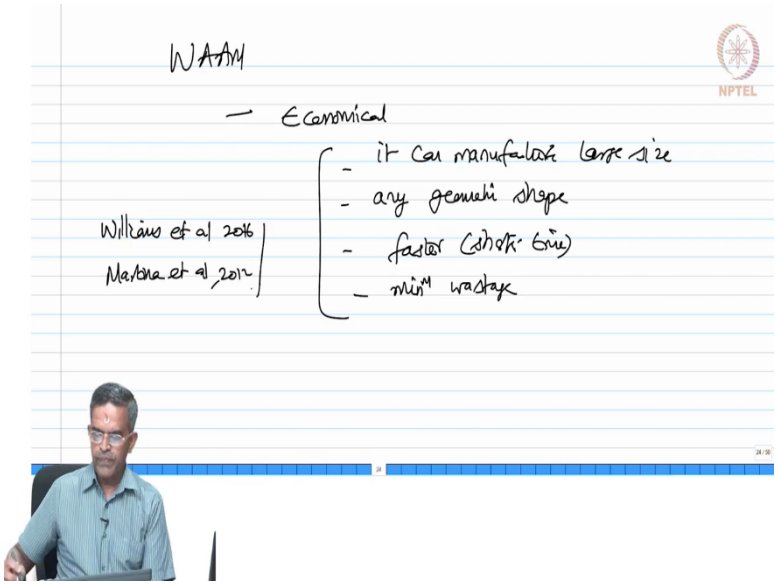

WAAM is considered to be economical because it can manufacture large size, it can manufacture any geometric shape, it can manufacture faster so shorter time with minimum wastage. So, it is economical these are of course, stated in many studies one classical example could be Williams et al 2016 and Martina et al 2011.

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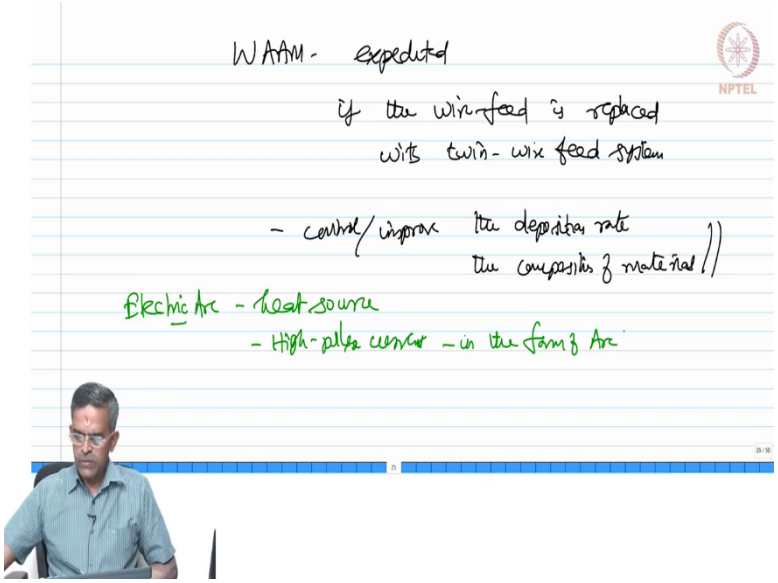

So, WAAM can be also expedited you can make this manufacturing faster if the wire feed is replaced with twin wire feed system. So, this can control and improve the deposition rate and the composition of materials. As I told you electric arc is used as a heat source it supplies high pulse current in the form of an arc between the electrode wires and the substrate and makes the deposition.

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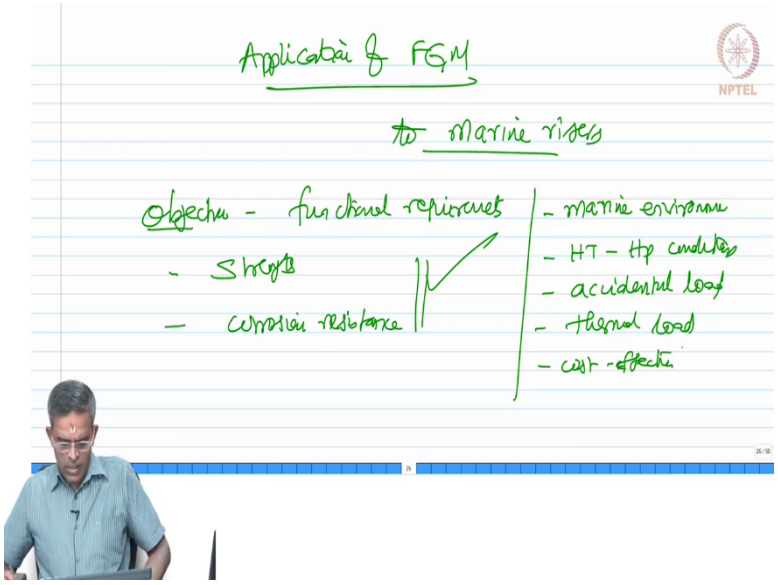

So, let us talk about the application of FGM to marine risers. So, what are the objectives in this case? Objective means what are the functional requirements for the marine riser? The requirements are it should possess the basic strength; it should have corrosion resistance. It should sustain marine environment high temperature, high pressure conditions, accidental loads thermal loads and it should be cost effective.

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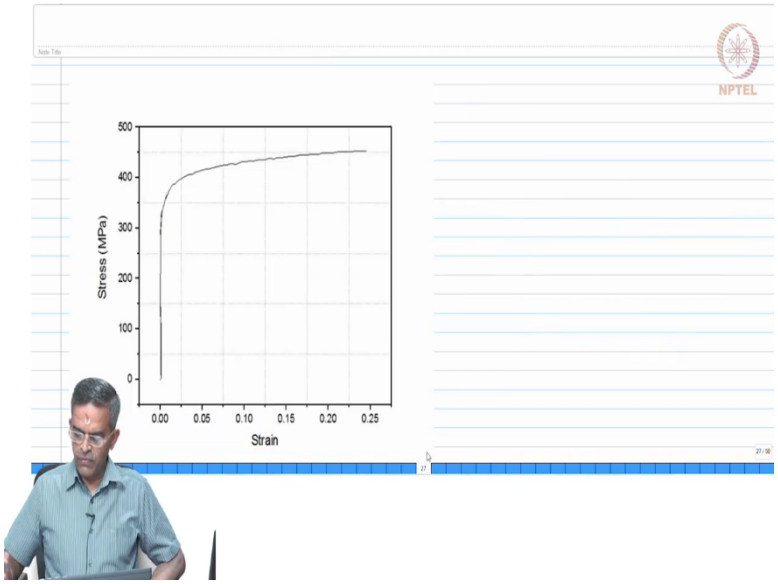

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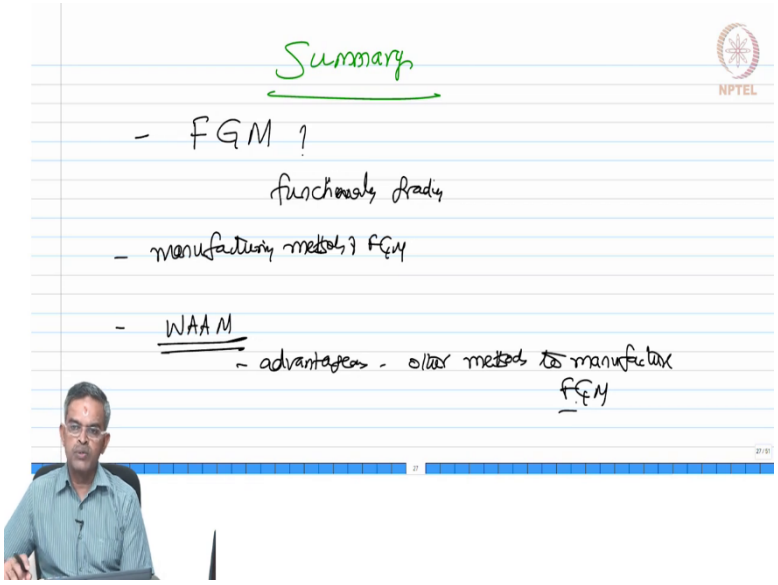

We will see this in detail in the coming lecture friends. So, as a summary in this lecture let see what we have learnt. As a summary we learnt, what is a functionally graded material, what do you understand by functionally grading, what are various manufacturing methods of FGM. In that we also saw what is wire arc additive manufacturing, how this method is advantages in comparison to other methods used to manufacture FGM correct.

So, in the next lecture we are going to talk about evolution of a new material for marine riser which is an FGM. We will see what are the constituents of this material, how are they composed, how it is manufactured and then once we attain this material as a single material without any stepwise layers.

Let us see the assessment of mechanical properties of this FGM and compare those properties with the constituent materials and see is any improvement on FGM or not. So, we will do that study and learn them in the next lecture.

Thank you very much, have a good day bye.