Advanced Design of Steel Structures
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Lecture - 10
FGM for marine application - 1

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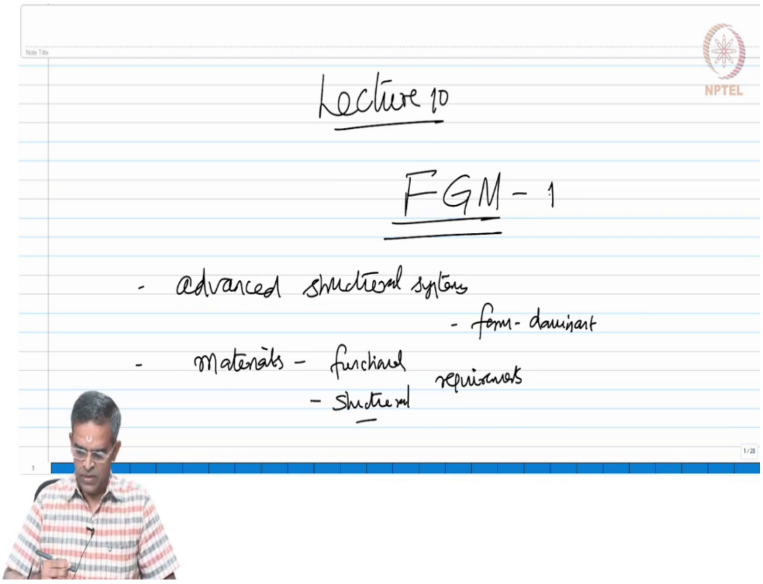

Welcome to the 10th lecture in which we are going to learn more about the Functionally Graded Materials let us quickly highlight what we discussed in the set of last lectures. That we are looking for advanced structural systems, which are designed to be form dominant. We are also looking for materials which support the system for its functional and structural requirements.

Structural requirements refer to the mechanical properties such as yield strength, Young's modulus Poisson's ratio of a t strength, fracture resistance, which are generally and possibly very good as far as different steel grades are concerned, there are no issues about it. When you come to the functional aspects of steel especially under the influence of environment to be very particular in marine environment steel undergoes corrosion.

And that is one of the disastrous requirement which is not agreed upon by any engineer in practice for marine systems. So, looking forward for a material, which is having similar strength to that of steel, but possesses better corrosion resistance so, were looking for a functional requirement of the material. So, advanced steel design is dealing with two aspects of the design procedures - one is a geometric centric design, where the structural assembly takes care of the load acting upon the structure apart from the advanced design procedures such as plastic design etcetera.

In addition, we are also looking for a material which is compatible with this large displacement structural systems. What does it mean? The material should possess enough ductility; to adopt plastic design the elastoplastic domain of the material should be very dominant. To have good toughness the area of the stress strain curve should be large enough, the material should exhibit ductility etcetera.

Apart from possessing these advantages properties we will also choose a specific requirement let us say corrosion resistance which is indeedly required in marine environment. So, we did a recent research at IIT Madras with assistance with Professor Murugayan in Department of Metallurgy and Material Sciences, we came out with an fabrication of a new novel material which is functionally graded of different constituents to have corrosion resistance and strength at par with steel.

So, in this lecture we are going to talk about that particular recent innovation on FGM which is yet to be applied to marine systems, but still it is a research stage and I believe you love to know more information about this kind of recent advancements in structural design as far as steel is concerned. So, in FGM again steel is an important ingredient, but the corrosion resistance is improved by combining or alloying this with another metal.

That is what we have tried to do it. Let us do this and see how do we proceed with this further.

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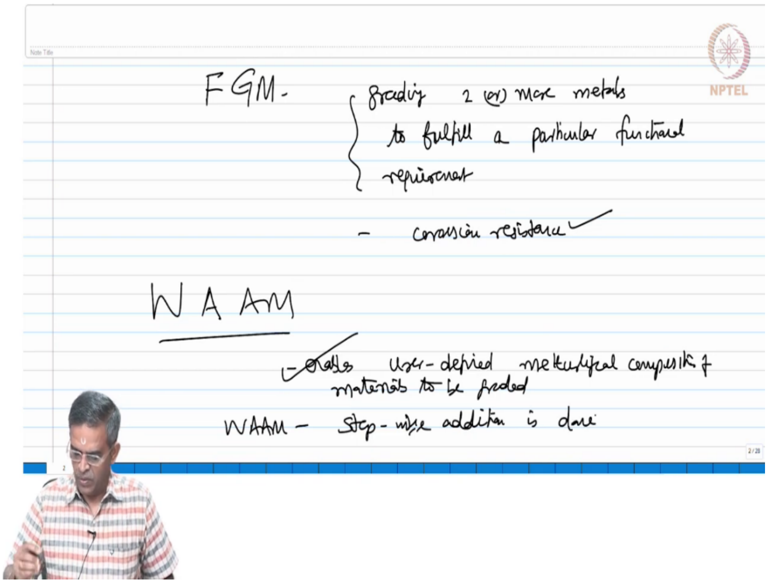

As we said in the last lecture FGM is actually grading 2 or more metal components or metal to fulfill a particular functional requirement. So, friends at this moment we are taking the functional requirement as corrosion resistance. There can be any such functional requirements, let us say though low thermal conductivity, high temperature performance, excellent fatigue characteristics.

You can dictate, you can choose any specific functional requirement and modify the characteristics of steel by altering the ingredient metals to form a functionally graded material. So, as I said there are many manufacturing processes which are available in the literature to fabricate a functionally graded material out of which, wire arc additive manufacturing is one of the prominent method which is compatible manufacturing procedure which enables the metallurgical components of the materials to be user defined.

So, it enables, it permits user defined metallurgical composition of materials to be graded. So, is user friendly, so it does it. So, in WAAM, stepwise addition is done; we have already said continuous and step wise are 2 different methods of FGM manufacturing in WAAM step wise addition is generally carried out.

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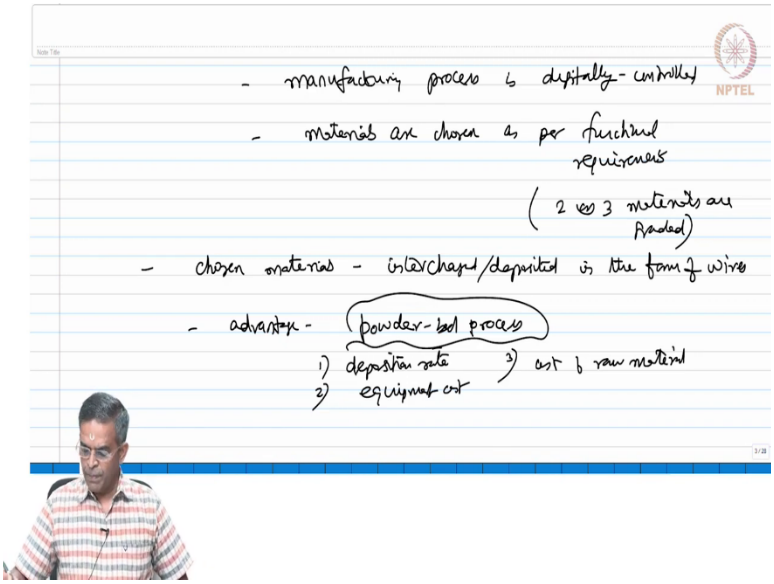

The manufacturing process is controlled in a digital mode. So, the manufacturing process is digitally controlled whereas, materials are chosen as per the functional requirements.

Friends usually 2 or 3 materials are graded, not more than that. You can have more, but the complexity of manufacturing will be very large. So, usually 2 or 3 materials are graded to get a FGM product. So, in WAAM what we do, this chosen materials are interchanged or let us say deposited in the form of wires. So, WAAM has got a great advantage over the powder bed process in terms of deposition rate, equipment cost, cost of the raw material etcetera.

So, this has got an edge over this particular process of manufacturing and WAAM is considered to be advantages compared to this.

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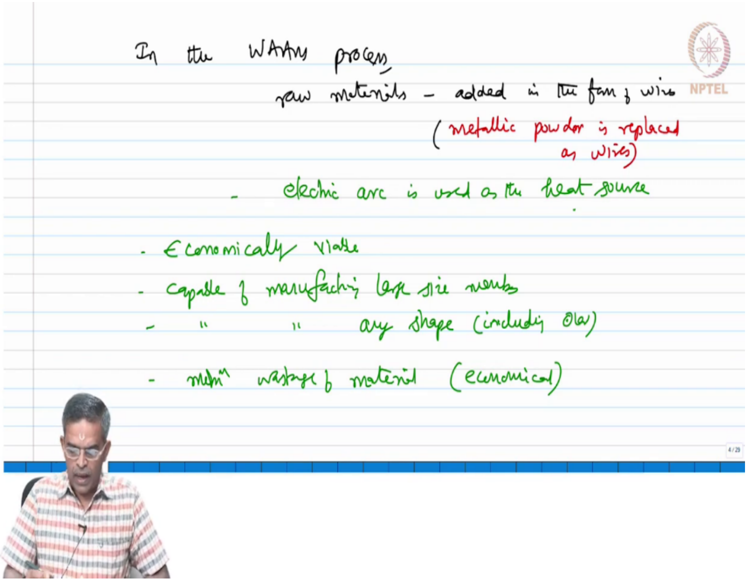

In the WAAM process, the raw material or I should say the ingredient metals are added in the form of wires. So, I should say the metallic powder is replaced as wires in metallic powder bed process, the metal powder were are actually added in this case the raw material is added in the form of wires and for manufacturing electric arc is used as a heat source.

Therefore, friends WAAM is considered to be economically viable and it is capable of manufacturing large size members, it is also capable of manufacturing any shape including circular, because circular is considered to be one of the most difficult fabrication process. Furthermore, it has got a minimum wastage of materials. So, I should say this process is highly economical compared to the conventional processes used in manufacturing alloys or composites.

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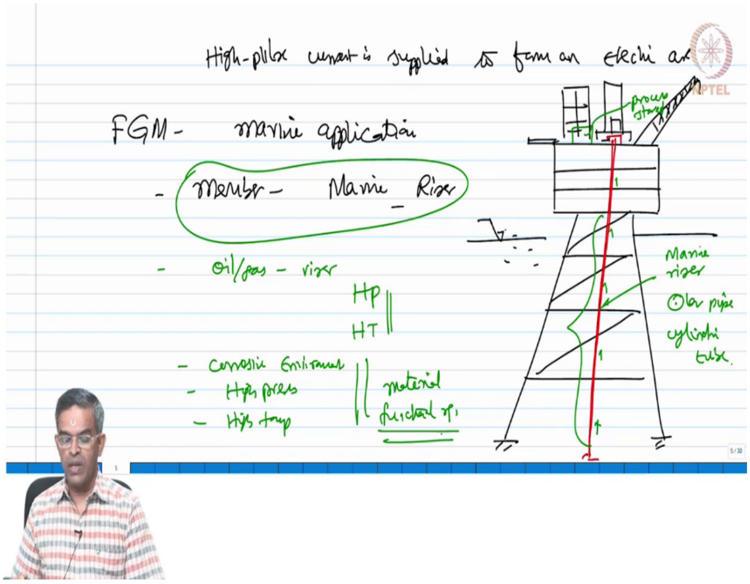

High pulse current rate is supplied to form an electric arc and that is remaining as a heat source for the problem. Now, let us talk about a specific application of FGM for marine riser. So, let us say we take a member for our consideration, the member of our choice is the marine riser. Now, the question is for the knowledge of other people listening to this course who are not offshore engineers.

Let us quickly explain what is a riser. Let us see if this is my offshore platform is having multi tire deck, which has got the crane facility, which has got the top soil details in terms of drilling platform, drilling derrick etcetera and a helipad. Or let us say the platform is constructed and resting on the sea bed by a template arrangement structural system and this becomes my water level let us say.

From the drilling, head a pipeline is driven to the sea bed which is now going to explode the oil and it is going to be carried up through this pipeline and then it is processed or stored on the top side. Since the oil is traveling against gravity this component is called as a riser and since it is used for marine application so it is a marine riser. So, marine riser is actually a circular pipe or a cylindrical tube, which is essentially used to explore, suck oil or gas from the seabed to the top side.

So, our application member is a marine riser, you can see here the marine riser is completely embedded in sea water which is corrosive in nature and in addition to that the oil and gas which is passing through this riser is of a very high pressure and high temperature. So now, we are looking for a member which is located in the corrosive environment, the member should sustain high pressure, the member should also sustain high temperature. So, looking for a material which caters to these functional requirements.

If you ask me a question what is the general material being used currently in the industry? Because oil and gas exploration is not today’s job.

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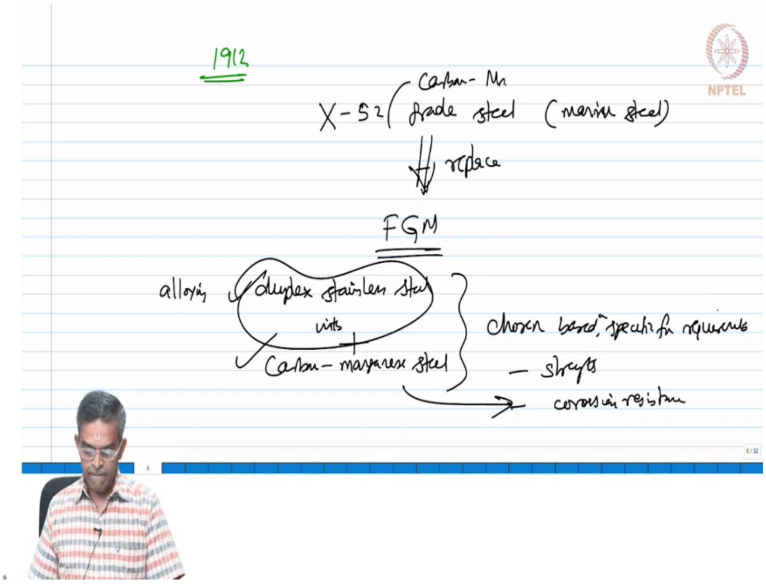

The first oil well was drilled in United States in the year 1912, 100 years back. So, this process is there for the past 100 years. So, people must have been using say material for marine risers, we state that they are corrosive in nature, but people have been using them.

So, what is that material being conventionally used so far is X-52 grade steel, which is the marine steel. I will show you the mechanical properties of this steel slightly in a minute later in the next slide. It is a conventional steel being used, now we want to replace this steel with a new material which is functionally graded. So, to improve the performance of corrosion resistance, we are looking for alloying the duplex stainless steel with carbon-manganese steel.

So, friends these ingredients, these metallurgical constituents are chosen based on specific functional requirements. The functional requirement what I have is of course, the strength, there is no compromise on strength we are also looking for additionally a corrosion resistance right. So, which is 2, we can choose these 2 material. If you ask me a question, do only these two-material available which are corrosion resistant, there are many titanium, there are many material available.

For example, we have demonstrating an FGM fabricated in our lab with these two material, you may ask me why duplex stainless steel that is a common material being currently used as a single material for risers. So, we want to add that to carbon manganese steel and see whether corrosion distance can be improved, that is the question here that is the argument.

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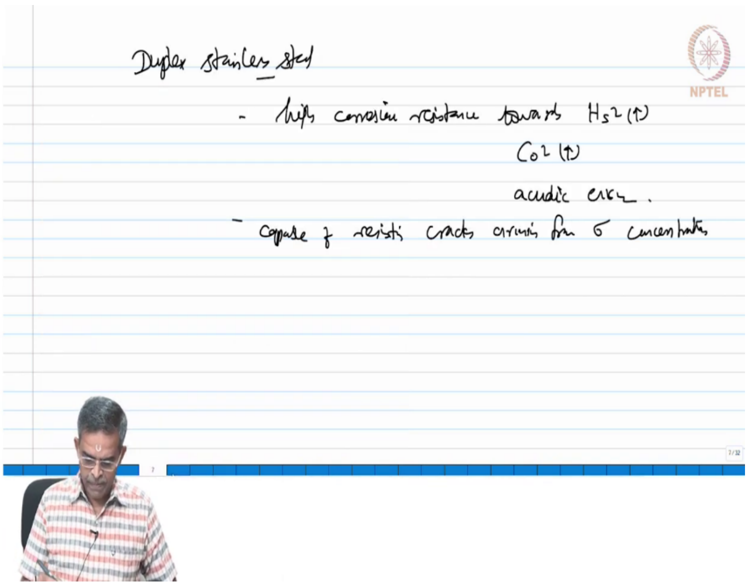

Having said this, if you look at the properties of duplex stainless steel, it has very high corrosion resistance towards hydrogen sulfide gas, carbon dioxide gas and acidic environment. It is also capable of resisting cracks arising from stress concentration. Now, we want to add this material with carbon manganese steel which X-52. So, X-52 is a carbon manganese steel which is currently used as marine steel in rises. So, we want to add this to duplex stainless steel and see what happens.

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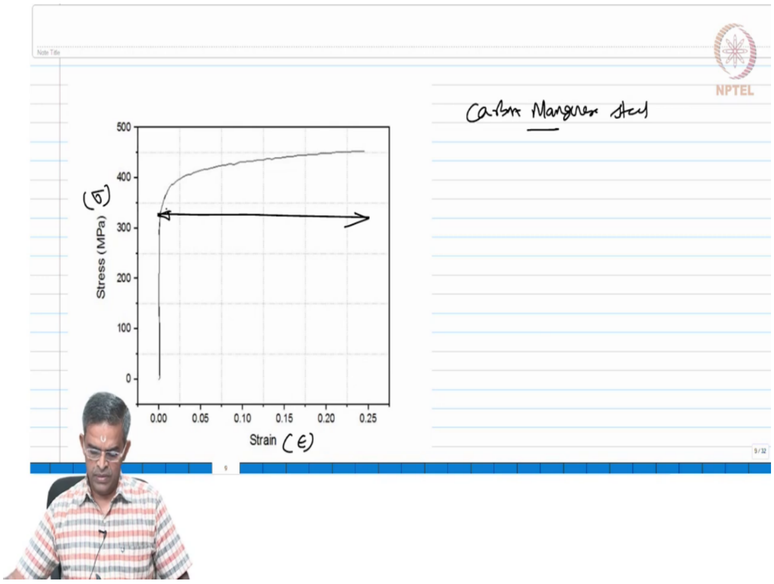

Let us quickly see the stress strain curve of materials what we are discussing now.

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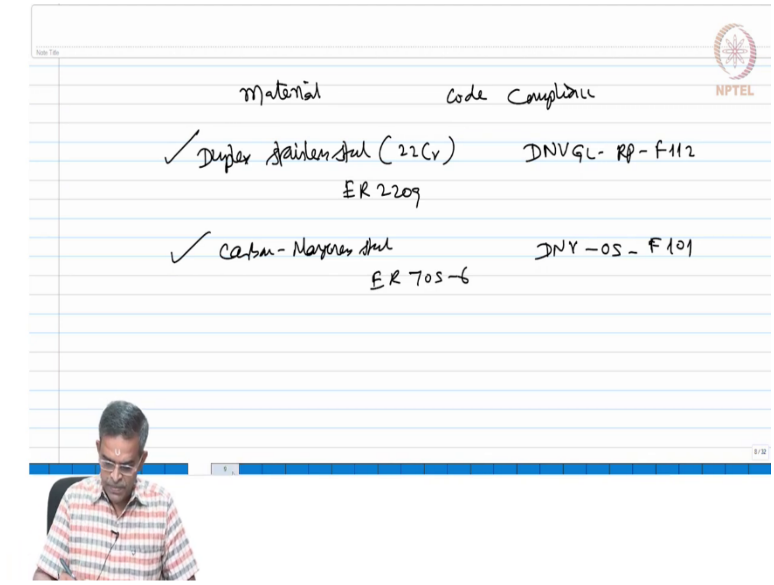

Before we go that, let us see the material what we are choosing and what is the code compliance of this. Because we already said the choice of the material also depends on whether the code accepts it or not. So, duplex stainless steel is anyway recommended as 22 Cr sorry, ER 2209, which is recommended by DNVGL-RP-F112.

Carbon manganese steel is also recommended for marine application, which is ER 70S-6 which is recommended by DNV-OS-F101. So, friends one can easily get convinced that these two ingredients steel are not new recommended for marine environment, already existing codes permit, use of this material for marine environment. So, code compliance is satisfied.

So, one can really go for alloying these materials and see what happens. Now, let us look into the stress strain curve of carbon manganese steel. The one what you see on the screen is the stress strain curve of carbon manganese steel. So, the carbon manganese steel does not have a pronounced yield point. So, to obtain this, one can easily find out the 0.2% proof stress value and get the yield strength, one can also see it has got enough ductility.

Carbon manganese steel possess enough ductility right, because the ductility ratio is significantly larger for this steel. So, this is the stress strain curve for carbon manganese steel, which is going to be the ingredient for my FGM. So, what is that element we are looking at how we are going to composite, let us see that here.

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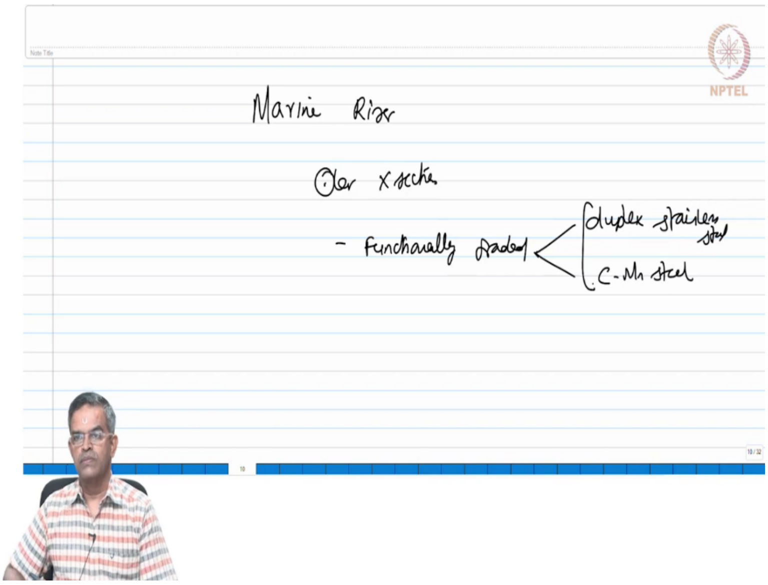

Now, I am looking for a marine riser which is circular in cross section, which should be now functionally graded correct, with two materials, one is duplex stainless steel another is carbon manganese steel. We are going to do this.

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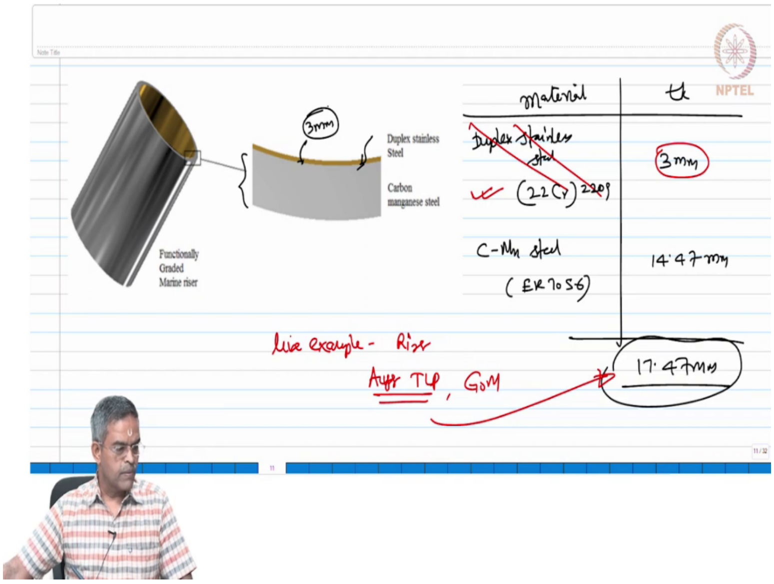

Let us see how we are going to show the cross section? A typical cross section of the proposed riser is now shown on the screen. So, the cost of duplex stainless steel is phenomenally high compared to carbon manganese steel. Friends it is because of this reason duplex stainless steel as such as a single material is not being used as a riser. The cost will be phenomenally high.

Carbon manganese steel is cheaper compared to duplex stainless steel. Therefore, what we propose is only a small portion will be duplex stainless steel and the majority will be carbon manganese steel. So, economically the proposed new material will not be very expensive in comparison to the conventional carbon manganese steel, because you are adding only one layer of duplex stainless steel.

But remember it is not a coating, it is not a composite, it is not a layering material. It is fabricated as a single material that is the beauty here. So, the functionally graded riser now has got 2 material where the inner portion will be susceptible to corrosion because of HPHT conditions, and the carbon manganese steel is located outside as you see in the screen here.

Having said this, that we now have the cross section, we now have the material let us see what will be the thickness we are proposing. Let us say what is the material and what is the thickness we are proposing. So, the material we are saying is duplex stainless steel, which is 22 Cr 2209 which is only for 3 millimeters. Whereas, the carbon manganese steel which is qualifying Er 70 S-6 gray is about 14.47 millimeters.

So, the total thickness of the riser is 17.47 millimeters out of which 3 millimeter is duplex stainless steel and remaining is carbon manganese. So, now, one will be curious to know how do we get this thickness of the riser, that is a very interesting question friends. We have taken a live example of a riser present in Auger TLP, tension like platform in the Gulf of Mexico and we have adopted the same cross-sectional dimension of the riser for the analysis.

The marine raiser present in the Auger TLP is of thickness 17.47, please note the existing riser present in Auger TLP does not contain duplex stainless steel, it is a single layer material it is not FGM. So, we are now improving the corrosion resistance of that material by adding stainless steel of a marginal thickness, without compromising the string let us see what happens to this combination right. So, we are looking for a thickness of this order.

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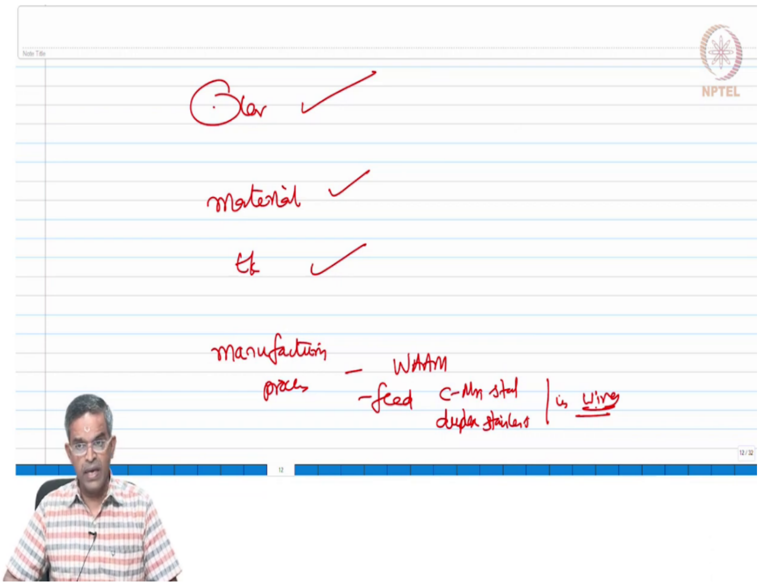

Now, we have the cross-sectional dimensions ready, we have the material composition ready, we have the thickness to be done ready. We also have the manufacturing process which is also finalized I am going to use wire or additive manufacturing, where I am going to feed the carbon manganese steel and duplex stainless steel in the form of wires. I am going to manufacture this in layers.

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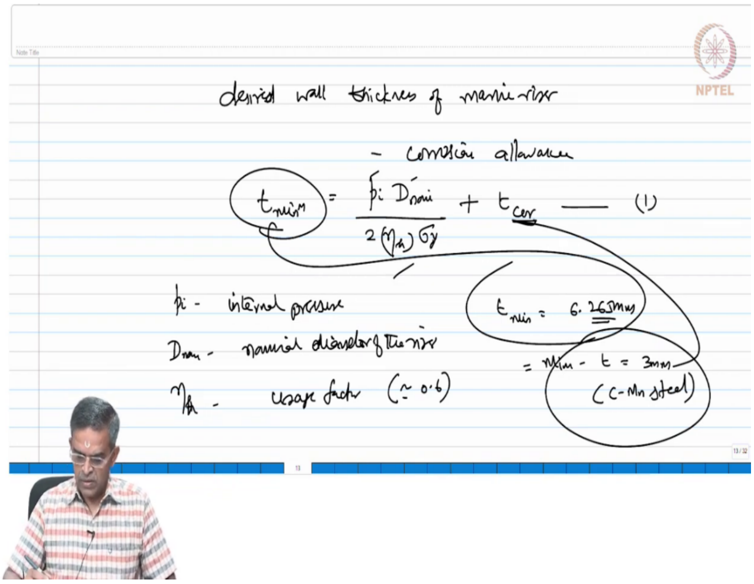

Having said this, let us see what the code advises for the desired wall thickness of risers. The desired wall thickness of marine risers should take care of the corrosion allowance. So, the minimum thickness is the internal pressure, the nominal diameter divided by twice of eta h σ_y plus thickness meant for corrosion, equation 1.

Whereas P_i is internal pressure, D nominal is a nominal diameter of the member of the riser eta h is a usage factor which is a factor used in the design usually this value is taken as 0.6 and the corrosion allowance given is about 6.265 millimeters. As per international practice the minimum corrosion allowance given is 3 millimeters; if you provide carbon manganese steel.

So, this is not t steel this is t minimum. So, you provide t minimum for corrosion as 3 millimeter, then work out for the given pressure and diameter and this work out t minimum that comes to be 6.265 millimeters. So, friends please note along the inner surface of the riser, there is a corrosion resistant layer of 3 millimeter, which is going to handle the scouring effects of the carbon dioxide.

You see here along the inner side, along the inner side there is going to be 3 millimeter of corrosion distance material, which is the duplex stainless steel, which is now going to handle the corrosion problems right. So, that is what we are planning now.

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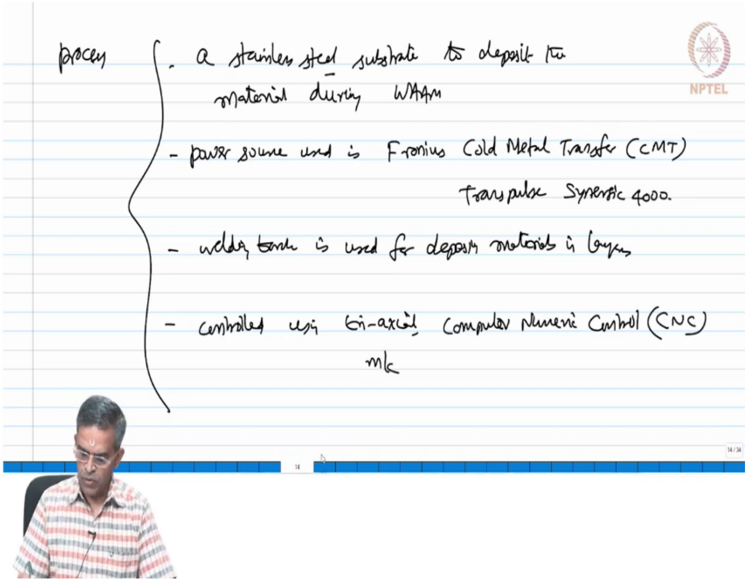

So, furthermore, a stainless-steel substrate is used to deposit the material during WAAM. Now, we are looking at the manufacturing process.

The power source used for deposition is Fronius, Cold Metal Transfer which is CMT trans pulse synergic 4000, a welding torch is used for depositing materials in layers. The whole process is now controlled using tri-axial computer numeric control machine which we call as CNC which I am going to show the photograph here.

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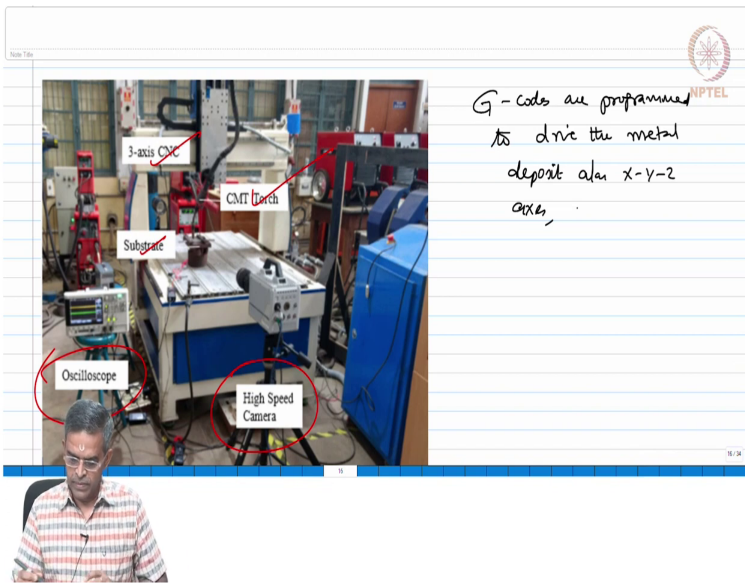

So, you have the CMT torch, you have the substrate and you have the 3 axis triaxial CNC machine which is now going to be used to manufacture or fabricate this FGM. Of course, the whole process is also measured and monitored using an high speed camera and also an oscilloscope for varying the pressure and also measuring the response of the wire feed or the rate of wire feed with respect to the manufacturing process. So, G codes are used, G codes are programmed to drive the metal deposit along x-y-z axes.

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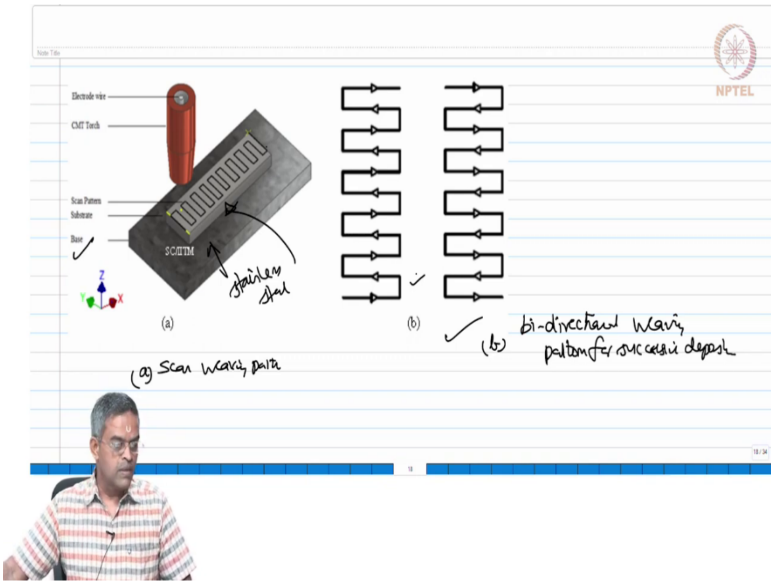

So, a typical G code which is used for a bidirectional strategy is shown here. So, this is the bidirectional weaving pattern for successive depositions and this figure shows the scan weaving path of metal deposit. So, one can say this is scan pattern what you see here is being mapped here and that is the substrate, which is actually stainless steel, below that there is a base and CMT torch and electrode wire are being fed.

And the wire is fed in the same pattern, which is actually obtained depending upon what is the wire feed rate and how the pattern will be established to get the normal thickness of the desired value.

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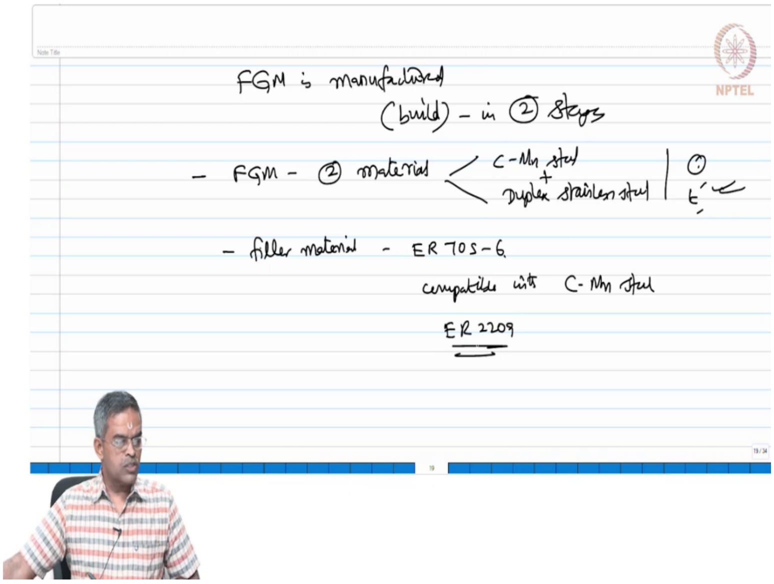

Having shown this, the functionally graded material now is manufactured or I should say is build in 2 stages.

So, essentially, we must realize that this FGM contains 2 materials; one is carbon manganese steel other is duplex stainless steel. The thickness, shape, everything is fixed. So, they are fed in wires in the form of wire and we are going to deposit in 2 stages. So, to bind these two we also require a filler material. The filler material is actually used in this case ER 70 S-6 which is compatible with carbon manganese steel and ER 2209 grade, which is a duplex stainless steel. So, now we can show the chemical composition of the filler material.

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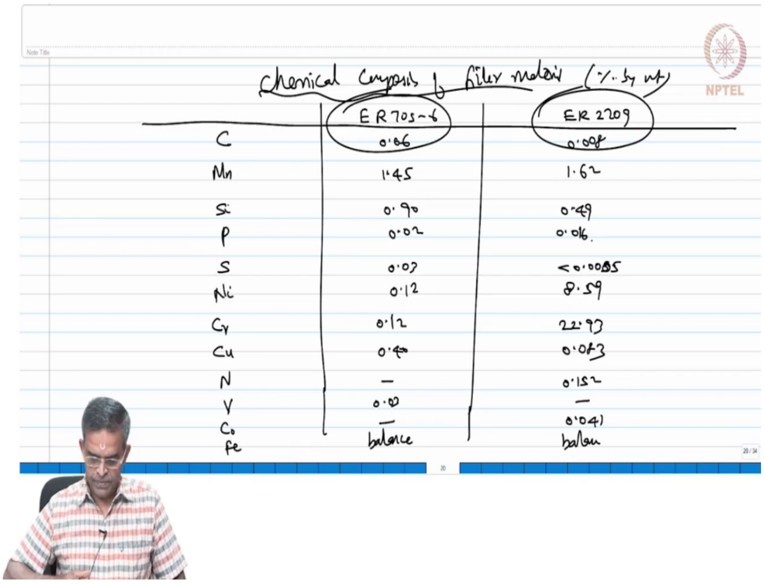

The chemical composition of the filler material is shown percentage by weight. It is got carbon, so ER 70 S-6 and ER 2209. In fact, there are two filler materials I am giving the value of both the filler material being used in our research. Suppose 0.06, here it is 0.008.

We have also used manganese, the component sorry the content which has got 1.45 and this contains 1.62; silicon, 0.9 and 0.49; phosphor, 0.02 and 0.016; Sulphur 0.03 and less than about 0.005, I mean 0005, very very negligible it contains nickel of 0.12, 8.59 very high content.

It contains chromium of 0.12 and this contains 22.93, it has copper of 0.4 and this contains 0.083, it also has nitrogen which is very insignificant whereas, in this case it is 0.152. It also has vanadium, cobalt and Ferrum. Vanadium is 0.03, cobalt is negligible and ferrum is the balance. Whereas, in this case vanadium is negligible, cobalt is 0.041 remaining is the balance.

So, we have got the chemical composition of two different filler material, which has been tried in this current research to fabricate the functionally graded material, constituting two ingredients, duplex stainless steel and carbon manganese steel.

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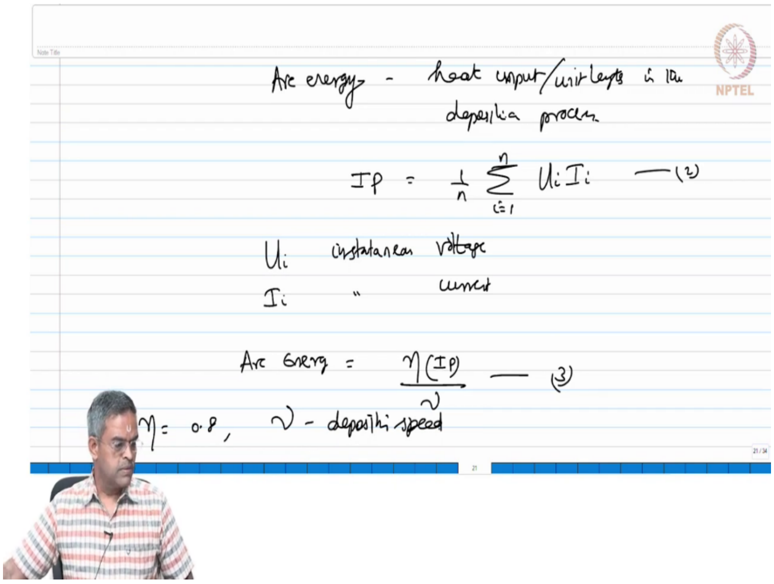

The arc energy being used for manufacturing or otherwise the heat input required per unit length of the wire in the deposition process is given by this equation which is IP, the heat input which is 1 by n of summation of i equals 1 to n.

u_i and I_i where u_i is the instantaneous voltage and I_i is instantaneous current. Arc energy is therefore, given by the efficiency multiplied by the input, heat input divided by nu usually the efficiency of vamp wire deposition process is taken as 80% and the variable parameter in this case is going to be the nu which is called as a deposition speed.

The deposition speed depends upon the wire feed rate and also depends on the ingredients of the metal.

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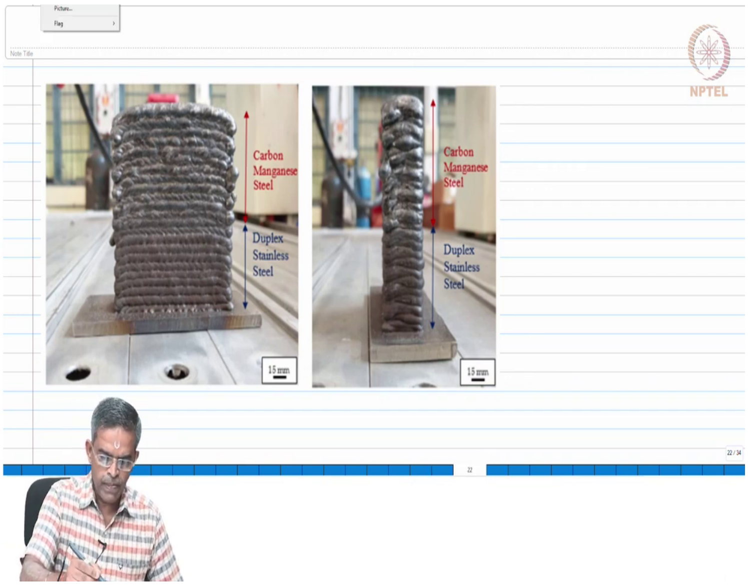

So, the deposition parameters is an optimized and these are the following data being used in the current study.

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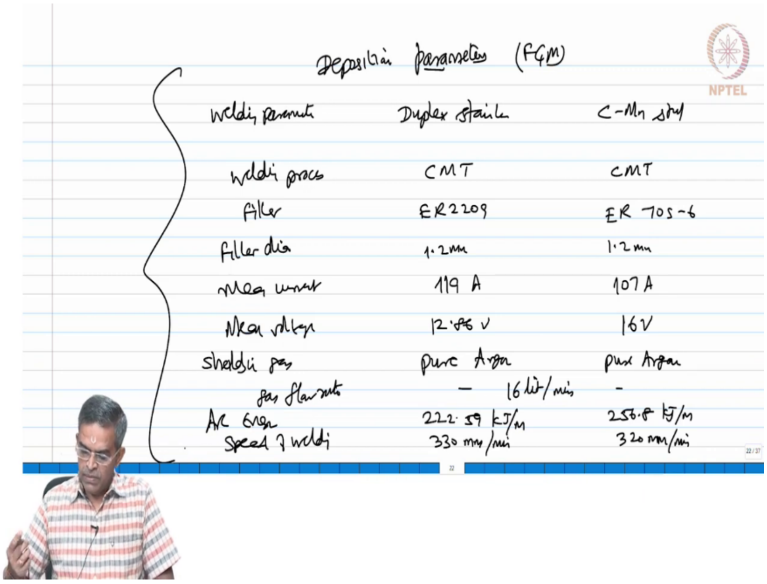

So, the deposition parameters for FGM composition, these are the welding parameters for duplex stainless steel and for carbon manganese steel. The welding process being used is CMT in both cases.

The filler material being used is ER 2209 and, in this case, it is ER 70 S-6, the filler diameter is used for fabrication is 1.2 millimeter in both the cases. The mean current being used for depositing is 100 and time 19 amperes whereas, in this case 107 amperes. And the mean voltage developed during the deposition process is 12.86 volts whereas, in this case 16 volts.

The shielding gas being used is the pure organ gas in both the cases. The gas flow rate being used is 16 liters per minute in both the cases. The arc energy developed is in this case 222.59 kilo joules per meter whereas, in this case is 256.8 kilojoules per meter. The welding speed of the torch is 330 millimeters per minute for fabrication; whereas, in this case it is 320 millimeters per minute. So, these are the deposition parameters which is being used in fabricating this FGM.

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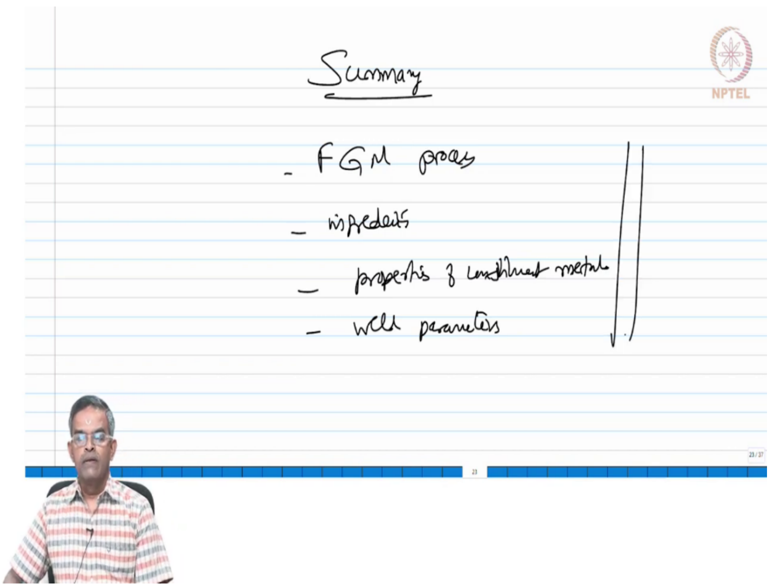

So, friends we have learnt in this lecture more details about the FGM process, the ingredients of the experimental FGM we did, the properties of the constituent metals and weld parameters. So, in the next lecture we will discuss more in detail about the welding process, fabrication of FGM and the mechanical and structural properties of the fabricated FGM and compare it with the parent metals and see how they have improved when FGM is formulated.

Thank you very much have a good day.