Advanced Materials and Processes
Prof. B. S. Murthy
Department of Metallurgical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 1
Structure of Materials Part – I

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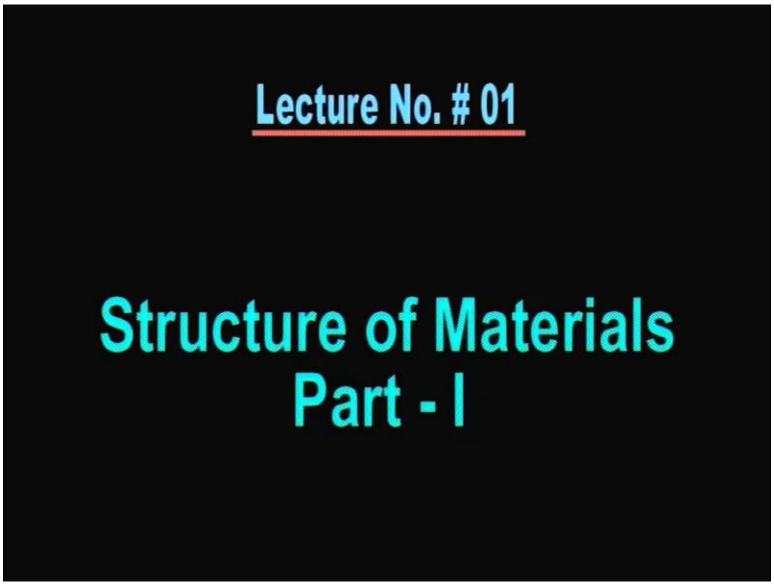

The objective of this, present, today's class is to understand the relations between the structure of a material and to the properties of the materials. And, when we talk of the structure there are different levels of structure - the electronic structure, the atomic structure, the crystal structure, and the micro structure.

So, today we will try to understand what are the various crystal structures in the material and how do we derive them, and how they are correlated to the mechanical properties, particularly as a metallurgist we are more bothered about the mechanical properties of the materials; so, how mechanical properties are related to the structure of the material.

So, if you want to talk about the structure of material the first thing that comes to our mind is long back the Plato. I do not know whether you have heard any type, platonic solids. Have you heard of platonic solids? You have heard of Plato? The most famous student of Socrates in 400 BC that was the period when he was born.

So, that is the time itself he thought the whole universe is made up of 5 solids. He thought that the whole universe can be thought of arrangement of, periodic arrangement of 5 solids though ultimately people have proved that it is not really true; but those 5 solids are called the platonic solids which are the only 5 regular solids that are available.

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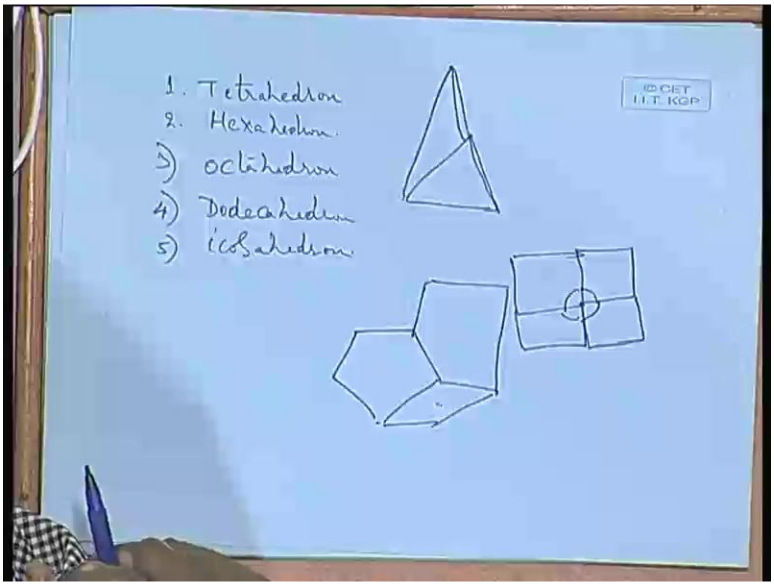

So, what are these solids? The first solid is what is called tetrahedron. You know what a tetrahedron is? What is a tetrahedron? Not tetrahedron crystal system. So, tetrahedron is a solid made up of, any solid for example has some phases. For example, cube you all know, cube has how many faces?

Student: 6 faces.

6 faces. What are these faces?

Student: Squares.

Squares, is it not? So, it is a solid made up of 6 square sides. So, similarly, a tetrahedron is a solid made up of triangles; it has 4 triangles. So, if you imagine a triangle as a base and put a point on top, a vertex, and then join all the 3 sides with that vertex you get basically a tetrahedron.

So, that means, it has a base, triangular base, and an apex on top, and the 3 points corners of the triangle are joined to the apex. So, ultimately what will end up is the 3 triangles and a triangular base. So, basically, it has 4 triangles. And, this is a regular solid means see, have you heard of what are regular solids? What are regular polygons?

Student: It has same size.

Is equal. There are number of polygons starting from a triangle. So, for example, if you want to have a polygon, minimum you need to have 3 sides. If you have only 2 sides it cannot become a polygon, is it not? You should have atleast 3 sides. And, the lowest polygon is basically a triangle. But all triangles are not regular triangles. There is only one triangle which is a regular triangle. That is, what is it, it is an equilateral triangle, we all know that.

So, the next, polygon is basically, if it is a regular polygon, it is a square. So, you can also have a rectangle which is also a 4 sided polygon, but it is not a regular polygon. So, that is a square, then you can have a regular pentagon, you can have a regular hexagon, and septagon, octagon and so on. And, if you can make a solid which is made up of regular polygons we call it as a regular solid.

So, cube is a regular solid made up of squares because square is a regular polygon containing 4 sides. So, we can call a cube as a regular solid. And, in principle, actually a crystallographer would like to call that not as a cube but as a hexahedron. Why we call it hexahedron? Because it has 6 sides. Tetrahedron is, we call it tetrahedron because it has 4 sides, tetra is 4.

So, that is a tetrahedron, then you have a hexahedron, and you have a octahedron. Hexahedron is the second solid, third solid is octahedron, then we have another solid called dodecahedron, and finally icosahedron. What is a dodecahedron? It is not 10; do deca, it is 12. And, icosa, anybody knows? Is a very crucial solid, crucial structure which is very commonly found in one type of materials.

Have you heard of quasi crystals? So, quasi crystals are usually made up of structure which is icosahedral arrangements of atoms. If you think of a solid, for example, a cubic crystal structure we say, a cubic crystal structure how do we visualize it? We visualize it having atoms at each corner, is it not? So, that is a cubic structure. We have face centered cubics, body centered cubic, we will come to them a little later. So, that is, a cubic structure basically we imagine as if there are atoms at the individual corners.

So, similarly, an icosahedron structure is also the same that you have an icosahedron with 20 faces. Icosa is 20. You have 20 faces which are triangles. And, these 20 triangles will make up a icosahedron with atoms at each corner. And, the dodecahedron is a solid which is made up of pentagons. For example, icosahedron is also very crucial in buckyballs.

Have heard of buckyballs? Carbon buckyballs, no? Buckminister Fullerings, you have heard of Fullerings? Atleast material scientist knows about it; is a real fascinating subject, a lot of people are working on them. And, offshoot of that is a nano tubes nowadays people talk about, carbon nano tubes. So, Buckminister Fullerings is nothing but a carbon molecule containing 60 atoms, c 60 people call it, c 60; and the 60 atoms are organized in such a way that they have this icosahedrons structure.

So, the atoms are arranged in such a fashion that they have the icosahedron atomic packing, and that is supposed to be the closest packing feasible so far. So, if you want to have, we say in a cubic structure, the closed pack cubic structure is, what is it? FCC. What is the packing density feasible there? How much packing density you get?

Student: 74.

74 percent. So, icosahedron can give you much more than that. So, that is why icosahedron packing is the best packing as per as packing is concerned. But the only problem is, a cube you imagine it as a brick; if you translate that brick in 3 dimensions you can build up a structure. You think of a wall, how do we make wall? We take a brick and translate that brick in 2 dimensions, that is a wall; if you do it in 3 dimensions you can get a structure, a crystal structure.

But unfortunately, if you try to take an icosahedron and try to translate it in 3 dimensions you cannot have a continuous structure without any voids left out. An icosahedron if you try to translate, you will always have, because 2 icosahedron, if you put them together there will be some voids left out, and those voids are in crystallography we call them as frustration.

So, that means, you will have a soil with lot of porosity, if you imagine that way. And, such a material with a lot of porosity cannot be really thought of; so, long back people thought that it is not possible to have solids with icosahedron packing. We will talk about it a little later, and to see how this is feasible in quasi crystals because quasi crystals in 1984 people have discovered.

And, since then a number of systems, starting from aluminum manganese alloy to number of alloys such as aluminum, copper, vanadium, and I mean copper, iron, there are so many alloys available now. Where, even if you just take the liquid and solidify it under slow cooling conditions you can get what are called stable quasi crystals. So, we will talk about them a little later when we come to quasi crystals.

So, basically these are the 5 regular solids. Why these are the only 5? Is there any way to prove it? In 400 BC itself Plato has shown that it is impossible to have any solid, any regular solid which is outside this gamut of this 5. How do we say that, yes there are only 5? How do we define a solid? Can you, have you ever thought about how we define a solid?

Say 5, anything more than that. Geometrically how do you prove, how do you define a solid, geometrically? No, no, we are not talking of any atoms here, it is just a solid. For example you take a cube, unfortunately I did not bring any model here. So, may be next class I would bring a model for icosahedrons, I have a few models. And, if we look at a cube and carefully look at it, if I somebody has to define a cube, you would say a equal to b equal to c, that is how you define it. What is the best way to define any solid?

Student: It has a definite shape.

Definite shape; and, what should be the angular relation? Any solid, what is the definition, difference between a plane and a solid? You see this table top, it is a plane, we do not call it as a solid. Do we call it as a solid? No. This book which you have in front of you is a plane, it is not a solid. Correct.

So, if you take any apex, any corner of the body, if the total angle is less than 360 degrees, we call it as a solid. Take any corner, for example take square, join 4 squares, let us say simply like this; take a square and put another square, another square, another square. See, there are 4 squares. And, what are the, what is the angle at any corner of a square, 90 degrees.

So, you take these 4 squares, and what you get? You get 360. And, so, if you take 4 squares and put them together what you get, is you get a plane; you cannot get a solid; but the beauty of a cube is that in a cube at any corner, how many squares are meeting? 3. The moment 4 squares meet at a corner at any point it cannot become a solid; it has to become only a plane. For example, plane tilings, we see in our houses, tilings.

So, if you take square tilings, you put 4 tilings, it becomes a nice tile without any frustration, without any voids left out. You people have even thought about a pentagonal tilings. Have you ever seen Tajmahal? If you see the walls of the Tajmahal, in Mughal period for some reason they like pentagon so much that if you carefully go and observe the walls of the Tajmahal you will see all pentagonal tiles.

The only problem with pentagonal tiles is if you take one pentagon, a regular pentagon for example and add another pentagon to it, so if you keep on, if you want to add pentagons of the same size you will always end up in some voids like this, if you continue like that. So, that is one of the problems with pentagon. So, but, that gives you very nice patterns which one of the mathematicians by name Penrose worked on it, what are called Penrose tilings.

There is a lot of work. Firstly, there is a book called Penrose tilings, you should look, have a look at it. And, is all about pentagonal tiles; how to have nice tiles with pentagon. Anyway, let us not bother about it at the moment. So, our job is to understand these 5 regular solids. So, the definition of a solid is that at the corner the angle should be less than 360 degrees.

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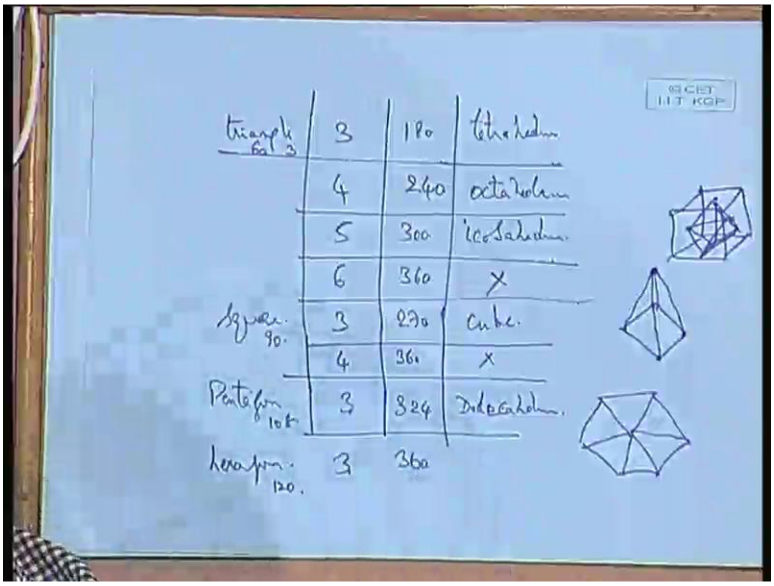

And so, if you try to have a look at what are the feasibilities of such a thing, first let us take a triangle; triangle, how many sides it has? It has 3 sides, is it not? And, try to bring 3 triangles at a corner. If you bring 3 triangles at a corner, 3 regular triangles at a corner, what should be the total angle? If you bring 3 triangles at a corner, what will be the total angle?

Student: 180 degrees.

180 degrees, yes. So, 180 degrees is less than the 360, so, it is feasible. And, what is such a solid where 3 triangles meet at a corner?

Student: Tetrahedron.

Tetrahedron. So, that is tetrahedron, we got it. Imagine now 4 triangles meeting at a corner; have you ever thought of any solid where 4 triangles can meet at a corner, and what would be the angle if 4 triangles meet at a corner? If the, what would be the total internal angle if 4 triangles are meeting at a corner? 2 into, I mean 4 into 60, so, 240. So, and what would be such a solid? Can you imagine? You know it.

Student: Sir, octahedron.

Octahedron, correct. For example, in cube we all talk about tetrahedral voids and octahedral voids; how do you imagine an octahedral? Think, for example, in a cube if you want see an octahedron, particularly we talk about octahedral voids in FCC, the body center is an octahedron void we say. Take all the force face centered positions, join them, and then take the top face centered position, join it with this, and take the bottom body centered, face centered position, join it, what you end up is an octahedron.

Basically it is like, with a point on top; this is half of the octahedron, other half will be at the bottom. So, what you see is basically at this corner, or at any other corner if you see basically 4 triangles meeting each other, and that is a octahedron. And, if you think of 5 meeting, what would it be? What will be the angle? 300. And, that is a icosahedron. So, if you take any icosahedron basically there will be 5 triangles meeting at each corner.

And, if you have 6 triangles meeting, what would happen? What would be the angle?

Student: 360.

360. And, what would be such a solid? It is a, it is not a solid. You imagine a 6 equilateral triangle meeting at a point, what would it become? It would be like a hexagon. Imagine a hexagon, regular hexagon; regular hexagon is nothing but a 6 triangles, equilateral triangles meeting at a point; that is a regular hexagon. So, this is like a triangular tiles or hexagonal tiles.

One can think of a hexagonal tiles like that, or triangular equilateral triangular tiles like that. We rarely see triangular tiles basically, because one has to make such tiles which is, which, large number of tiles we need instead of having a square tiles. So, square tiles is much more easier to manage with. So, that is why people use usually square tiles, otherwise you can have hexagonal tiles like this.

So, that is, so, it is not a solid. So, the next possibility is, obliviously we have come upto 360 degrees, so we cannot think of going beyond 360. You cannot imagine 7 triangles meeting at a point because then the angle will become more than 360. And, it is impossible to have an angle at any point more than 360, is it not? That is a maximum angle that we have. So, obliviously the, there is no more solid that is feasible.

Now think of what is the next polygon that we have, we have a square. Now, again imagine if there are 2 squares meeting at a point it cannot become a solid. For a solid to have, there has to be at least 3 polygons meeting at a point, and so you think of 3 squares meeting at a point; and, what would be the angle?

Student: 270 degrees.

270 degrees. And, that is what solid is it?

Student: Cube.

Cube, yes. We know it from our childhood, it is, that is the hexahedron are cubes; in a Layman terms it is cube; for a crystallographer it is a hexahedron. So, that is it. That is the one with where 3 squares meet at any corner. You take, you can choose any corner. There are 8 corners in a cube.

Every corner you carefully observe there are basically 3 squares meeting. This is true in all the regular solids. Though, for example, octahedron I have shown you only at the apex, but you choose any other corner; at all other corners there will be 4 triangles meeting. So, this is the beauty of any regular solid.

Then come to the next possibility. 4 squares meeting at a point, it becomes 360. So, it cannot be a solid; it becomes a tile. So, there is no solid where 4 squares meet at a point. So, obviously we have already come to 360, so you cannot imagine another solid with that. So, the next possibility is only a pentagon. Pentagon, what is the internal angle? 72, 108; this is square is 90; 72, 108; with 108 imagine 3 pentagons, regular pentagons meeting at a point it becomes 324, and that is the dodecahedron; and that is it, we have finished.

We cannot have any more. If you can imagine 4 pentagons meeting it would cross 360. So, obviously it is not feasible. And, you can see in such a simple terms he has proved. In fact, Plato at his university, I think you must have heard of the academy of Plato where he writes it on the front, like anybody who does not know geometry should not enter into this university. So, that is the kind of fascination that he had with geometry.

So, this is the 5 platonic solids. And, even today it is impossible to prove any solid other than this. There are so many other solids which are basically truncated versions of these. For example, have you seen football very carefully any time? You all play football, what are the phases in a football?

Student: Hexagons.

For example, you think of putting hexagons together you can never make a football because you imagine, let us come to that, pentagon let us take. Now take next one hexagon. Hexagon, how many, what is the angle? Hexagon, the internal angle?

Student: 120 degrees.

120 degrees. Triangle is 60, not hexagon; 120 degrees. So, imagine 3 hexagons meeting at a point, minimum is 3. So, 3 hexagons meeting at a point would give you 360 degrees. So, obviously it is not a solid, it is a tile. So, it is a hexagonal tile or plane, it becomes a plane. So, if somebody wants to make a football with hexagons he would never succeed.

A football is not made up of hexagons. If you keep on putting hexagons together, he cannot make a football. Football is a solid, is it not? It has to be rounded solid. You cannot take a soccer kind of a football and play; you will not call it as a football then. It would become like a soccer. So, what is that football is made up of? What polygons? Everybody plays with foot.

Student: Pentagons.

Pentagons also not possible. It is a mixture of pentagons and hexagons. Go back today and have a look at any football. If you take only pentagons I told you there is a frustration problem; you cannot tile only pentagons and make a solid. Imagine taking pentagons, regular pentagons and putting them together and finally making a solid, it is impossible.

Accepting the thing like dodecahedron; dodecahedron is the only solid. And, dodecahedron is not really, you know, spherical. For a football, you, if you think of dodecahedron being used, I have it here, but at the moment I do not whether you people can have a look; maybe, I will show it you to a little later.

So, if you think of using only dodecahedron as solid, it is not really a spherical ball. It will have all apexes; and such a thing if use it obviously it will hit somebody and will create problem. So, instead of that what we need is a real spherical ball, and for making such a spherical ball people had to use a combination of hexagons and pentagons.

If you think of using a septagons and pentagons, that means 7 sided polygon and 5 sided polygon together, ultimately it gets averaged out and it becomes like 6. So, it becomes like a plane. So, obviously people would not use 7 sided polygon and a 5 sided polygon. So, they use a combination of 6 sided polygon which is a hexagon and a 5 sided polygon which is a pentagon, and that is how you get a football. And, that is the structure of a c 60 basically, buckyball; buckyballs is like a football basically. So, these are the 5 solids.

And, in fact, Plato has been so philosophical. He said the whole universe, we think of 5 elements in the universe, is it not? The earth, the air, the fire, all those 5 elements. So, he thought this 5 solids, the 5 elements in the universe are basically made of these 5 solids. So, that was the kind of philosophy he had which slowly people have shown that even these 5 solids excepting tetrahedron, octahedron, and cube, the remaining 2 do not come in most of the crystal structures.

So, that brings us to the next step what is called the crystal structure. So, we know that though Plato has talked about these 5 solids if you can imagine putting these 5 solids into a crystal like, for example aluminum. So, aluminum if you think of the atoms which are arranged in a 3 dimensions, they are arranged in what kind of a fashion, cubic FCC; we call it face centered cubic.

So, basically it is a cubic type of arrangement of atoms. But there are no arrangements of atoms which are like really icosahedrons, dodecahedron, that kind of an arrangement. The problem that comes is if you have that kind of an arrangement you will have large amount of voids left out; to understand that we need to understand what makes up the crystal structure.

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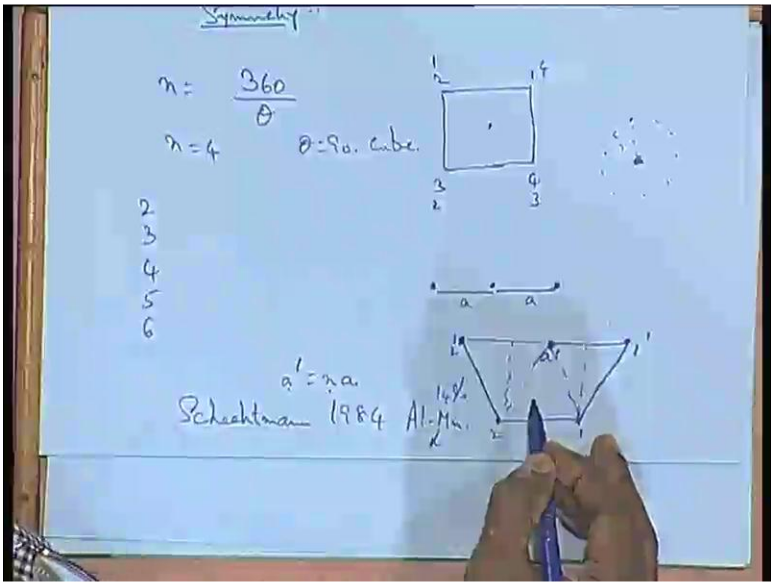

Basically, if you talk of crystal structure there are 2 important points that one need to understand. What is called the symmetry of a crystal structure? When I say cube, how do you visualize the symmetry of a cube? Have you ever thought about what should be, how do you compare a cube with tetragonal? We have the cubic crystal system and tetragonal crystal system, so, how do we usually compare these 2?

Student: Sir, sides are equal and also the angles are equal.

Angles are equal that is for a cube; and, for a tetragonal? Tetragonal, how do you define tetragonal? Cubic, tetragonal? Very good, where did you hear this? Very good, very good, this is the actual definition of the 2. We usually talk of, a equal to b equal to c, alpha equal to beta equal to gamma equal to 90 degrees for cubic. And, we talk about the a equal to b that is not equal to c for tetragonal and the alpha beta gamma being equal to 90 degrees for a tetragonal system; that, that is not the real definition of these two.

The definition always comes from the symmetry of it. When we talk of symmetry there are 2 kinds of symmetry in any material. You have to have 2 types of symmetries in any material what is called rotational symmetry and a translational symmetry. In a crystal if you have only one of them we do not call it as a crystal. In fact, the definition of a crystal is that, that it should have both rotational symmetry and a translational symmetry.

What is a rotational symmetry? Rotational symmetry means you take any solid or any plane, for example you take a square, a square has a 4 fold symmetry we say. Why it has a 4 fold symmetry? I take a square, rotate the square around a particular axis let us say. I take the square and choose the centre of it, rotate it by 90 degrees. When I rotate it by 90 degrees if you think of there are 4 corners, when I rotate this by 90 degrees, 1 goes to 2, 2 goes to 3, 3 goes to 4, and 4 goes to 1, is it not?

And, this kind of a rotation does not create any new vertices or new points. So, that is the characteristic of the symmetry of the square. Instead of 90 degree if I rotate it by about 60 degrees, I will, this 1 goes to some other point and 2 goes to some other point. So, I am generating new points. So, 60 degrees is not a characteristic rotation for a cube; whereas 90 degrees is a characteristic rotation for a cube, so that no new points are generated.

So, the solid or the polygon merges into itself. You cannot differentiate between the original position and the new position, and that is called the symmetry of that particular polygon or of the particular solid; here we are talking of square as a polygon. So, this 90 degree symmetry, if you put it in terms of what is called the rotational symmetry, the, what is the order of the symmetry, so we define it as n fold symmetry which is nothing but 360 degrees divided by the theta with which you rotate; for a cube because it is 90 degrees rotation then n is becomes equal to 4 because theta equal to 90 degrees per cube.

So, we call that a square has a 4 fold symmetry. What is the symmetry of a rectangle? It has a 2 fold symmetry, it does not have a 4 fold symmetry. So, it does not mean that every 4 sided polygon will have a 4 fold symmetry, no. A rectangle will have a 2 fold symmetry. And if you take a triangle? It depends on which triangle? So, the moment I say triangle you should not jump to 3, 4 symmetry; only equilateral triangle has a 3, 4 symmetry, not every triangle; only equilateral triangle has a 3, 4 symmetry.

And similarly, we can talk of a regular pentagon has a 5 fold symmetry; a regular hexagon, you watch my words, regular hexagon I am saying, regular pentagon. You can have any pentagon with each side not being equal but such a pentagon will not have a 5 fold symmetry, but a regular pentagon will have a 5 fold symmetry. And similarly, a regular hexagon will have a 5 fold symmetry. We can draw a hexagon with not all 6 sides being equal. So, that will not have a 6 fold symmetry.

So, like that we can talk of symmetry of a polygons. What would be the symmetry of a circle? Can you please tell me? It should be infinite; a circle has an infinite symmetry. So, like that we can talk of symmetry of a polygon but as a, in a crystal structure we have a 3 dimensional arrangement of atoms, is it not? So, 3 dimensional arrangement of atoms means I am not concerned only about 1 point.

When I am talking of rotational symmetry, various rotational symmetries, for example, 2 fold symmetry, 3 fold symmetry, 4 fold symmetry, 5 fold symmetry, 6 fold symmetry and so on; these are all concerned to 1 point. I take in a square, for example, that centroid and then I am rotating around that point. So, that is why these are called point group symmetries. Rotational symmetries are called point group symmetries. That means, everything happens around a point.

So, that means, in a crystal structure you are talking of unparticular point where how the atoms are arranged but that is only a localized arrangement at that point. For example, we call, we talk about short range order. So, something like a short range order you are talking about, in a small region. But, how is that translated in the 3 dimensions – x, y, z? And, that is what gives us the crystal structure. So, that is what brings us translational symmetry.

So, what is the definition of a translation symmetry? Translational symmetry basically means that if I take any 2 points or 2 atoms, I do not usually call atoms basically because a crystal structure need not have 1 atom at each corner. It depends on what kind of a material we are talking about. If we are talking of pure metals we know that at each corner you have 1 atom.

For example, aluminum if I take for a centered cubic, I know that at each corner I have 1 atom of aluminum. But, if I talk of H 2 O, simple structure that we know, what is the crystal structure of H 2 O anybody knows?

Student: Hexagonal.

Hexagonal structure, yes. There are people who have gone to the clouds and tried to put seeds in the clouds to get ice crystals to understand what is the structure of an ice, crystal structure of an ice. There is lot of work on that to understand because otherwise the way people have found out the crystal structure of a water, you know how? Is that the ice crystals that fall, the snow that falls, people tried to look at the morphology of that snow crystals.

And usually, we know to some extent the external morphology reflects the internal crystal structure. So, most of these ice crystals grow in 6 kind of directions; so, in a 6 fold kind of a pattern. So, from that people thought probably it should be hexagonal. We will come to it a little later that just because anything has a 6 fold symmetry it does not mean it is a hexagonal system; we will come to it a little later.

So, here if you take, talk in terms of a translational symmetry then you take any 2 points, take what is the distance between those 2, let us say a, and if you traverse, travel by the same distance a, you should find another point in the same direction. That is why in crystal structure we talk of lattice points; I am sorry, we talked about water but missed the actual point.

The point is that, that in water the hexagonal crystal structure we talked about, at each corner you have 3 atoms, not 1 atom. What is that? The molecule of H 2 O, 2 atoms of hydrogen and 1 atom of oxygen. So, that molecule exist at each corner. In water, hydrogen does not exist separately and water does not exist separately. They all always exist as 1 molecule.

That is why in thermodynamics when we talk of the number of components, when we say water it is only 1 component. We do not take it as hydrogen and water. The Gibb's phase rule you all remember, that the p plus f equal to c plus 2, or c plus 1, depending on whether it is condensed phase rule or so. So, there the number of components when you are choosing, if you are talking about water we will always take it as 1 component, not as 2 components. So, that is very crucial. So, it always exist as H 2 O.

So, similarly, a number of components are, there are some components where at each corner more than 100 atoms are present. So, I cannot say that a crystal structure is regular arrangement of atoms at each corner, I should not say. So, that is why we always call it as lattice points. 3 dimensional regular arrangement of, or 3 dimensional periodic arrangement of lattice points is what is a crystal structure.

And, at each lattice point what you put, depends on the type of material. Same phase centered cubic structure, in one material may have only 1 atom, and some other material may have more than 1 atom, depends on what material we are talking about. If it is pure metals usually it is 1 atom. So, that is the actual structure, definition of a crystal structure.

And, if we come to this translational symmetry then basically that if you see the distance between any 2 lattice points, I do not say atoms, any 2 lattice points, it should be the same in 1 direction wherever you go in the material, and that is the translational symmetry. And, if a material processes both the rotational symmetry and a translational symmetry we call it as a crystal.

If it does not process both, we call it as a; if it does not process both?

Student: Amorphous

Amorphous; we call it as an amorphous which does not have any structure. A quasi crystal is something which is, in a midway, it has a rotational symmetry and does not have a translational symmetry because it has a special rotational symmetry.

Student: 5 fold symmetry.

That is the 5 fold symmetry which in crystallography we call it as a forbidden symmetry. Why we call it as a forbidden symmetry? Because if you have a 5 fold, you cannot have a translational symmetry. Go back to Kittel; you know, the book of Kittel? “Solid State Physics”? Atleast all the physicist should know. So, if you see Kittel, he shows a proof of why a 5 fold symmetry cannot have a translational symmetry attached to it.

The simple way to prove it is, take any points, 2 points, where the distance between them is let us a, and now rotate this point with respect to this point, let us say point 1, point 2; rotate point 1 with respect to point 2 in a 5 fold rotation; if you rotate the 5 fold rotation means 108 degrees. So, I rotate it by 108 degrees. I come to another point somewhere here, I rotate this. That means, this has been rotated and you brought it to somewhere here.

And similarly, rotate number 2 with respect to number 1, you come to another point somewhere here. So, this is, I can call it as 1 dash and this is I can call it as 2 dash. And, now if you think of this direction, and the distance between 1 dash and 2 dash, if the distance between 1 dash and 2 dash is not integral multiples of this distance a, then it is not a crystal structure; it does not have a translational symmetry.

If it has this, a dash, if a dash is integral multiples of a, then only a crystal, that particular structure we can say has a translational symmetry, otherwise it is not translational symmetry. If you take a 3 fold or a 4 fold, you will always see that, a dash, is always integral multiples of, a. Think of a 3 fold, for example, 3 fold is 60 degrees.

When you take this, rotate by 60 degrees, you come to a point. So, you come to a situation like this, so, where this distance is basically, 0 times a. And, if you take 90 degrees, so this goes to here and this goes to here. So, again you make something like a square. So, this, a dash, will be, 1 time of a; a dash is equal to a. Similarly, if you take as a hexagonal 120 degrees, you rotate it by 120 degrees you will see basically that will again be integral multiples.

But only with 5 fold you have problem; 5 fold, 7 fold, 8 fold, these are some of these rotational symmetries which cannot have this kind of a translational symmetry. So, that is why we people have always thought that a crystal should not have a 5 fold symmetry. Unless, I mean, until 1984, when a person by name Schachtman, in 1984, in a aluminum manganese alloy, aluminum - 14 percent manganese, he made this alloy, rapidly solidified this, and then looked at this the ribbon that you get in rapid solidification in a TEM, and he found that this shows an interesting symmetry.

The diffraction pattern looked like this. It has a transmitted spot, and it has 10 spots around it; 4 plus 4, so, yes, it has 10 spots around it. It is like a 10 fold symmetry. All spots are equally spaced. That means, if you think of the angle between these 2 spots, what they make with the transmitted beam, that angle is 36 degrees which is same for all of them. So, the diffraction pattern looked really strange which has never been observed in any material till then. So, he thought he has come up with a new type of material which shows entirely a new type of a diffraction pattern.

And, since then, people have worked on a number of materials, and now it is feasible to obtain such diffraction patterns in so many varieties of materials, and these materials are called a quasi crystals now. And, that is why the definition of a crystal has been now changed. People do not say that earlier the definition is that a crystal should have both translation symmetry and a rotational symmetry.

Now, that definition people do not take it anymore; they say anything that gives you a sharp diffraction peak or sharp diffraction pattern is a crystal, so that, quasi crystals also can come into those, that particular class. Amorphous materials, if you do x-ray diffraction or electron diffraction, amorphous materials will never give a sharp diffraction pattern, they give you a broad peak, is it not?

X-ray diffraction pattern of any amorphous space if you see, it is just a broad peak. It will never give you a sharp. The moment there is a sharp peaks means each peak coming from some particular HKL plane, is it not? In x-ray diffraction, you all know, each peak comes from a particular HKL plane. And, that means, that particular plane basically indicates that there is a regular arrangement of atoms.

In a quasi crystal also there is a regular arrangement of atom; only thing is there it is not periodic, it is quasi periodic. We will talk to, about it, when we come to quasi crystals a little later; that what is this quasi periodic arrangement of atoms, we will come to it a little later.

Student: Sir, in that case, if at all the material has to exhibit the symmetry in this particular fashion it can exhibit 4 fold symmetry without being like this, where it is not exhibiting 4 fold symmetry.

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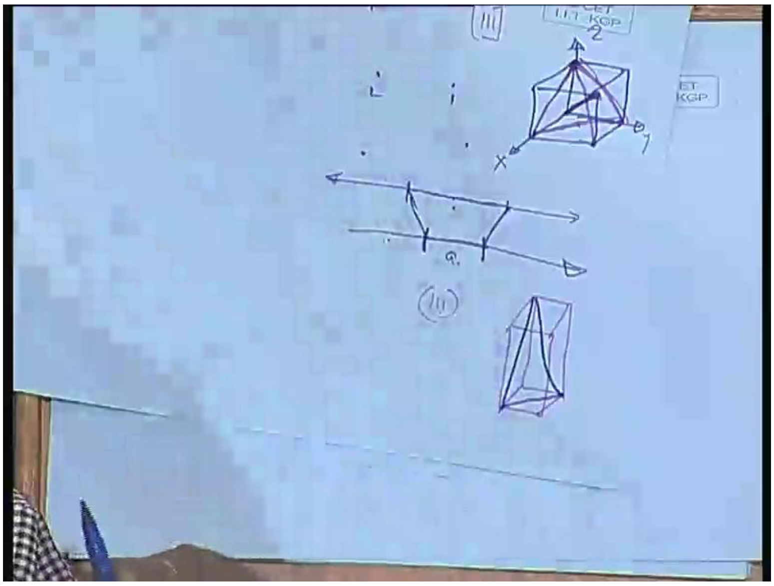

It is simple. If you think of, take 2 points; and if you take point 1, point 2, rotate point 1 with respect to point 2, 90 degrees, how do you rotate? The only way the point 1 comes here, 1 dash; there is no other place it can go; either it goes this side or it goes this side.

Student: If it, it has to exhibit in 5 fold, then it will exhibit the kind of pentagon system.

Correct. But if you take that pentagon, that means, a solid like this, this is a pentagon with another point somewhere here joining, let us not worry about that point now. Now, think of what is this distance; this distance can never be integral multiples of this; can never be. And, that is why we say it is cannot have, because you see, you think of this direction, this is one direction, atomic direction in a crystal structure; this is also another parallel atomic direction, is it not, in a 3 dimension.

So, what should be the difference between these 2? You see, crystal structure is something what we imagine. The atomic arrangement in a material, it does not know what is its crystal structure; it has only regular arrangement of atoms, that is it. We are trying to join these atoms by some lines and imagining some kind of a crystal structure. It does not join, all these atoms are not joined by lines in any crystal structure, no; we are joining them.

So, in principle if there is one way of arrangement of atoms in one direction, a parallel direction in the space should have exactly similar arrangement. If the spacing between 2 atoms is, a, the spacing between here also should be, a; it cannot be less than a or it cannot be more than a, that is the problem. So, because of it this cannot be compatible with translational symmetry. So, that is why we say a pentagon is a forbidden symmetry. And now, people have started using this forbidden symmetry in crystal systems.

So, this is as far as the crystal structure is concerned that symmetry is very crucial, that we should have a symmetry which is both rotational and translational symmetry. And, if we talk of rotational symmetry alone and try to see how the 7 crystal systems can be divided in terms of this rotational symmetry, we can see that basically we can characterize, take a cubic structure which is a first crystal system that you all know.

A cubic structure, what should be the characteristic of a cubic structure in terms of the symmetry? Tell me? He ShubuDas has told earlier.

Student: It should have 4 fold symmetry.

It should have 4 fold symmetry; of course, it has a 4 fold symmetry, but it is not just 4 sold symmetry.

Student: 3 fourfold symmetry.

3 fourfold symmetry, that is the beauty of a cube. You imagine a cube, a axis, a, b, c; imagine the 3 a axis. For example, I take a cube, draw a cube; you have a, this is one axis, this is another axis, this is another axis; x, y, z or a, b, c whatever you want to call it; we will try to repeat it further minute later. So, this is the 3. And, all the 3 axis have a 4 fold symmetry; all the 3 of them have 4 fold symmetry; and, that is the characteristic of a cube.

And, if you take a tetragonal system, how do you, can you think of generating a tetragonal system from a cube? How do you make a cube into a tetragonal, tetragon? No, no, not like that. I give you a cube, can you make it into a tetragon? I ask you to make it into a tetragon physically, how do you make it? Simply take the cube and pull it along the c axis, or a or b axis, anyone of the 3 axis; either pull it up or compress it.

You make basically, that if you think of pulling it, so c axis becomes longer, a and b remain the same. So, a equal to b, but not equal to c, that becomes a tetragonal system. And, imagine in a tetragonal system, how many 4 folds will be there in a tetragonal? There will be only 1 that is a basal plane. There is a base which is a square now. The all 4 sides are no more squares, they are rectangles now.

The moment you have pulled it along the c axis you made it a long elongated cube kind of thing; it is no more a cube now. So, once it has become like that, so, you have lost 2 fourfold axis by just pulling a cube, giving a tension to a cube. So, you have only 1 fourfold axis which is at the bottom or at the top. Basically, is the same axis, so, we do not differentiate between the axis going from bottom or axis going from the top; so, it is 1 fourfold axis.

So, the basic difference between cubic structure and a tetragonal structure is that in a cubic structure you have 3 fourfold axis and in a tetragonal structure you have only 1 fourfold axis. In addition to 4, 3 fourfold axis, the cube also has a 3 fold axis. Can you imagine where is this 3 fold axis situated?

Student: Diagonals.

Diagonals; imagine all the diagonals; how many diagonals you have?

Student: 4.

4 diagonals. So, here you see, imagine an axis going from this corner to this corner, this diagonal axis; I will use maybe a different color for you. So, imagine this diagonal or imagine from this point to this point, a diagonal going like this; that diagonal will be having a 3 fold symmetry. For example, you imagine that is a plane. What is that plane?

Student: 1 1 1.

1 1 1 plane. There is a name given to that 1 1 1 plane, do you people know? What is that name given to that plane? In metallurgy we always talk about it.

Student: It is a closest pack plane

It is the closest pack plane in?

Student: FCC.

FCC, yes; it is a closest pack plane and it is a slip plane in FCC. Why do we need to study all these crystal structures, is basically because the deformation behavior of a material depends on this. That is for the number of slip systems of crucial which define the deformability of a material, and we know that FCC is a closest packed and the largest number of slip systems it has.

So, that is why it is easily deformable, and then comes the BCC and the HCP and so on and so forth. That is why the symmetry is very crucial. Because the FCC has the highest symmetry that is why we say it is easily deformable.

So, if you try to take this, this particular plane is called octahedral plane. The reason why we call it octahedral plane is because there are 8 such planes, 1 1 1; if you can think of what are the possible combinations of 1 1 1, bar 1 1 1, bar 1 bar 1 bar 1, 1 bar 1 1, like that if you can try to think of what are the possible combinations, you will see 8 such combinations possible; so, it is 8 octahedral planes in a tetragonal.

Let me draw that tetragonal for you. Imagine this is a tetragonal crystal structure or tetragonal unit cell; take the 1 1 1 plane in here; what kind of a triangle is this? It is an isosceles triangle; it is not an equilateral triangle anymore. The moment it is an isosceles triangle it cannot have a 3 fold symmetry. Yes. So, we can see clearly all the 1 1 1.

We will stop.