Advanced Materials and Processes
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Lecture - 2
Structure of Materials Part – II

We talked about 3 4-fold axis and 4 3-fold axis. And a tetragonal if you come to there is only one 4-fold axis.

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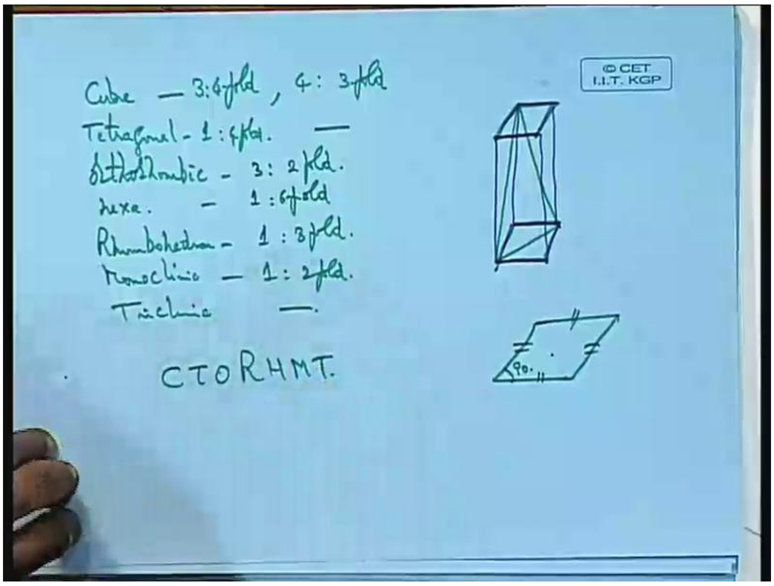

Cube — 3: 4-fold, 4: 3-fold
Tetragonal - 1: 4-fold. —
Orthorhombic - 3: 2-fold.
hexa. — 1: 6-fold
Rhombohedron - 1: 3-fold.
Monoclinic — 1: 2-fold.
Triclinic —.

CTORHMT.

As I told you, the only the plane which has a 4-fold axis is the top and the bottom. What will be the 4-fold axis, what will be the indices of the 4-fold axis, in a tetragonal 0 0 1. So, that is the only thing, which has the 4-fold symmetry. All other 1 0 0, 0 1 0 will not have a 4-fold symmetry. And what would be the symmetry of 1 0 0 in a tetragonal?

It will only have a 2-fold symmetry, it will not have 4-fold symmetry. So, you have only 1 4-fold axis. And 0 3-fold, it has no 3-fold. So, just by a simple tension of a cubic system, a little bit elongated. That means, c by a ratio has been changed from 1, to either less than 1 or more than 1. Immediately the system changes, the symmetry of the system changes. And that is the characteristic of a tetragonal. And then come to the next one, what is a next one?

It is a orthorhombic, and orthorhombic crystal. That is the definition that we usually give, is a not equal to b, not equal to c, alpha equal to beta equal to gamma is equal to 90 degrees. That is the way we usually define. And when we come to the crystal, the symmetry of the crystal, what should be the symmetry of that orthorhombic crystal?

Student: ((Refer Time: 02:32))

Correct, it will have three mutually perpendicular 2-fold symmetries. Because, we have defined it as a is not equal to b not equal to c, if you remember orthorhombic. That means, all the planes, the six planes which formed a orthorhombic crystal unit cell. All six of them are basically not squares, they are all rectangles, is it not. All 6 of them are rectangles. So, a rectangle has a 2-fold symmetry we all know.

And they have three mutually perpendicular 2-fold symmetry. Why do we say mutually perpendicular, because the angles are all 90 degrees. Alpha is equal to beta is equal to gamma is equal to 90 degrees. So, you have three mutually perpendicular 2-fold axis. See this is important to know, that when there is 4-fold axis, we do not talk of a 2-fold axis.

For example, when we are talking of tetragonal, we did not say that it has one 4-fold axis, and two 2-fold axis. 1 0 0 and 0 1 0 directions are basically 2-fold axis, but we do not talk about it. Why, because whenever we define a crystal system, we define it with the maximum symmetry. That is feasible with that system. A 4-fold symmetry is a symmetry, which is higher than a 2-fold symmetry. It is a 4-fold symmetry indicates always a higher symmetry, than a 2-fold symmetry.

So, when a 4-fold symmetry is already existing in a crystal system, we do not talk about a 2-fold symmetry, which is already there. For example, cubic also, when we say it has three mutually perpendicular 4-fold symmetries. Automatically every 4-fold symmetry, will have inherently a 2-fold symmetry is it not. If for example, think of a square, I rotate it by 90 degrees, I talk about 4-fold.

Instead of 90 degrees, I rotate it by 180 degrees, I have a 2-fold inside a square. Every square will have a 2-fold in it. In addition to the 4-fold, but we do not talk of the 2-fold which is their inside a square, but because the 4-fold symmetry is a higher level symmetry than a 2-fold symmetry. So, when a particular solid or polygon has a 4-fold symmetry, if a it has a 2-fold symmetry, we do not talk about it, because it is inherent indices.

So, a particular crystal system, is always defined by the highest symmetry, that is feasible in it. So, that is why in a cube, we say it has 3 4-fold axis, we do not talk about the 2-fold axis there. In fact, we even do not talk about the 3-fold axis in it. Because, 3-fold symmetry is lower than the 4-fold symmetry. So, always a cube is defined with, I mean 3 4-fold axis.

Nobody defines it as 3 4-fold axis, 3 4-fold axis is inherent into 4 3-fold axis. When you have 4 3-fold axis, automatically you will have 3 4-fold axis. When a equal to b equal to c, and alpha equal to beta equal to gamma equal to 90 degrees. Automatically you end up in the 3-fold axis coming into picture, so we do not talk about it.

So, when it comes to the tetragonal, we only talk about the one 4-fold we say. We do not talk about the remaining two 4-fold, two folds. Because, they are lower than the 4-fold. So, the characteristic of tetragonal is the 4-fold symmetry, one single 4-fold symmetry. And when you come to the orthorhombic, the highest symmetry, that it has is a 2-fold symmetry. It has nothing beyond that, it does not have a 3-fold symmetry.

Because, you imagine a 1 1 1 plane in a orthorhombic. You see 1 1 1 plane can be thought in any crystal system, why only in cubic, we can think of 1 1 1 even in a triclinic. 1 1 1 is just a plane, it is joining the three corners you get a 1 1 1 plane. But, only interesting thing in a cubic is that, that 1 1 1 plane is a equilateral triangle, which gives it a 3-fold symmetry. And that is characteristic of a cube.

Only cube has that, when you come to an orthorhombic, you have the 1 1 1 plane there. But, the 1 1 1 plane is not a equilateral triangle. Obviously, if it is not equilateral triangle, it will not have a 3-fold symmetry. So, there is no 3-fold symmetry, no 4-fold symmetry in a orthorhombic system. So, the only possible symmetry is a 2-fold symmetry. And that 2-fold symmetry interesting thing is that, it has three mutually perpendicular 2-fold symmetry, because the angles are 90 degrees.

So, that is the characteristic, so it has three 2-fold symmetries. Come to the next one, what is it, it is hexagonal. In a hexagonal system what do we have, imagine the hexagon, you all know about hexagonal. It has a 6-fold symmetry, it has 1 6-fold symmetry, which is the direction perpendicular to the basal plane. What is the indices of that plane, when I Yamini can you tell me? What will be the indices of the direction, which is perpendicular to the basal plane?

Student: ((Refer Time: 08:23))

No

Student: 0 0 0 1

0 0 0 1, that is the c axis. 0 0 0 1 is the direction, which is perpendicular to the basal plane and that has a 1 6-fold symmetry. So, that is the characteristic. So, it still has a 2-fold symmetries, if you think of the six planes, which form the hexagonal. Hexagon I mean the hexagonal parallel piped, which is what is the actual hexagonal system, we represent with. And that is composed of the 6 rectangles. And all of them have basically a 2-fold symmetry, but we do not talk of that 2-fold symmetry there.

We talk of only that 6-fold symmetry, which is characteristic of the hexagonal system. Then, you come to rhombohedral, rhombohedral system. What is the characteristic of a rhombohedral? How do we define rhombohedral?

Student: ((Refer Time: 09:45))

Not equal to 90 degrees, is exactly similar to cubic in all respects, accepting that the angles are all equal, but not 90 degrees. Can you think of how do we generate such a solid from a cube. Basically it is similar to cube, so it can be generated from a cube.

Student: ((Refer Time: 10:13))

Shear yes, it is a shear kind of thing, anything else. You take the any one of the body diagonals 1 1 1 directions, pull it along that 1 1 1 direction. You basically make the cube into you lose that 90 degrees angle. Give a small pull along the 1 1 1 direction and it becomes a rhombohedral. A equal to b equal to c, it will remain and the angles will just change from the 90 degrees. To some other angle, again the angles will be equal, because you are pulling along diagonal.

You will retain the angles, but the angles will be less than 90 degrees, but they will be the same. And such a thing will have only one 3-fold axis. You lose the 4-fold, because the angles are not 90 degrees. See the characteristic of a square, square has a 4-fold symmetry. But, if I take a solid plane like this, it has 4 sides. All of them are equal, this is equal to this equal to this equal to this, but this will not have a 4-fold symmetry.

Yes or no, it will not have a 4-fold symmetry, because the angles are not 90 degrees. If you want to have a 4-fold symmetry, in a four sided polygon, you should have the angles 90 degrees. Only the square will have a 4-fold symmetry plane like this, will not have a 4-fold symmetry. So, you lose all the 4-fold symmetry. There are 3 4-fold symmetries axis in a cube, you lose all three of them. And there will be 0 4-fold symmetries, the only highest symmetry that is possible is 1 3-fold symmetry.

And then you come to the monoclinic and the triclinic, the two other systems. A monoclinic has 1 2-fold symmetry, a triclinic has none. In fact, when we were students like you, we use to remember this, this order that you see here. Cubic tetragonal, a orthorhombic, rhombohedral, hexagonal, monoclinic and triclinic. This order, really gives you the order of decreasing symmetry. The symmetry is the highest for cubic, lowest for the triclinic.

So, we usually call it as CTORHMT, I will never forget it, when I learnt it during my B. Tech. So, that clearly tells you, the road map for the symmetry. How the symmetry decreases, and that is which is very crucial in the crystal structures. For example, every metal wants to be as symmetric as possible. Every metal wants to be very symmetric, that is why if you see out of all the elements, that are available in the periodic table. Most of them fall into cubic, and hexagonal.

Because, cubic and hexagonal are the high symmetry systems. In fact about 80 to 90 percent of the total number of elements or cubic. Why is just because there is an inherent tendency, for the atoms to arrange in the most close pack or the highest symmetry. So, that is why you will see, most of them are cubic. And there are almost none, which a triclinic kind of crystal structure, there are no elements with a triclinic.

Excepting that, there are certain inter metallic compounds, which coming to that. But, there are no elements almost with triclinic. So, like that we know the tendency of a system is to have the highest symmetry. And that is what defines, when we come to the unit cells also, why we have 14, if the time, we will stop here. We will take it up next class.

Thank you.

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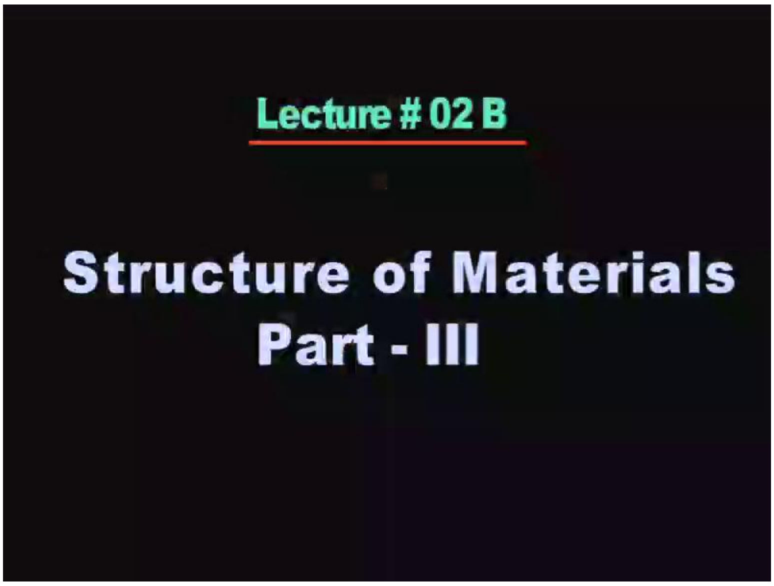

Lecture # 02 B

Structure of Materials
Part - III

While talking about the symmetry, we talk about the 5 platonic solids. So, what you see on the screen here is the 5 platonic solids.

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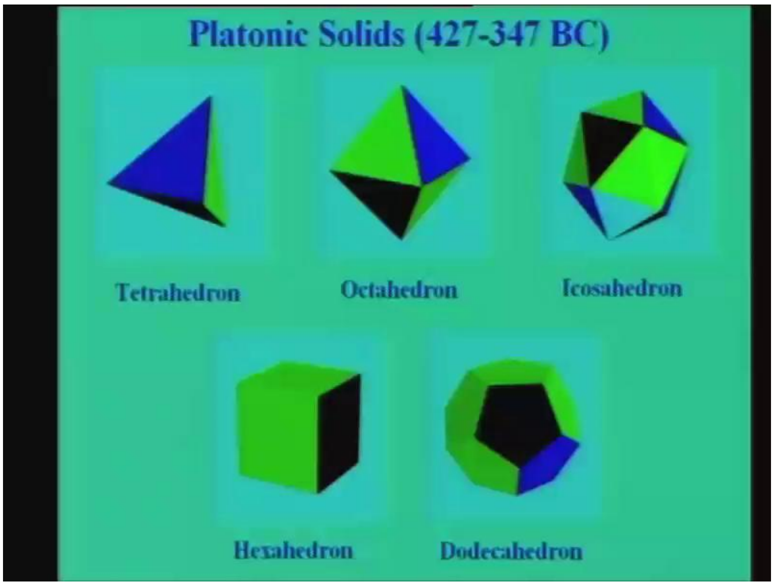
Platonic Solids (427-347 BC)

The tetrahedron, octahedron and icosahedron, the hexahedron, which is the cube and dodecahedron. So, these are the 5 platonic solids, I was talking about. And basically this was kind of postulated by Plato, during the period 427 to 347 BC, that was his life period, and if you look at the same thing in a different form.

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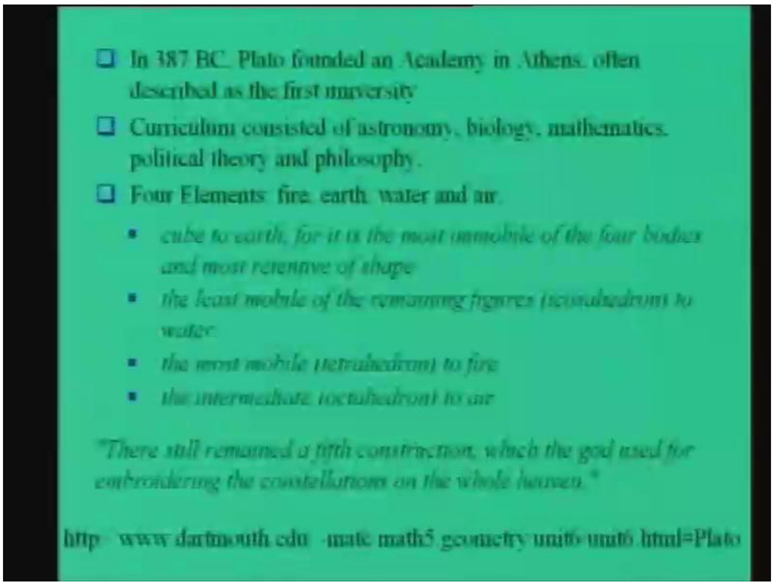

- ☐ In 387 BC, Plato founded an Academy in Athens, often described as the first university
- ☐ Curriculum consisted of astronomy, biology, mathematics, political theory and philosophy.
- ☐ Four Elements: fire, earth, water and air
  - *cube to earth, for it is the most immobile of the four bodies and most retentive of shape*
  - *the least mobile of the remaining figures (icosahedron) to water*
  - *the most mobile (tetrahedron) to fire*
  - *the intermediate (octahedron) to air*

"There still remained a fifth constriction, which the god used for embroidering the constellations on the whole heaven."

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And if you just look at bit of the history, how this was done. This was 387 BC basically Plato founded the academy of Athens, which is probably the first university in this universe. And interesting thing is, there was no engineering those days as a subject. And the subjects that were thought those days in that university were these 5. Astronomy, biology, mathematics and political theory and philosophy. So, you can see how important people thought mathematics those days.

So, mathematics is the only there is no physics even, there is no chemistry. So, people thought the whole world can be understood, just by knowing mathematics. So, that was the philosophy of Plato. And he thought these 5 solids are basically they represent the elements in the life. Those we for example, the fire, the earth, water and the air, the four elements which are crucial for the universe.

So, he thought these four solids, are basically represent these four elements of this universe. And he thought that these elements of this universe are made up of these solids. For example, he thought that earth is can be imagine something like a cube, he represents a cube to the earth. I really do not know, why he thinks of that way, but particularly the reasoning that he gives is that. Because, it is the most immobile of the four solids, that we can think of among those platonic solids.

So, he thought probably earth could be the cube and so on, the four of them. And the fifth one he says, it is a he gives it as you can see here. They still remain the fifth construction, which the god used for the embroidering of the constellations on the whole heaven. So, which is what we call the ether the fifth element people call is basically the ether, which pervades all through the universe. So, that is what probably he thinks that this fifth element. So, anyway this is just a bit of a philosophy. The website that is, from where I got this information is given below, which I can give a little later.

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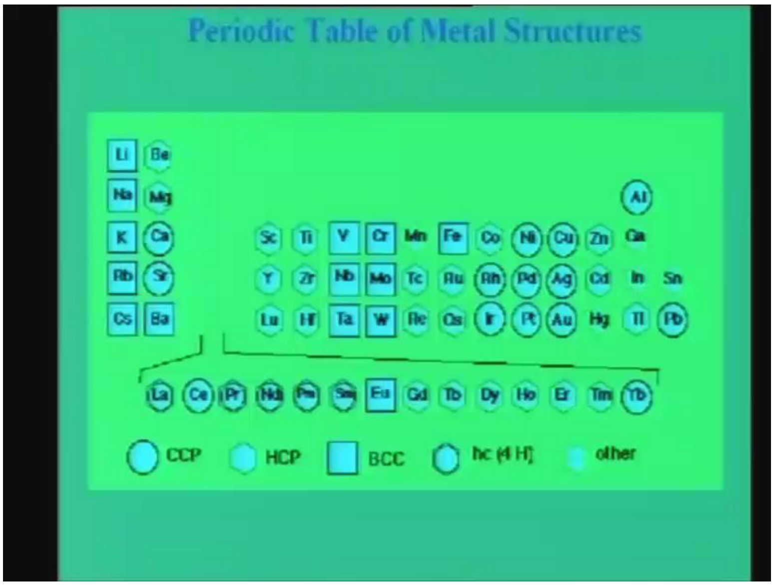
Periodic Table of Metal Structures

And we talked about the crystal structures. We talked about the symmetry of various crystal systems, in the last class. We talked about from the cubic up to the triclinic system, how the symmetry changes. From the highest symmetry in the cubic, to the lowest symmetry in the triclinic from the 3 4-fold axis to almost no symmetry in the triclinic.

So, what is the symmetry in a triclinic system, can you tell me? What would be the rotational symmetry in a triclinic system? It will be a 1-fold symmetry, which is what people call it as a trivial symmetry, because every solid should have a 1 fold symmetry. So, that is a trivial symmetry. So, that is what is a triclinic system has. And so if you look at most of these, these elements in the periodic table, you can see most of them are close packed.

Reason is every atom has a tendency to have the highest symmetry as possible. So, it wants to have the highest symmetry. But, at the same time the electronic configuration in some cases prevents it to have the highest symmetry. That is why not every element has this highest symmetry. For example, if you see almost 80 to 90 percent of the elements, fall into the cubic close packed. Cubic closed pack is what is called, FCC, then the HCP and BCC.

These are the three which mostly constitute, all these crystal structures of all the elements more or less 80 to 90 percent. And the remaining are very few. For example, if you take tin, indium, gallium, these are all the body center tetragonal structures. So, tetragonal structures and the other structures, are very few x. And most of the elements, basically follow the cubic or hexagonal. The reason as I mentioned to you is the symmetry.

So, if you take it from the symmetry point of view, when you look at the unit cells. We talk about the every system, the crystal system, we say there are 7 crystal systems. You all know those 7 crystal systems starting from the cubic to the triclinic. But, each cubic system has different ways of arranging atoms. The moment I say a crystal system, what I am talking about is the rotational symmetry, in the system.

For example, we represent a cubic as 3 4-fold symmetries. But, the moment I put in, I call it as a face centered cubic. That means, in that cubic system, I am trying to locate where the atoms are positioned, or were the molecules positioned. For example, in a face centered positions. So, the moment I talk about that, I am talking of the real periodic arrangement of atoms there.

Whether they are arranged in the body centered fashion, or the face centered fashion or the simple cubic fashion. So, simple cubic, for example you see primitive unit cell. Every one of those 7 crystal systems, will have this primitive. Even the triclinic has this primitive cell, which is called the simple triclinic cell, for example. So, every one of those 7 crystal systems will have this primitive cell.

In addition to the primitive cell, they also different other ways of arranging atoms, which you see in the form of body centered, face centered. And in some cases, a special way of arranging, what is called the base centered, is it not. For example, which is that system, which has all these four types of arrangement of atoms.

Student: Orthorhombic

Orthorhombic, orthorhombic is a only system, which has the simple orthorhombic, the base centered, the body centered and the face centered. So, if you take it that way, basically there are four possibilities, for the atoms to be arranged, in any one of those crystal systems. So, if you take there are 7 crystal systems, in principle there should be 7 into 4, 28 possible unit cells. But, how many unit cells we have?

Student: Only 14.

Only 14, there are no more than 14 unit cells. So, that means there is something, which prevents these 7 crystal systems to have these 28 unit cells. What is that, that prevents them. For example, let us take cubic, in a cubic what are the possibilities.

Student: ((Refer Time: 22:55))

And simple , you have simple cubic, body centered cubic and face centered cubic. But, you do not have a base centered cubic. Why is that, you do not have a base centered cubic, have you ever thought about it What prevents a cubic system not to have a base centered cubic. What happens, if I put an atom in the base centered and...

Student: Sir ((Refer Time: 23:20))

It would become tetragonal, why it becomes tetragonal?

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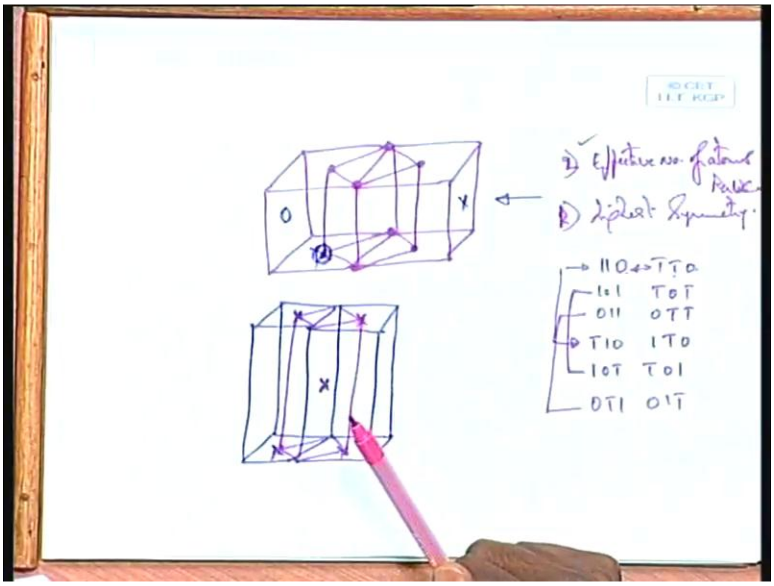

The way we can show that, some of you might already know. That imagine this unit cell of the cube. And extend it to one more unit cell, consider that any two unit cells in the crystal structure of a base centered lattice, base centered cubic lattice. Base centered means, I have an atom at the base bottom. And I also have an atom on the top. So, when I talk of base, it does not I mean matter, whether I am talking of the bottom or the top.

There are also unit cells on top, were we are talking of a crystal structure. We are not saying there is only one unit cell in a crystal structure. There are innumerable number of unit cells. So, this top of this unit cell will become bottom of the next unit cell, which is on top of it. So, the moment you say base centered. So, it means there is atom here, there is atom here, there is atom here and there is atom here.

So, if you imagine that, there are atoms at these base centers. And try to join these atoms with these corners and then join the top base centered to the bottom base centered. And you also have atoms at these corners, is it not. Now, you can see this unit cell, which we have created by joining these atoms is a tetragonal unit cell. What kind of a tetragonal unit cell is this? Simple tetragonal.

Now, the question that comes is, why should we call this as a tetragonal unit cell, instead of calling it as a base centered cubic. See this name that we are giving, it is who are giving this name. The crystal structure does not know what it is, it only knows that the atoms are sitting somewhere. So, there are atoms sitting inside the lattice. And we are joining these atoms at our own convenience and then giving a name to, it is it not.

So, in such a case, I would say that instead of calling this as tetragonal. I would prefer to call it as a base centered cubic. Why cannot I call it as a base centered cubic, what prevents me?

Student: ((Refer Time: 26:01))

This is tetragonal, I accept that this is tetragonal. Whatever we have joined now is a tetragonal. But, this joining is I am joining it, there are no joints there inside the crystal structure. There are only atoms, in a three dimensional arrangement the atoms are sitting in the space. Now, that kind of atomic arrangement in a three dimensions. Instead of calling it as a base centered cubic, we are calling it as a tetragonal, why?

Student: ((Refer Time: 26:37))

This is very crucial, to define what is the unit cell, to be chosen among the unit cells available. There are three criteria's, one is the effective number of atoms per unit cell. And if I take base centered cubic, the number of atoms would be how many per unit cell, 2. And if the same thing I would call it as a tetragonal, there is only one. So, always the unit cell should be chosen, should be that which has the lowest number of atoms per unit cell.

If there is a confusion like this, for a choice to be made. We should always choose, this is a definition at the beginning of classifying this unit cells, people have talked about it. So, this is basically again a definition that we are giving. So, for each one para light, we call it para light that is it. If you ask me, why should we call it para light, there is no answer to such a thing. If you take a cat we call it as a cat, that is it. If you ask me why should it be called cat, there is no answer.

So, first fellow who has discovered it. has started calling it as a cat we started repeating the same. thing always like that. So, at the time when all these unit cells were being talked about, or being classified. So, this was one of the things. That the lowest number of atoms, then take another possibility. So, obviously then that means base centered cubic is not possible. So, if at all there is a base centered cubic, we should call it as a tetragonal. But, at the same time, there is a problem here with this kind of a argument.

The problem with this argument is tetragonal. What is the symmetry of it with respect to cubic, which has a higher symmetry. Cubic always has a higher symmetry. So, when there is a choice between a cubic and tetragonal. Always the choice should be the highest symmetry. Whenever, there is a choice between 2 unit cells, the first priority. In fact, I should put the first one as number 2 and the second one as number 1. The first priority always is the symmetry.

So, because the cubic has a highest symmetry. In principle the tetragonal that we are talking here, should not be called as a tetragonal. We should call preferable as a base centered cubic only. But, there is a problem with this base centered cubic, other than what we have thought just now. The problem with this base centered cubic is, according to the crystallography. The moment I put an atom at any of these bases in a cube; all faces are the same squares, is it not.

So, now if I call these are the base. For example, this one if I am calling as the base. Because I am looking it in this direction, that is why I am calling as the base, but if somebody looks at in this direction, he would call this as the base. So, there is no difference between this plane and this plane. In terms of the symmetry, they have exactly the same symmetry.

So, as a result why one cannot preferentially put an atom here. And just call it as base centered. The moment I put an atom here, automatically I have to put an atom here, because there is no difference between this plane and this plane. I cannot preferably call this as a base, but if it is a tetragonal, I can still call it as base. Because, if I take a tetragonal unit cell, I can call this as a base without any problem, because this plane and this plane are different from each other.

So, I can differentiate between this plane and this plane, because the symmetries of the 2 plane are different. So, I call this as a base plane. For example, in a hexagonal, we always call it as a basal plane. The moment I say basal plane, you never get confused. You always think it is 0 0 0 1 plane, is it not. Because, we know the symmetry of it is such that, the basal plane has a 6 fold symmetry. And the side 6 planes that we have, around this hexagon have only a 2-fold symmetry.

So, we never get confused between the basal plane, and the planes which are on the pyramidal planes or prismatic planes. Not pyramidal planes, prismatic planes. So, those prismatic 6 planes, which are there have only a 2-fold symmetry. So, as the result in cube, the moment I put a atom at one of the bases, automatically you have to put an atom, at all other phase centers.

The moment you put at all other phase centers, it becomes a phase center cubic. So, because of the symmetry problem, of the cubic, a base centered cubic cannot exist. The moment you have a base centered cubic, in principle it would turn out to the a phase centered cubic. That is one problem. Then, come to the tetragonal. If you take the tetragonal, similarly take 2 tetragonal unit cells. What are the number of unit cells, that we have in tetragonal. Tell me, there are 3 unit cells in the tetragonal, tell me Yamini. How many units are there in tetragonal system?

Student: ((Refer Time: 33:01)

Few, what are they?

Student: Simple and body centered

Simple and body centered, that is it. Now, that previous logic that we have used, for base centered cubic, if we try to extend that logic to the base centered tetragonal. And try to see, why base center tetragonal is not possible. You will see clearly, that the moment I take any two base centers, like this. These are the base centers and join them, what happens is that base center tetragonal has turned out to be a simple tetragonal.

And a simple tetragonal has lower number of atoms per unit cell, than a base centered tetragonal. And both of them have the same symmetry. Because, this is also tetragonal, that is also a tetragonal is it not. Obviously, the new one that we are creating is also a tetragonal. It has a equal to b, but not equal to c, alpha equal to beta equal to gamma equal to 90 degrees, there is no difference.

So, as long as it is tetragonal, the symmetry remains the same, that it has 1 4-fold symmetry. So, as a result now, we can clearly see that base centered tetragonal is out of question; and we rule out that possibility. Now, take the other one, the phase centered tetragonal. What happens to the phase center tetragonal, it would convert to a body centered tetragonal, same thing true.

You put one atom at this phase center, another atom at this phase center, one at this phase center. I mean these base centers also are basically phase centers, and one atom at this phase center. Now, again exactly the same way you join. The center, this phase center atom of this unit cell, would now become a body centered atom to the new unit cell that we have generated.

That is again a tetragonal unit cell only. Because, again the same thing true that you have the a equal to b equal to b, but not equal to c. And alpha equal to beta equal to gamma equal to 90 degrees. And the symmetry is again the 1 4-fold symmetry. The only difference is that, now you have another atom at the center of this body. And now if you compare this body center tetragonal with the phase centered tetragonal, which is possibly you can imagine; that arrangement of atoms.

The difference between these two is…

Student: 4 and 2 affective.

4 and 2, the affective number of the atoms in a body centered tetragonal is only 2. The affective number of atoms in a phase center tetragonal is 4. So, using this approach in principle, we should choose the body centered tetragonal. And not the face centered tetragonal. Like this in principle all of them can be thought of. From the 28 you can really reduce it to the 14 unit cell.

So, I do not know, whether you have ever thought in this direction. But, this is a very important for us to understand why only 14, instead of just accepting that there are 14. And this is very crucial, because each one of them affects the properties of the material. We know that, if there exist a base centered cubic. The slip systems in that, would be different from that of a FCC and a BCC. And it is deformation behavior would be definitely different, is it not.

So, we now clearly that the deformation behavior, depends on the slip systems. And because, the deformation in most of the metals occurs by slip, except in special cases where it occurs by pinning or in special cases such as high temperatures, where it occurs by creep. Otherwise under normal conditions, whenever the temperature is below the homologous temperature, always deformation occurs, usually by slip, unless you go to very low temperature, where slip becomes very difficult.

Or in those cases were the number of slip systems are so small, that you have no other solution, but to have a twinning occurring to have some kind of a deformation. So, because slip is a crucial deformation mechanism. The number of slip systems is very crucial. And as a result the number of closed pack planes; and the number of closed pack directions. And how closed pack those planes are, and how close pack those directions are is very crucial.

For example, you all know that in BCC, the number of slip planes are more than the number of slip planes in the FCC. FCC how many slip planes we have?

Student: 4.

4 and how many slip planes in BCC? Slip planes, which is the slip plane in BCC.

Student: 1 1 0.

1 1 0, what is the name of that 1 1 0 plane, have you ever thought about…

Student: ((Refer Time: 38:32))

It is a closed pack plane. The 1 1 0 has a name which tells you, how many planes are there? What is the 1 1 0 plane in FCC, we talked about it in the last class. It is a octahedral plane. So, that clearly tells you that there are 8 such planes in FCC, 8 such planes, but because there are parallel planes. For example, 1 1 0 and bar 1, bar 1, bar 1 are parallel to each other.

So, that is why we basically say, there are 4 sets of 1 1 1 planes. But, when it comes to 1 1 0 plane it is called

Student: ((Refer Time: 39:11))

No, it is called dodecahedral plane, it is a dodecahedral plane, there are 12 such planes. Imagine 1 1 0, bar 1 bar 1 0, 1 0 1 and 0 1 1, bar 1 0 bar 1, 0 bar 1 bar 1. How many are there? Now 6 any other combination possible. For example, bar 1 1 0, 1 bar 1 0, that is the first one and this one are connected to each other. 1 1 0, I would put 1 bar in one of those, it becomes bar 1 1 0. Similarly, the second one you take and connect it to that 1 0 bar 1 or bar 1 0 1.

And take the third one, again you can have one more combination possible 0 bar 1 1, 0 1 bar 1, how many are there, there are 12 planes. And if you compare this and this are parallel to each other. All these if you see, basically this is one set and this is another parallel set. So, because of which we can say there are basically 6 parallel planes. Though there are 6 planes and FCC has only 4 closed pack planes. The actual packing fraction of this plane 1 1 0 is different from, in fact it is lower than the 1 1 0 plane.

That is why in fact, in BCC slip also occurs in other type of planes, such as 1 1 2, 1 2 3 and things like that. But, still those planes in fact, most of the books say there are 48 slip systems in BCC, true there are 48 slip systems. But, all of them are not really as closed pack, as any of those 12 slip systems in the FCC. And because of which BCC, always is less deformable than the FCC.

Though we say the number of slip systems are more. In fact, we now that it is a number of slip systems, which decides the deformation characteristics of material. But, still though BCC has more number of slip systems, because the slip systems are not as closed pack. Why should the close packing affect the deformation characteristics?

Student: ((Refer Time: 42:00))

Yes, it is the distance between, not the planes also, it is the distance between the atoms which is also crucial. In a closed pack planes 2 atoms are close to each other, whenever there is a slip occurring in a particular plane. Slip occurs by the breaking up of the bonds and reconstruction of the bonds, this location movement. Always occurs by breaking of the bonds and reconstruction of the bonds. And this braking of the bonds and reconstruction of the bonds, becomes easier. If the distance between that atoms in a particular slip direction is smaller.

In a close pack planes and close pack directions the distance being so small. That is why slip occurs to each other. If you choose those planes, were the distance between the atoms in any direction. If it is very large, such slip directions, such directions are very difficult for the slip to occur. That is why we always look for the closest packed plane, and the closest packed direction. So, that is why structure is very crucial, structure and the unit cells become very crucial, to choice of the unit cell for a particular atom. And we know at as you can see from here, that most of the elements prefer to have as closed pack structures as possible.

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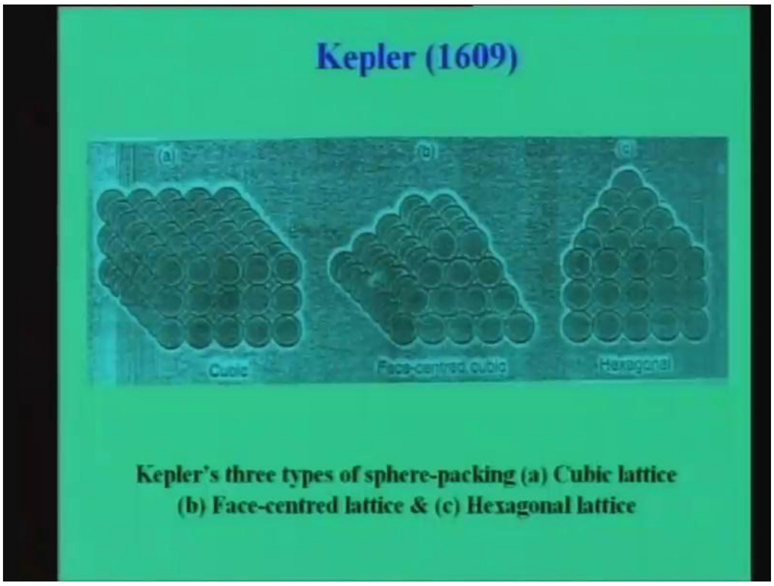

Kepler (1609)

Kepler's three types of sphere-packing (a) Cubic lattice (b) Face-centred lattice & (c) Hexagonal lattice

For example, even long back in 1609 itself, Kepler has talked about the most crucial arrangement of the atoms. The cubic arrangement, phase centered cubic, this is when he says it is cubic, it is basically the simple cubic. The simple cubic arrangement, the phase centered cubic arrangement and then the hexagonal arrangement, this figure is drawn in 1609. So, the crystal structures, people have even imagine has old as 1609.

And they have started realizing the importance of those, those days nobody knew about dislocations. Nobody knew about real deformation behavior of materials. But, at the same time they realized, the structure place a lot of important role, as per as properties of a material circumstance. And now we know very clearly, at why a structure plays a very important role. So, this is as per as a crystal structure is concerned.

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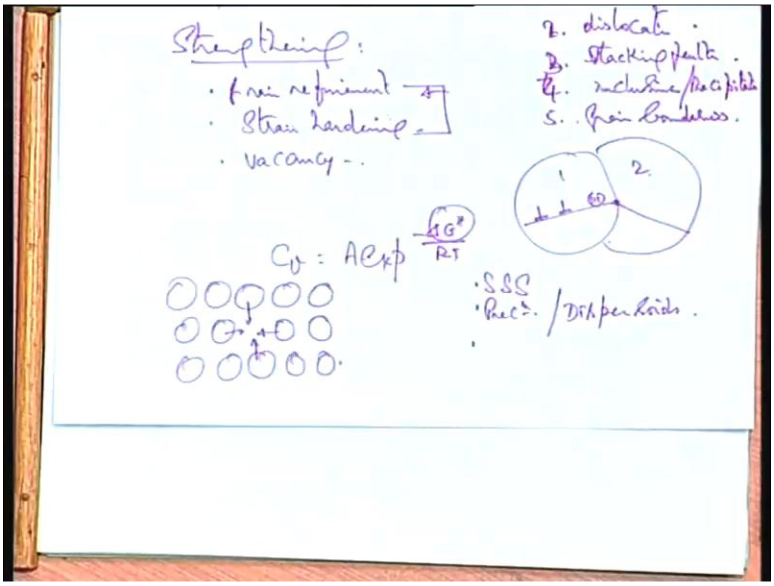

The next level of structure for us is the micro structure. Before, we really go into various advanced materials, we need to understand, how a micro structure place a very important role. To understand this, we need to understand what are called the strengthening mechanisms. All of you at your under graduate level, must have heard to some extant about the strengthening mechanisms.

For example, if I take a pure metal, let say aluminum. How do I make it strong, what are the ways by which I can make it strong?

Student: Grain refinement.

Grain refinement fine, that is one grain refinement, anything that can think of

Student: ((Refer Time: 45:17))

Pure metal, how do you precipitate?

Student: ((Refer Time: 45:21))

Cold working or strain hardening, how does the strain hardening occur? Dislocation interactions. So, when you have to many dislocations, each dislocation acts as a obstacle for the dislocation moment. And we all know, strengthening mechanisms are basically mechanisms, by which we can restrict a moment of the dislocation. Because, we know it is the dislocation, which is crucial for the slip to occur.

If at all, you need deformation in a material, it has to occur by slip, that is one of the most crucial mechanism of deformation. And if slip has to occur, the dislocation has to move. And if you can somehow prevent the dislocation to move, you can make the material stronger. Because, the stress required for the moment of dislocation is what decides, the strength of a material.

For example, the yield strength when we say, yield strength is the minimum strength required, for the plastic deformation to be initiated. That means, it is the minimum stress required in a gross sense if you want to talk, required for the dislocation to move. So, if you can somehow prevent the dislocation to move by some means. Then, we know that we can increase the stress required for the dislocation to move. And that means, you can increase the strength of the material.

So, this was the basic philosophy behind all the strengthening mechanism that has come up. First one as you mentioned grain refinement, because people have realized, that there are various obstacle possible for dislocations. What are the obstacles possible for dislocation, one obstacle is the dislocation itself. Second obstacle is what are called, the vacancies. In fact, I should put this on top, because that is what is called that 0 dimensional defects.

And the dislocations are what are called the one dimensional defects. Then, the third one is what are called is stacking faults. If you have more stacking faults, that means more obstacles you have. In fact, stacking faults itself we know is nothing but is a spacing between any two partials dislocation partials. And then you have the next one is a volume defects. What are the volume defects?

Student: Inclusions

Inclusions possible, precipitates; inclusions, precipitates or even grain boundaries for that matter, people can really take it as the a volume defects, though we talk a boundary as a surface, because it always has a thickness. So, it is very difficult to put it either into a surface defect or... So, in many respects, we take it as almost surface defect. But, at the same time grain boundary is not just a layer, but it always has a certain thickness.

So, we can even take it into volume defect, but it does not matter. Whether we consider what is a, whether it is as surface defect or a volume defect, but what is more important is that, it acts as a barrier for the dislocation, that is crucial. Why it acts as a barrier, why grain boundary acts as barrier?

Student: ((Refer Time: 49:12))

Why should it, yes it is because of the orientation. See you imagine a dislocation moving on a plane, in a particular direction slip plane. Imagine that there is a two grains, that you have a plane on which a dislocation is moving. The movement you come across a grain boundary. Grain boundary means, a discontinuity as per as that plane is consult. If the plane is continuous into the other grain, they usually do not call it as a second grain at all.

What is definition of a grain? What is the definition of a grain boundary? Is that is a boundary where, there is a orientation difference we say. That means, this plane which is let us say 1 1 1 plane in a FCC crystal is oriented in a different direction, in the other grain, if it was not oriented in other direction. Then, these two grain 1 and grain 2 would not have been two different grains. But, they would have been the same grain.

So, grain boundary basically represents a orientation difference. So, that means this plane ends here. And as I mentioned the grain boundary always has a certain thickness. And within that thickness, the atoms are arranged in a random fashion we say. If there is a kind of a disorder, at that boundary and because, there is a disorder we cannot imagine any plane really in that boundary.

So, you cannot really say, that there is a continuity as for of the atomic plane is concerned. The moment it comes to the grain boundary, there is a abrupt discontinued. And because of which the dislocation cannot move further in that plane. So, you now that you have to put in more stress. So, that the dislocation, what is called the cross over into the other grain. So, obviously that means, more stress required, so the more the number of such obstacles the higher the strength of the material. So, this is another, so grain boundaries strain hardening, anything else that you can think of in a pure metal. What is called vacancy hardening? There is a possibility of what is called quenched in vacancies, which can act as obstacles. For example, you heat a pure metal to high temperature, cool it rapidly. When you cool it rapidly, we all know that the vacancy concentration in a material is always temperature dependent.

In fact, one can talk about concentration of vacancies is nothing but exponential minus delta g star by r t, where this is nothing but the energy required for the formation of a vacancy you see is it not. So, as a result vacancy concentration is exponentially related to the temperature, and higher the temperature, the higher the concentration of vacancies. And now if you quench it, you are not providing sufficient time for those vacancies to annihilate or to those vacancies to go to the surface of the material or grain boundaries of the material, during the schooling process. And as a result, they get retained inside the material as what are called quenched vacancies. This is very crucial, particularly in precipitation, that the more coinciding vacancies you have. The higher the precipitation kinetics, because they act as nucleating sites for precipitation in many cases.

So, whereas here they can also act as a barrier, why because every vacancy has a stress field around it. Because, whenever you imagine atoms arranged like this. Think of a vacancy there, the movement there is a vacancy there. Then, the atoms are pulled into the vacancy. So, once they are pulled there is a compressive stress there. And that stress and that stress acts as an obstacles, for a dislocation, which is moving in that direction.

So, any vacancy can also act as an obstacle. So, this is one way to we but then nobody thinks of that, because the extent of strengthening that you can achieve by that is too small. And as a result people do not take it as a design criteria to improve the strength of the material. But, the most crucial are these to as per as pure metals are concerned.

Another way if you want to, if you go into the alloys is you can have much more opportunities coming into picture. First starting with what is called solid solution strengthening. You can you have solid solution strengthening and then you can have precipitation strengthening we all know or dispersoids.

What is difference between these two?

Student: ((Refer Time: 54:43))

So, what do you prefer you want

Student: ((Refer Time: 54:48))

You, do not prefer if for low temperature. What happens if you use that for a low temperature he is right, he is right in the sense that for high temperature we prefer dispersoids strengthening. Because dispersoids are the once which are externally added they have not be yes.

Student: ((Refer Time: 55:14))

Yes, dispersoids are usually incoherent with the matrix. They are incoherent precipitates if you want to call it that way, they are incoherent second phase particles. And if they are incoherent usually at room temperature. The incoherent precipitates give you lower strength than either coherent or semi coherent precipitates. That is why in principle if you now in precipitation hardening. If you plot the hardness as the function of the time of aging, you see that hardness is increases up to a certain extent.

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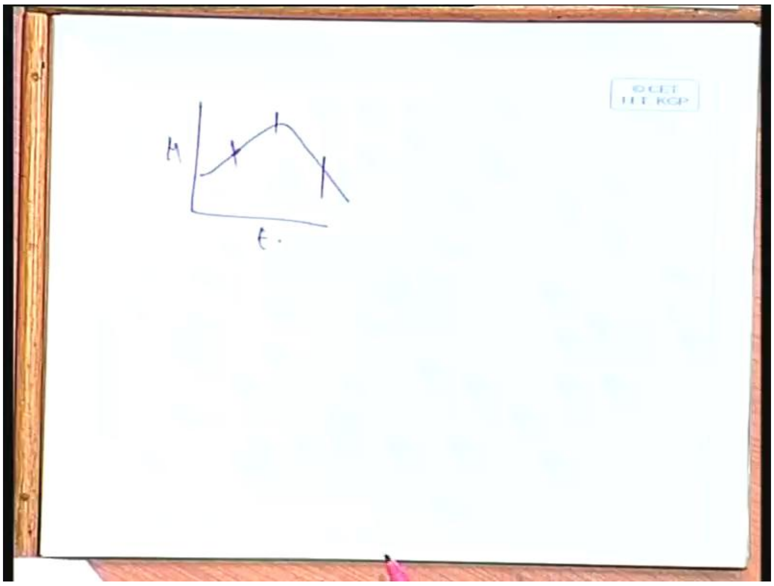

For example, if you plot hardness as a function time. You see this kind of a nature is it not. And we say this is because, you have coherent precipitates coming at this stage. And then coherent and semi coherent here. And then once they become incoherent one the once the precipitates grow and become bigger they become incoherent, because of the too much strain. That is required to maintain coherency that strain is, so much that the precipitate would prefer to be incoherent rather than maintaining coherency. And once it becomes incoherent then you lose the strength.

As a result why it is preferred at high temperature, yes I am not saying that the precipitates are preferred at high temperature. Dispersoids are different from precipitates in the sense, precipitates come from the matrix by precipitation process. That means these precipitates if you heat them to high temperature they are soluble. And then bring them to low temperature they precipitate out. Whereas, dispersoids are externally added like. For example silicon carbide in aluminum composites is a dispersoids or (Refer Time: 57:11)) in a nickel based super alloy, it is oxides.

People are, for example there are also composites which are called SAP alloys Sainted Aluminum Product. Sainted aluminum product what is that, which is the dispersoids there alumina Al2o3. This Al2o3 does dissolve into aluminum. ((Refer Time: 57:33)) an oxide. So, it would not dissolve. So, even if you melt aluminum it will remain a suspended as a particle in the liquid aluminum it would not dissolve back and that is a dispersoid.

Student: ((Refer Time: 57:46))

Correct.

Student: ((Refer Time: 57:53))

It depends on the which type of precipitates we are talking. If it is coherent and semi coherent then the interfaces is a little more diffuse kind of an interface, but it is incoherent. Yes we can talk really of an interface, but what is important is that this precipitation hardening.

There are two possibilities when you heat it to high temperature. One is the precipitates can grow what is called coarsening oust walled refining that occurs. We know that smaller precipitates dissolve back and the precipitates tend to grow, because there is a diffusion. I think in the thermodynamics class we talked about why precipitates grow.

So, there is always a concentration gradient and because of which the precipitates aluminum copper alloys. The most famous precipitation hardening system you, do not use at beyond 300, because though the actual solution treatment temperature is about 550. By the time you cross about 300 go to 350 are, so the precipitates become. So, big that the strength is lost.

So, that is why precipitation hardening becomes very important only at low temperature and we do not use dispersoid strengthening at low temperature, because as I mentioned they are incoherent. So, when we compare them with this precipitation hardening. Precipitation hardening once take an advantage at low temperatures. And when you go to high temperature dispersion strengthening takes an advantage.

So, did not why that is very crucial, yes we will stop here.