

**Advanced Design of Steel Structures**  
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**Lecture - 11**  
**FGM for marine application - 2**

So, friends welcome to the 11<sup>th</sup> lecture where we are going to discuss more in detail about the FGM.

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Lecture 11      FGM-2

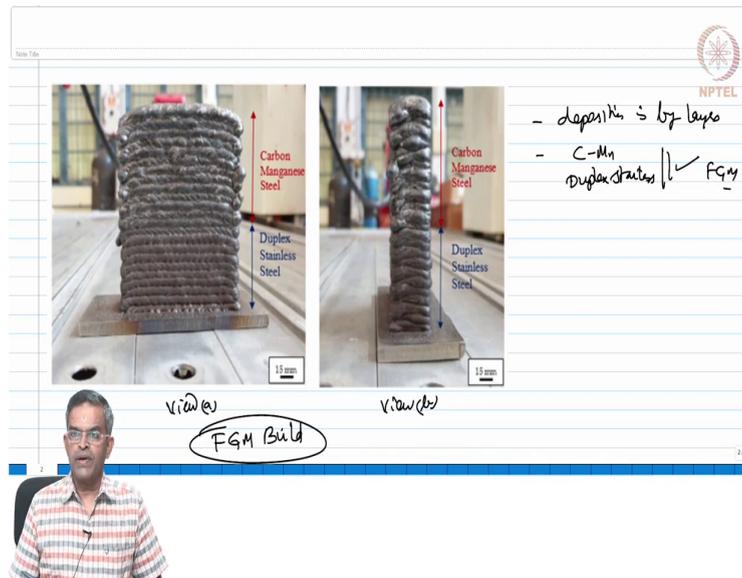
- FGM
- corrosion resistance
- code compliance
- etc.
- base material
- weld parameters (fabrication)

Duplex stainless steel / filler  
C-Mn

So, in the last lecture we discussed about the ingredients of FGM which has got a specific functional requirement which is corrosion resistance. We have checked the code comprehensive of the ingredients of the material. We have assessed the thickness requirement of the material. The cross sectional diameter and then the ingredient materials depending upon the strength and functional requirement. We have chosen duplex stainless steel and carbon manganese steel with respective fillers.

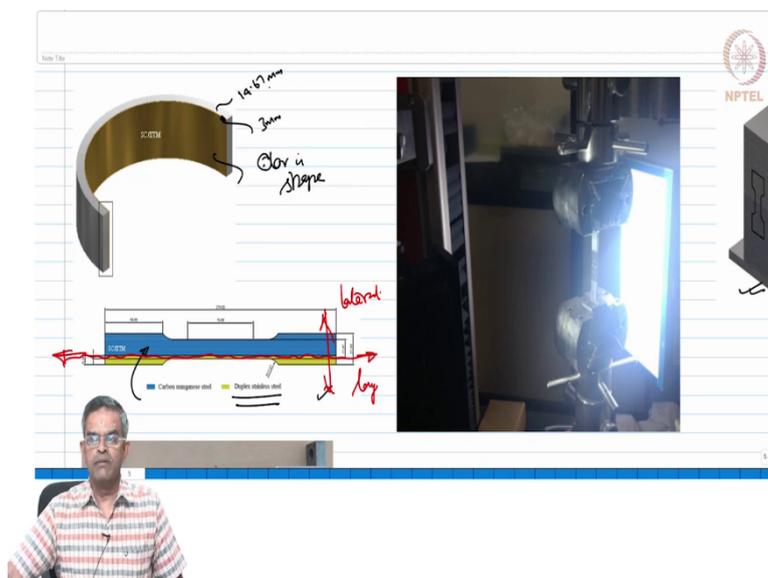
Then we arrived at the weld parameters we do not call as weld parameter actually they are fabrication parameters, why it is called as weld because we are using a torch to control the rate of flow of the wire. So, we call that as a weld actually So, once you deposit this by layers this is what you get.

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So, this is a view a and view b of the build. So, one can see, that the deposition is by layer. And you can see both the material carbon manganese steel and duplex stainless steel deposited like this, to form an FGM. The mechanical characteristics of this is assessed using a high speed video camera and we are able to find out the wire electro discharge machining of this.

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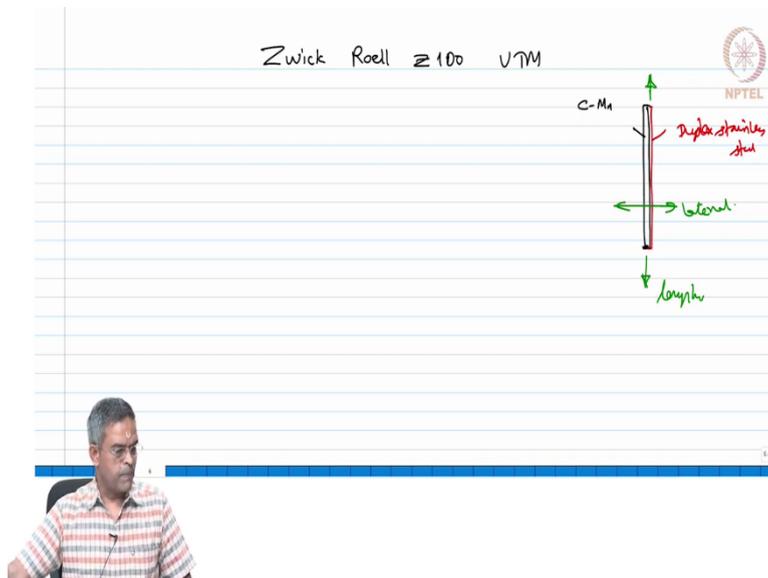
So, now when this is manufactured in a circular form this is what we get. So, we are able to get a cross section where it is circular in shape. The inner material what you see is a duplex

stainless steel. Now, outer material what you see is the carbon manganese steel, which is shown in different two colours you can say this is only a very small thickness of 3 millimetres and this is a large thickness of 14.67 millimetres. Friends very interestingly we cut a portion from here to test it in UTM for mechanical characteristics, to assess the mechanical characteristics.

So, what we do is we have taken a stratum from the FGM build which you see an enlarged view here, which is cut from the build as you see here and placed in an UTM. Now, before we put it in UTM we try to also place the markers for measuring strain. So, you can see there are markers I am marking it in a different colour. So, this and this are for longitudinal strain and the other one are for lateral strain .

So, these are placed in a UTM. So, please note here this is the direction of pull. So, very interestingly friends, we are applying a tensile pull parallel to the layer right. So, this becomes my longitudinal direction and this becomes my lateral direction . And we assess now the stress strain characteristics of this material.

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So, Poisson's ratio is estimated based on this and we are using the Zwick Roell z 100 UTM. So, the specimen is placed in the UTM I am just indicating the carbon manganese steel and stainless steel in different colour. So, this is duplex stainless steel and this is carbon manganese steel and we are going to apply the pull parallel to this . That is very important.

This is my longitudinal direction and this becomes my lateral direction. So, I am going to measure the Poisson's ratio based upon these two. Let us see how do we do it. So, the tensile strain and stresses are observed when you place an UTM. So, we use a video extensometer to measure this three specimens are tested and then we used to do the metallographic investigations on the finished surface.

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To determine the elemental composition of FGM

- build, SEM - Quanta 200F
- @ interface of
  - a - steel
  - b - Fe-Mn
- for 35 micrometers
- Wolpert Wilson Micro Vickers digital hardness tester
- X-ray diffraction - Bruker D8 X-Ray Diffraction Equipment

So, now to determine the elemental composition of the FGM build, scan electron microscope which is quanta 200 F to check the elemental composition essentially at the interface of two metals. Let us say a and b a is duplex stainless steel and this is carbon manganese steel at the interface we want to see. So, the observations were recorded for about 35 micron length.

The micro hardness test is also carried out on the polished surface of the FGM build . And hardness test is conducted using Wolpert Wilson Micro Vickers digital hardness test. Further the samples obtained after tensile testing are subjected to x ray diffraction using Bruker D8 X-ray diffraction equipment.

Let us now see first the metal transfer characteristics which are obtained. The metal transfer characteristics very clearly showed that there is a uniform distribution or uniform spread of metal a with metal b. There is no distinct layer seen between these two. So, there is a good mixture good composition mixture of these two which was verified from the metal transfer characteristics of this.

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X-Ray Computed Tomography

- check the porosity
- formation of micro-cracks

NPTEL

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The slide features a white background with blue horizontal lines. At the top right is the NPTEL logo. The title 'X-Ray Computed Tomography' is written in black. Below it, two bullet points are written in black ink. A small inset image of a man in a striped shirt is visible in the bottom left corner of the slide area.

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(a) 3d view  
(b) Top side  
(c) side  
(d) front view

FGM build

both - stainless steel  
- C-Mn steel free from  
manufact defects

- WAAM - ✓ prod for FGM ✓

NPTEL

3/28

The slide displays four X-ray CT images of a cylindrical FGM build, labeled (a) through (d). (a) is a 3D perspective view, (b) is a top-down view, (c) is a side view, and (d) is a front view. To the right of the images are handwritten notes in black and green ink. The NPTEL logo is in the top right corner. A small inset image of the man from the previous slide is in the bottom left corner.

Further, X-ray computer tomography was conducted, to check the porosity and formation of micro cracks during the manufacturing process. So, the figure now shows the view what you obtain using X-ray computer tomography, a and b shows a shows the 3 dimensional view, b shows the top side view and of course, this is c and this is d c refers to the side view and d refers to the front view of the FGM build .

So, from the figures and the x the photographs one can say that both duplex stainless steel and carbon manganese steel are free from manufacturing defects. There are no micro cracks.

So, it confirms that the wire arc additive manufacturing method used is good for building FGM and it can be used for engineering applications .

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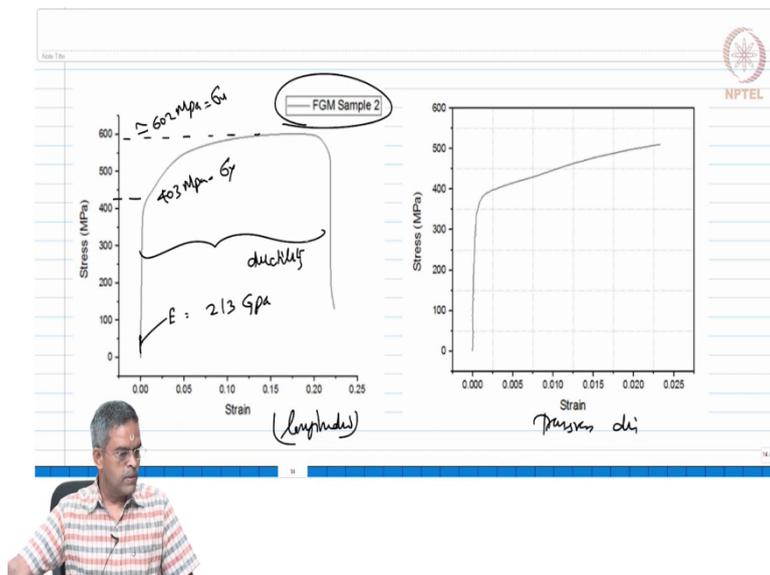
The slide contains handwritten notes in black ink on a white background with a blue border. The text is as follows:

- Tension Test
- axial tension
- strain rate  $1 \times 10^{-3} / s$
- FGM sample
  - longitudinal
  - transverse

The NPTEL logo is visible in the top right corner. A small inset image of a man in a striped shirt is visible in the bottom left corner of the slide frame.

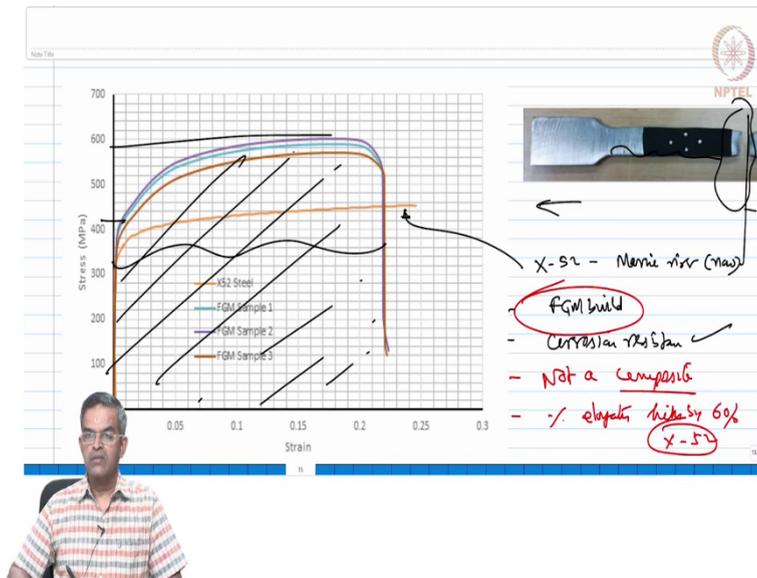
Furthermore, tension test was conducted under the axial tension the strain rate used to do this was  $1 \times 10^{-3}$  per second. The stress strain curve of the FGM sample along both directions longitudinal and transverse can be seen here.

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So, this is longitudinal and this is transverse of sample 2. There were many samples tested one of the sample. So, one can very well see here that the ultimate strength is approximately 602 megapascal. The yield strength was about 403 megapascal. The modulus of elasticity the slope of this line is about 213 gigapascal and the material show very good ductility. In fact, we want to compare this with the X52 steel and see what happens.

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Let us show a comparison of this with all the 3. This is my X52 steel friends which is the conventional steel being used for marine risers now. And the remaining three colour curve show you the stress strain curve longitudinal of course, longitudinal for three samples of FGM build. One can easily see here that FGM has got a similar ductility as that of X52 while the ultimate strength the yield strength and the toughness is much higher, compared to the conventional X52 steel which is currently being used for marine risers.

In addition to this the FGM build what we proposed had a exclusive corrosion resistance is it not. So, it is functionally graded without compromising the strength of the parent material that is the beauty of the whole research problem . Even at fracture which is pulled along you will see there is no separation is it not. It is fracturing like a normal ductile material. There is no layer separation which generally is expected when it would have been a composite.

So, FGM is not a composite . Though it is manufactured in layers, though the deposition is done by wires, but because of the manufacturing process and technique the chosen two materials got unified and you get a single material as an outcome . That is the whole

emphasis we want to make here. Having said this if you look at the fractured sample the fractured sample does not show any layer interference between the stainless steel and carbon manganese steel.

It also showed the percentage elongation higher by about 6 percent in compared to X52. So, interestingly friends one will be very curious to know the test results of X52 and FGM.

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Material Property	X-52 Marine Riser Steel (Lypain et al. 2015)	FGM (ref-work)
Young's Modulus	210 MPa	209.66 ± 4.48 MPa
Yield strength	358 MPa	390.66 ± 12.23 MPa
Ultimate strength	453 MPa	587.66 ± 12.76 MPa
Strain ratio	1.265	1.5 ± 0.02
Ductility ratio	32.207	45.47 ± 0.82
Tensile toughness	104.92 (J/m <sup>3</sup> )	120.50 ± 2.84

So, we will compare this with X52, which is marine riser steel with our FGM under: Young's modulus, yield strength, ultimate strength. Let us also try to work out the strength ratio. We will also work out the ductility ratio from the curves. Then we will also compute the toughness tensile toughness then Poisson's ratio.

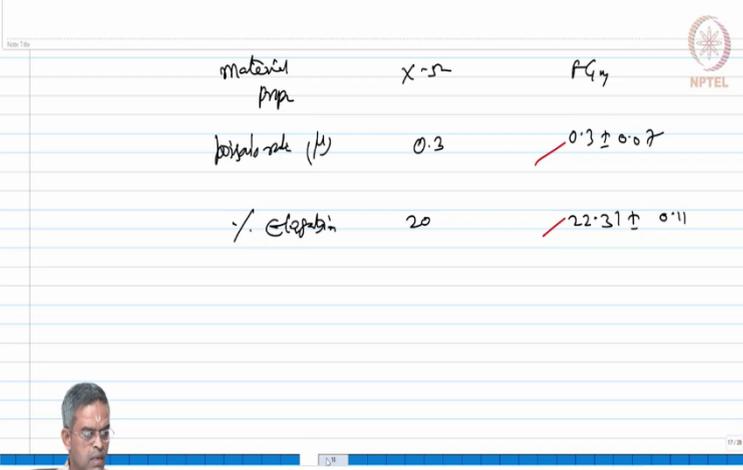
The Young's modulus in this case is established as 210 MPa whereas, we got 209.66 plus or minus 4.48 MPa, as far as yield strength is concerned X52 exhibits 358 whereas, we got 390.66 plus or minus 12.23. That is the variation we have in samples. Ultimate strength showed 453 MPa in X52, whereas, we had a very exorbitant value of 587.66 plus or minus 12.76 MPa.

So, therefore, the strength ratio in this case 1.265, which is actually the ratio of ultimate strength yield strength whereas, we have 1.5 plus or minus 0.02. The ductility ratio usually is 32.207 for 52, but we have 45.47 in FGM. The tensile toughness which is expressed in joule per cubic meters is 104.92 for X52. Whereas, in our case we got 120.5 plus or minus 2.84.

So, the marine riser values have a very strong reference which is taken from Lyapin et al 2015 and FGM is our own paper.

So, one can see here that the Young's modulus being in the same range all other parameters are excellent compared to the current steel being used as marine riser.

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material prop	X52	FGM
Poisson's ratio ( $\mu$ )	0.3	0.3 $\pm$ 0.07
% elongation	20	22.31 $\pm$ 0.11

So, let us go one step ahead and check. What is happening to Poisson's ratio. And percentage elongation, because these are very required. So, the Poisson's ratio classically for X52 is 0.3 whereas, we have 0.3 plus or minus 0.07 variation. Percentage elongation is 20 whereas, we get 22.31 plus or minus 0.11. So, all parameters are excellent and in fact, more than the requirement as recommended by the code compliance for marine risers.

So, friends advanced steel design also comes from material renovations. So, this is a very interesting example research study which I am presenting to you which are of course, available in our published papers and references given in the course material for this particular course. You can have more information about this.

We have also authored a book on FGM for marine risers please look into the book it contains more details about the manufacturing process, the constituents of FGM and other mechanical and structural characteristics which are more promising compared to the marine steel. Having said this let us compare the interface strength.

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Comparison the interface strength  
(ASTM E8 sub size specimen)

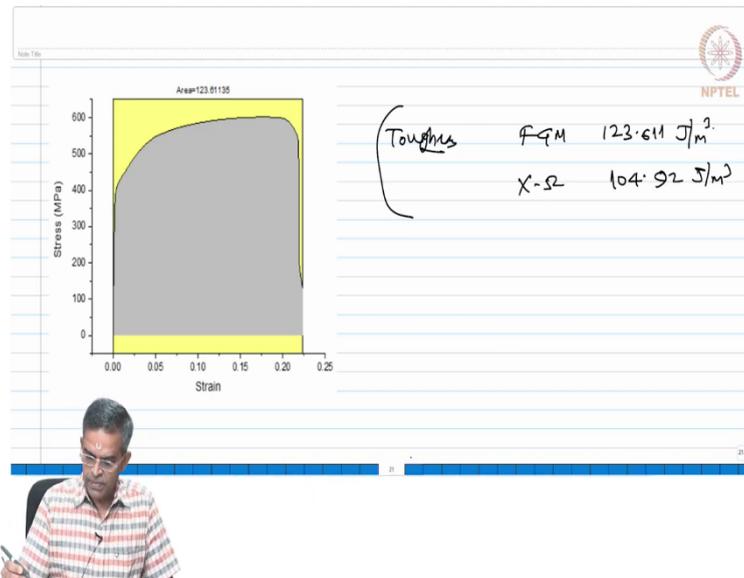
Material	$\sigma_y$ 0.2% proof stress (Mpa)	$\sigma_u$ (Mpa)	% Elongation
X-52	358	455.05	21
FGM	340	483 ± 2.5	16.02 ± 0.4



Now, let us compare the interface strength. So, we have used ASTM E8 sub size specimen. So, do this test and compare. So, we are now comparing the material for yield strength which is 0.2 percent proof strength in megapascal. We will also compare ultimate strength in megapascal. We will also compare percentage elongation quickly for this material.

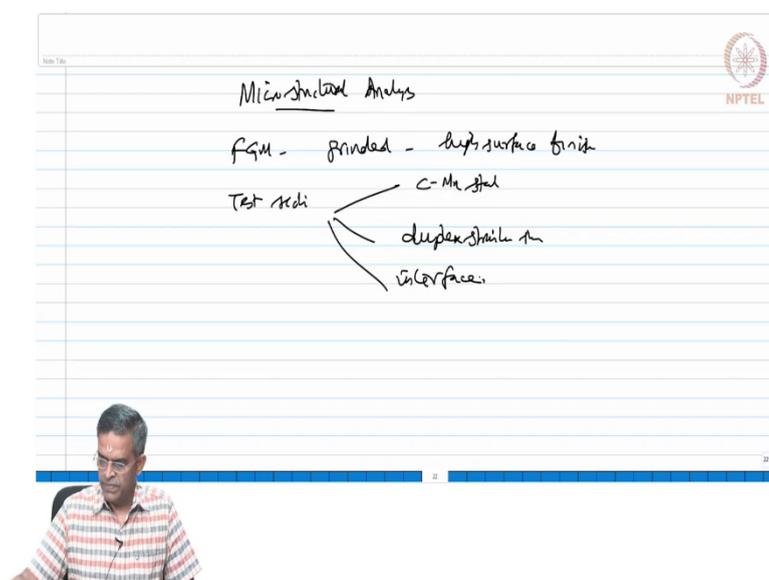
For X52 this is 358 is 455.05 and this is 21 whereas, for FGM we have 340 and 483 plus or minus 2.5 and 16.02 plus or minus 0.4. So, they are in the acceptable range of variation with respect to the parent material being used. So, therefore, we further investigated more structural properties of FGM and compare it with X52.

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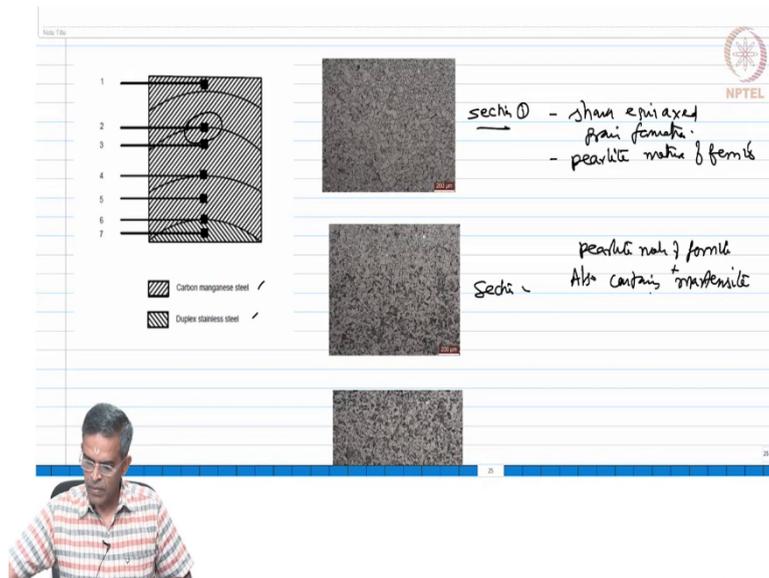
So, we also investigated the toughness properties. So, toughness is actually the area what you work out with the stress strain curve. The area has been computed and the toughness value what you get from the stress strain curve of FGM is what you see here which is comparable. So, the toughness value what we obtain for FGM sample is 123.611 joules per cubic meter whereas, for X52, we also worked out this and that came to 104.92 joules per cubic meter. So, FGM proved to be equally tougher compared to X52 steel .

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We further did microstructure analysis on the FGM mould. The FGM mould is grinded to high surface finish. The test section what we now consider consists of carbon manganese steel, duplex stainless steel and interface . So, the microstructure analysis is carried out in different sections.

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So, there are different sections about 7 sections are cut. Carbon manganese and duplex stainless steel are very clearly shown here. So, this is at Section 1. So, the microstructure Section 1 shows an equiaxed grain formation . This comprises of pearlite matrix of ferrite. Section 2 shows an equiaxed formation of pearlite matrix of ferrite, it also contains martensite.

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Section 1 - Schematic diagram of the bimetallic joint showing the interface between Carbon manganese steel and Duplex stainless steel.

Section 2 - Micrograph showing sham epitaxial ferrite formation in a pearlite matrix of ferrite.

Section 3 - Micrograph showing a higher concentration of martensite.

Section 4 - Micrograph showing pearlite matrix of ferrite, also containing martensite.

Section 5 - Micrograph showing the face of Carbon manganese steel.

Section 6 - Micrograph showing the interface between the two materials.

Section 7 - Micrograph showing the interface between the two materials.

Legend: Carbon manganese steel, Duplex stainless steel.

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Section 1 - Schematic diagram of the bimetallic joint showing the interface between Carbon manganese steel and Duplex stainless steel.

Section 2 - Micrograph showing the interface between the two materials.

Section 3 - Micrograph showing the interface between the two materials.

Section 4 - Micrograph showing a clear distinction between the pearlite formation in a matrix of ferrite.

Section 5 - Micrograph showing the face of Carbon manganese steel.

Section 6 - Micrograph showing the interface between the two materials.

Section 7 - Micrograph showing the interface between the two materials.

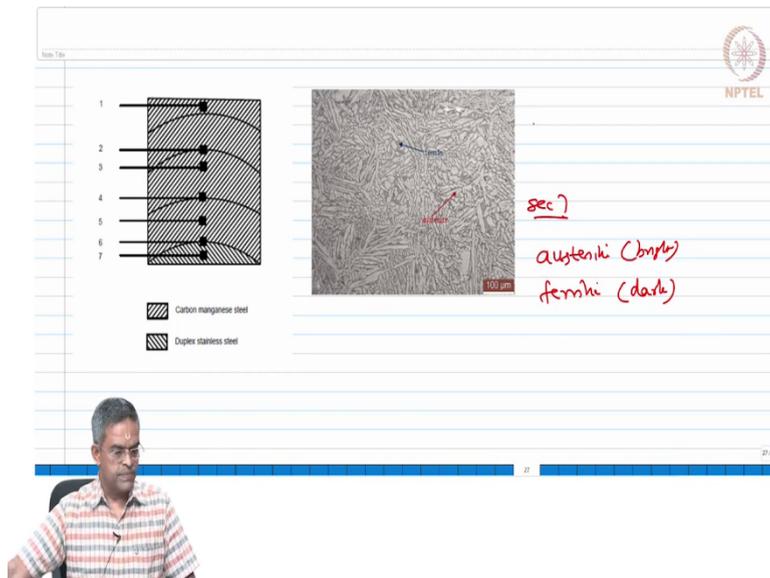
Legend: Carbon manganese steel, Duplex stainless steel.

This is Section 3 which is here. Section 3 shows high concentration of martensite. then we move on to the next section. Section 4 show a clear distinction between the pearlite formation in a matrix of ferrite. There is a clear distinction. Section 5 shows, the face of carbon manganese steel now. Section 5 is here and carbon manganese steel is this.

See the legend. It shows a perfect blending and mixture of both the metals is it not. This is Section 6 is the location of interface, because you can see Section 6 is located exactly at the

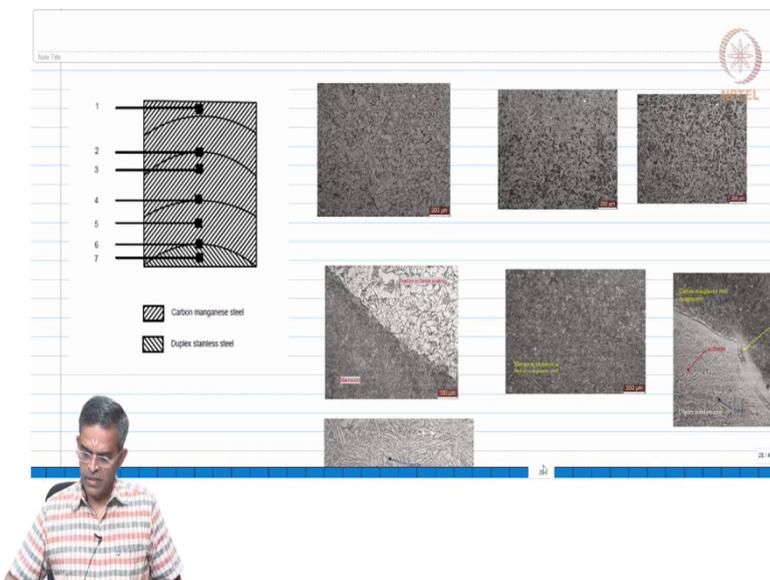
interface between the stainless steel and carbon manganese steel. So, one can very clearly see the interface in the image.

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And Section 7 the microstructure shows the austenitic, which is shown in bright colour and ferritic, which is shown in dark grains of the composition. So, friends the micro structure analysis very clearly shows there is a uniform blending of both the material as we fabricated it.

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Energy Dispersive X-Ray Analysis (EDX)

- @ the interface C-Mn duplex steel

EDX scan analysis -

- determine chromium variation across interface

The slide features a whiteboard background with handwritten text in black ink. At the top right is the NPTEL logo. A small inset video of a man in a striped shirt is visible at the bottom left of the slide area.

Furthermore is a comparison of all the images as we just now saw. Then furthermore we also did energy dispersive X-ray analysis, what we call as EDX. So, this analysis done at the interface of carbon manganese steel and duplex stainless steel at the interface. an elemental EDX scan analysis is carried out. The purpose is to determine the chromium variation across the interface. That is the idea.

So, the figure is shown on the screen now. So, at the interface this is the figure it shows the chromium content as seen in the figure.

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Carbon Manganese Steel Duplex stainless Steel

Interface

Cr - content in duplex stainless steel 20-22% @ 32-35 microns from the interface

Cr - close to the deposit process

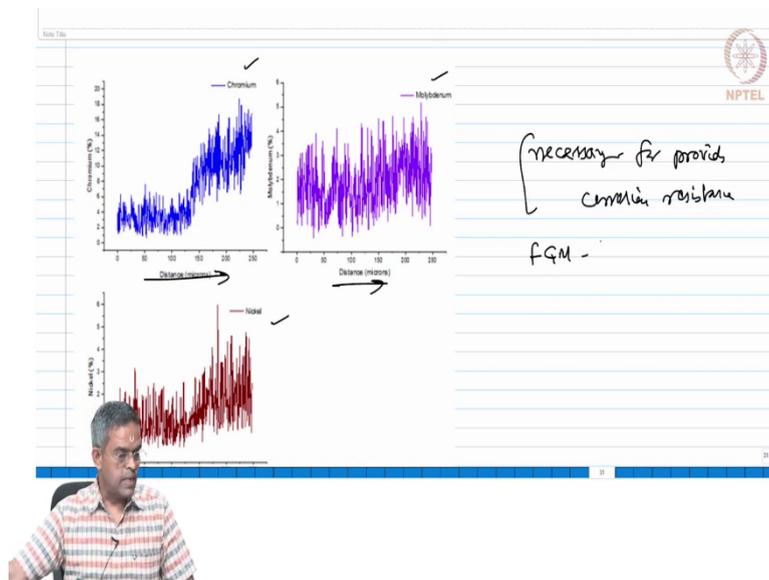
Cr - content - corrosion resistance

The slide features a micrograph on the left showing the interface between Carbon Manganese Steel and Duplex stainless Steel. The interface is labeled. To the right of the micrograph are handwritten notes in black ink. At the top right is the NPTEL logo. A small inset video of a man in a striped shirt is visible at the bottom left of the slide area.

The chromium content in duplex stainless steel is about 20 to 22 percent at 32 to 35 microns from the interface whereas, the chromium content is closer to the deposition process. So, it is important to note that the chromium content which is responsible for corrosion resistance has not moved away from the interface. It is not dispersed that property is protected.

So, we also wanted to check the chromium molybdenum and nickel content of this.

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So, this is a chromium molybdenum a nickel content of the FGM build, which ensures that as you move away the distance from the microns you will see there is a uniform spread of all these metals which are all necessary for providing corrosion resistance. So, though the FGM build is manufactured in wires, but still the parental characteristic of the duplex stainless steel which offers corrosion resistance is still maintain its enrichment in the formulated FGM build . That is what we observe from this image analysis.

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Micro-hardness

Duplex stainless steel - Vickers Hardness 267-235  
C-Mn steel 133-197

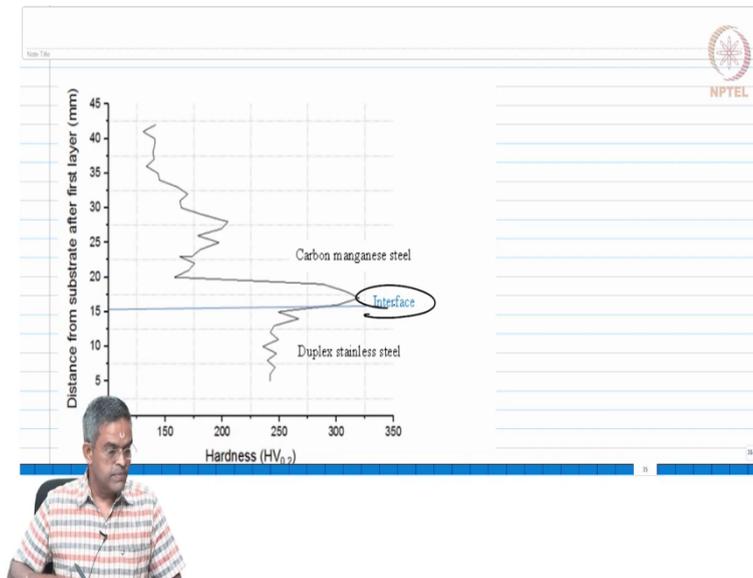
@ the interface, Vich 2mm  
Hardness = 307-320

- Martensite composition in the vicinity of interface ↑ Hardness

A micro hardness test was conducted using Vickers hardness, the duplex stainless steel showed Vickers hardness in the range 266 to 235. The carbon manganese steel showed between 133 to 197 . At the interface in the vicinity of about 2 millimetre thick the hardness number was seen as 307 to 320. So, the martensite composition in the vicinity of the interface has increased the hardness at the interface.

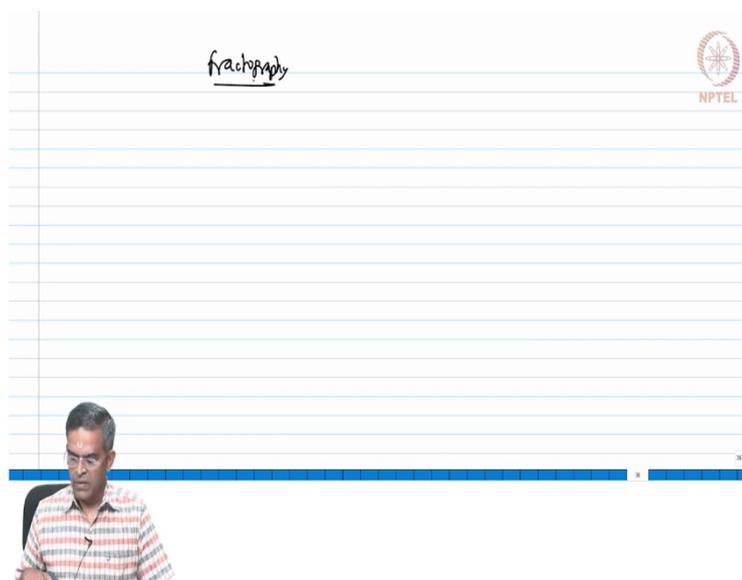
So, it has never failed in interface, because of this reason friends you can see in tensile test the interface separation did not occur. The increase in hardness contributes to the overall increase in strength of the material. It is also seen in the region of duplex stainless steel is of a higher oddness compared to carbon manganese steel which provides an additional strength to the FGM material.

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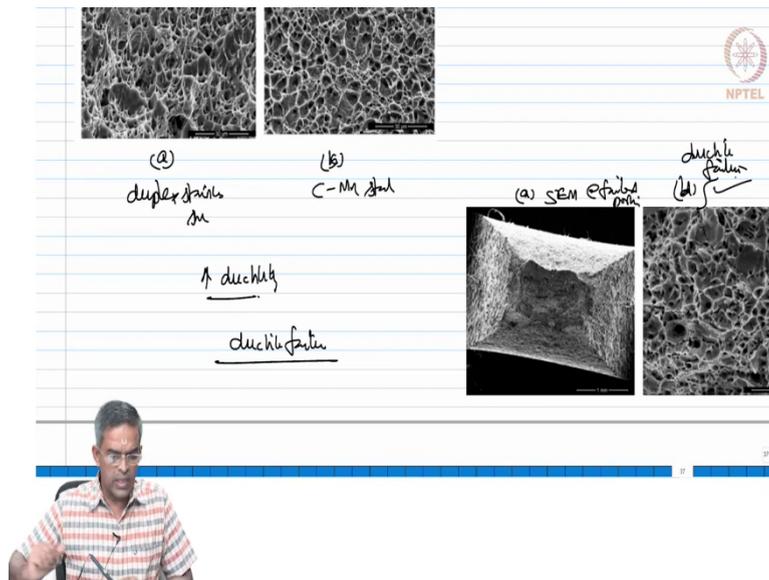
So, an image was also fabricated and tested, which shows at the interface the hardness is relatively higher as seen in the figure. Furthermore, a fractography analysis was also carried out.

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On the FGM mould by extracting a section comprising both carbon manganese steel and duplex stainless steel. Fractography is conducted at both this location of tensile sample. So, the fractography image is now what I am going to show you.

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This is duplex stainless steel, this is carbon manganese steel and this is the SEM image at the failed portion or at the fractured portion and this shows the fractography indicating a ductile failure. So, friends it is seen from the image is that the dimples are prominent on a large diameter in carbon manganese steel compared to duplex stainless steel. A full smooth cleavages present in duplex stainless steel is also noticed.

So, this shows an improved ductility. Furthermore, the stress partitioning was shown through an SEM image between the two materials, which shows that the failure is purely a ductile failure. So, the ductility characteristic of FGM is not compromised by mixing or by functionally grading these two materials.

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pitting corrosion test

ASTM - G48-11 method A

duplex stainless steel - 70.77 g/cm<sup>2</sup>

C-Mn - 823.35 g/cm<sup>2</sup>

NPTEL

Furthermore, a pitting corrosion test was also conducted on the build using ASTM-G48-11 method A. The test solution is used is about 100 grams of reagent grade ferric chloride in 900 ml of distilled water. All the surfaces of the mould were ground clearly using 120 grade emery paper and acceleration corrosion test was conducted for 24 hours.

The corrosion rate is determined by change in weight and surface area. The corrosion rate obtained for duplex stainless steel is 70.77 grams per centimetre cube and that for carbon manganese steel which is 823.35 grams per centimetre square.

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X Ray diffraction Analysis

- indicate presence of Chromia Oxide @ the interface of Fe-Cr

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X-ray diffraction analysis carried out, where you see the result on the screen now which shows that there is a central peak of chromium 0.1, in ferric 1.9 indicating the presence of chromium oxide at the interface. So, it indicates the presence of FGM. So, the formation of chromium oxide gives duplex stainless steel its corrosion resistance which is now available at the interface . So, that is a new material we have which has got a comparative value.

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So, the more details of the studies can be seen in these two textbooks. One is the Design of Marine Risers using FGM, which is written by me for Elsevier. There is another book which talks about use of FGM in Offshore Topside which is written by me for Wiley. So, these two books will serve as a very good reference material for you to know more about the material properties of FGM.

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Summary

FGM - better X-52 steel

- Manufact. With
- Mech ch
- durability

are reasons for marine application

So, friends as a summary we have learnt that FGM experimented using these two constituents of duplex stainless steel and carbon manganese steel proved to be better than X52 steel. The manufacturing process is using wire arc additive manufacturing detailed mechanical characteristics and durability characteristics are assessed using various tests and the results show a positive recommendation of FGM for marine application.

So, there is no compromise on strength there is only improvement on resistance of corrosion. So, that is how materials can also govern the steel design in the present context.

Thank you very much, have a good day.