Phase Transformation in Materials
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Lecture – 33
Solidification: Eutectic

Today we are going to start discussion on the eutectic alloys in detailed manner. Because eutectic is very important system as a part of the solid liquid to solid phase transformation. And last part of the last lecture, I have shown you eutectic phase diagram and discuss about some important features. Now today I am going to begin with showing you some morphologies of different eutectic types. These things this pictures are taken from one of my colleague's book.

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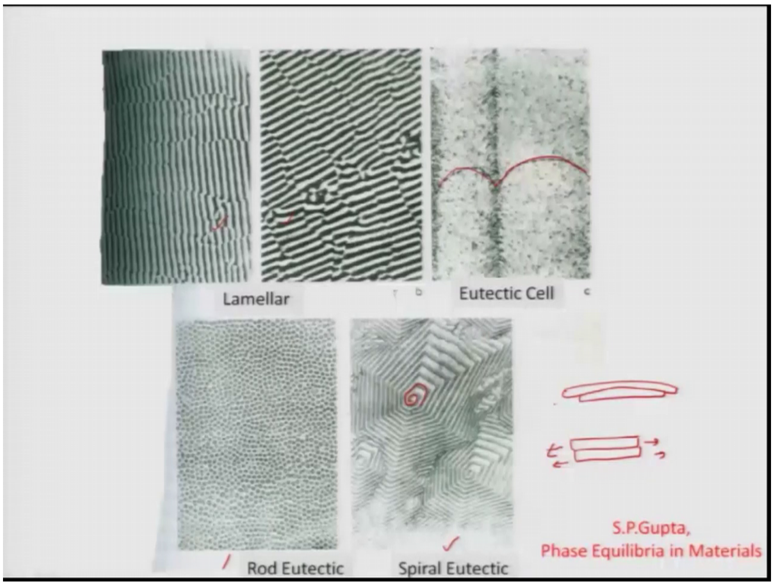

Feature Professor S. P. Gupta at IIT Kanpur. And the book call phase equilibria in materials. The eutectic because it is a multiphase specifically in the binary eutectic is 2 phase mixture.

So therefore, there are different morphology is possible. The most commonly observed one morphology is the lamellar. As you see here that black and white lamely of the 2 phases are seen in this microstructures. And sometimes they will be broken sometimes they broken lamellar or sometime they will be continuous, but they are actually in 3 d slabs of 2 different phases arranged in a particular fashion.

In some cases this lamellar morphology can also form cells. The cells which we have discusses for the dendritic growth same kind of cells can also form here. And you can see here that this is boundary or the front between solid and liquid boundary of a cell, much earlier now it has grown up bigger or larger portions. So, here again also the morphology is lamellar, but it forms like a shell cell between 2 eutectic. Also one can have a rod morphology shown, here rod is basically that one of the phase is instead of a lamely it becomes a rod other phase remains continuous. Lamellar morphology is seen in widely in lead tin bismuth antimony many other systems.

On the other hand rod is not observed. So, frequently it is seen it is seen either in nickel aluminum or diamond silicon type systems. Rod morphology is normally observed in the eutectic system where the rod phase volume fraction is relatively lower. As you see in the lamellar morphology the volume fraction with the 2 phase is almost similar, but when one of the phase is volume fraction is low, then this all type of morphology is observed.

One can also have a very peculiar morphology like spiral one shown in this picture. You see here the one of the phase has form a like a spiral star case. We if we observe a star case which is like a spiral it looks like exactly same. Many cases it is looks like a when a dislocation multiplication also. This one spiral eutectic normally forms in magnesium zinc system. And it has been found that if the thermal expansion coefficients of one of the phase is distinctly different from the other.

Then if this behaves like a like a you know 2 plates sitting on each other like this, and then if you heat it up or a high temperature one of the phase expand more, and then they tried to compare to the other and try to bend. And the process finally, it forms the spiral.

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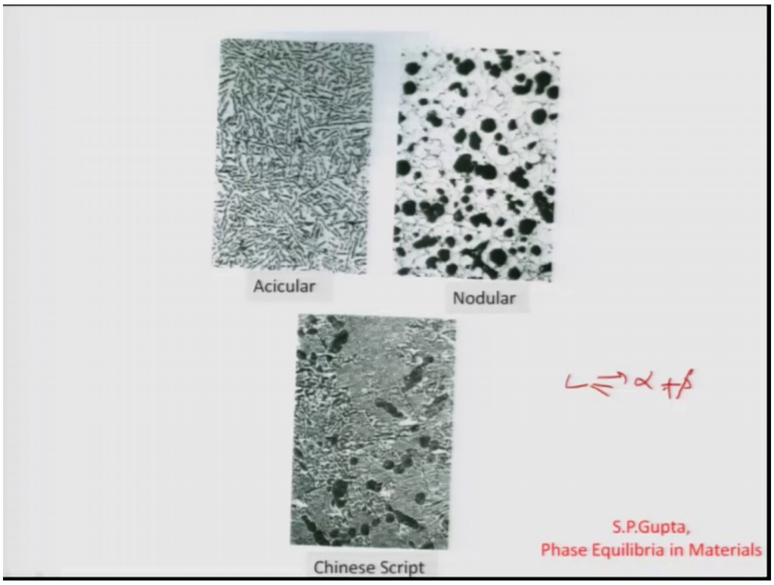

So, this is are observed in a magnesium silicon magnesium zinc system. Aluminum silicon or it is a discussed in the last also a very classical system because it is this eutectic alloys are used in the real industry. Like cylinder box in many of the cars car engines. And the eutectic morphology is known as acicular.

The continuous white phase is aluminum solid solution, and these long fiber like features you see here black colour is basically silicon pure silicon fibers. Normally this eutectic is very hard and brittle, but these can be modified using very small amount of sodium strontium or some other mixture of miss metal, and the morphology eutectic can be modified which you will discuss probably in next lecture. And this is typical feature of silicon actually is a metalloid. So, it grows like a fiber.

Now, another common very common eutectic is cast iron. Cast iron has different type of morphologies eutectic cast iron correct. Because cast iron is an eutectic alloy between iron and carbon. And by addition of magnesium can modify the morphology of graphite which is shown here is like a black blobs or spherical spirits, rather and the matrix here is basically a almost pure iron alpha iron. It can also be pearlitic type, but the important aspect is that eutectic reaction was happened and high temperature and lead to formation of these globular or nodular cast iron the graphite in a gamma iron matrix.

Once can also happen have a very distinct morphology known as Chinese script, and this is seen in bismuth cadmium system. And if you see clearly that eutectic looks like a typical Chinese characters, and that is why it is known as a Chinese script morphology. This is again a field of a intense research because these different morphology of a eutectic is mainly because of many aspects. So, that is cannot be discussed in a lecture like this because that is a separate aspects.

But fact that these different eutectic systems from different morphologies makes these alloys very interesting remember one thing eutectic is a reaction from a liquid forming 2 solids. So therefore, 2 solids forms in a system simultaneously cooperatively from the liquid. So now, in order to understand how this eutectic really forms, or how the eutectic really grows we will show you how it actually happens. So, let us go to the board.

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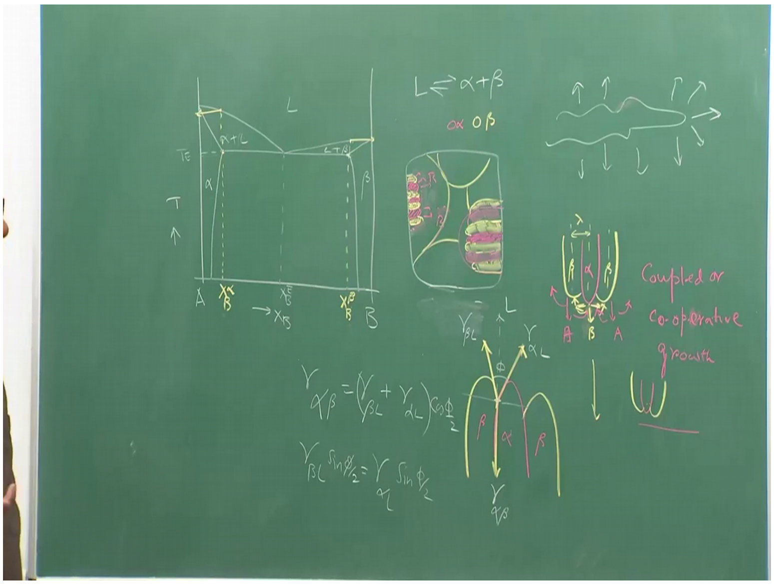

And I draw a simple phase diagram, and explain you how the eutectic what the mechanism of formation of the eutectic. See if I take a phase diagram which is shown you in the last lecture with 2 terminal solid solutions. One alpha, other one beta with a eutectic point at X B E temperature T E. This is typical phase diagram.

Now, we are going to discuss solidification of the alloy whose composition exactly x B. So, as you know the liquid transform to 2 phases alpha and beta, simultaneously once it is cooled down to temperature below T E. So, what actually happen? So, let us I have a liquid with a composition equal to X B E. Now nucleation can happen any of these 2 phases. Either alpha or beta this A B possibility that both can nucleate simultaneously or both can nucleate separately. Let us suppose alpha has nucleated. This is alpha nucleation. This I write down this colour is alpha and this colour is beta. So, once the alpha nucleates what happens? See alpha is basically a rich phase. If you look at it the composition of alpha is basically at the eutectic temperature is this, which is close to A. On the other hand composition of beta is close to B. So that means, it is A B rich phase.

So, once the but liquid has a uniform composition of X B E. So, as soon as the alpha nucleates from the liquid and it start growing alpha requires more A. So therefore, it will remove all the B when it grows. So, as the alpha grows as the alpha grows like this. Suppose alpha is growing like that. Now let us draw it from the boundary, that is better alpha grows it rejects all B all B will be rejected here in front of that all B will be rejected.

So, all the liquid has a compositions of X B E, because the growth of alpha requires more A less b/. So, these nearby regions will be rich in B, very rich in B. Because of that the composition of the liquid might reach the point corresponding to these. The point here which I have marked x B beta. So, as soon as it will happen there will be a finite driving force available for the beta to nucleate and grow on the both side of alpha. That is because you have sufficient B available in the region near to the alpha. Side by alpha or in front of alpha also, but it is always better to nucleate on the top of alpha, right. This is always better.

So now I have 2 beta lamella or beta phase to you know lamella of beta phase to lamely on the both side of alpha. So, if these 2 beta phases has to grow they will also reject A, because beta is beta is basically rich in a rich in B sorry. So, because of that it will reject all B. Sorry, it will reject all a yes right a will be rejected, as the beta grows beta is yellow color.

So, because a is rejected now again the liquid nearby beta will be rich in A. Because B beta requires more B. So, less A. So, a will be rejected and because of that again the composition in the regions nearby beta will be become very rich in A. And finally, it will reach x B alpha and again alpha will nucleate. And because it is a now the nucleation is very easy because you have already have a assemblies of alpha. And beta so obviously, alpha will nucleate on the sides of the beta. And again as the alpha grows it will reject a sorry it will reject B, and again nearby regions will become rich in B and then beta will nucleate.

So, that is why actually the lamella eutectic grows. See if I have to draw a complete full eutectic with a lamelles of alpha and beta, it will look like this. This is my alpha this is my beta another beta, on this side then another alpha and so on.

So, finally, you form a colony like this with alpha beta alpha beta lamely like that. And that is happens in everywhere in the liquid. So, it can also happen here, it can also happen there, it can also happen here, it can also happen there. So, finally, the whole sample will become full of eutectic. That is what actually seen in this microstructures.

Now, the things will be little bit different when you go from lamellar to rod or to even nodular or acicular eutectic, but mechanism will remain same mechanism is not going to vary because in all this eutectic phase diagrams. One phase will be rich in A, other phase will be rich in B. So, it does not matter whether you are forming morphology like lamellar or rod the rejection of the solute in the liquid and side (Refer Time: 13:58) will be very important.

The important lesson which you observe here as compare to a dendrites. So, a dendrite goes in to liquid, what happen? As a dendrite grows it also reject solids alloy dendrites right, and it is a solids in all directions because as a dendrite grows a solid phase the solid has a much lower solute contained on the liquid. And it goes from the liquid right. So, because of that the solute which is excess is rejected to the liquid. And for further growth of a dendrites these solutes needs to be taken or transported further; that means, this solute needs to be moved away from these portions of the dendrites.

And this kind of diffusion is long resistance this requires atom needs to be move a required a long distance. So, that is why dendritic growth is mostly governed by the diffusion of flux from the solutes from the tip of a dendrites to a larger distance. But on the other hand a eutectic if I draw and again this lamely only 2 lamely one alpha and 2 beta I will be able to explain you nicely.

So, alpha will reject A B. This B is required by beta right as the alpha rejects B for it is growth this B will be required by the beta for to grow. That is obvious because B is beta is rich in B. So, this B can be then transport and then get transported from the tip of alpha side wise. It does not required to be transported along this direction. It can be always transported side wise.

So, diffusional distance from the alpha to beta is very small, because these 2 lamely are sitting side by side.

In fact, we in a eutectic growth we always define a inter lamellar spacing called lambda. So, diffusional distance is related to lambda it is actually a either equal to lambda or a fraction of lambda or a fraction of lambda. Similarly as the beta grows it rejects A. This A can again transported to the nearby alpha.

So therefore, the growth of alpha and beta are coupled or cooperated. As the alpha grows it rejects B this B is used to feed the growth of beta, or this B is required to growth of beta, similarly as the beta grows it rejects A. This B a is required for the alpha to grow. So, this is like a cooperative phenomenon. They both are dependent on each other the growth of alpha is inter linked with a growth of beta. They cannot grow separately, it is impossible. And because they cannot grow separately, that is why it is called a coupled or cooperative growth in eutectic normally. So, this is distinctly different from the dendrites. Dendrites dendritic growth does not require such a kind of coupling of the diffusion fields. Remember the atoms from the tip of alpha basically B atom has to they have to diffuse side wise to reach the beta lamely.

Similarly, a atoms rejected by beta have to diffuse side wise to reach alpha, this arrows indicates that. And this is completely interlinked. So therefore, this growth of a eutectic is basically diffusional in nature. And any kind of a model or mechanism for the growth of a eutectic must considered how this atomic transport happens across the interface side wise. So, finally, you know when the eutectic grows it never have a flat interface it has a curve interface I have drawn that picture right.

The first question one always ask why can not you have a flat interface like this, instead of interface like that, at the way I have drawn. And this is the one we see in the actual case. This is mainly because alpha and beta has different melting temperatures you see here alpha has a melting temperature of this much, beta has a melting temperature of this much they have d different melting temperatures. These has a melting temperature of given by this point these has a melting temperature of given by this point.

So now question is that yes they have different melting temperatures. And obviously, they may have different crystal structural also. Even if they do not have or they have does not matter they have different melting temperatures, but because alpha and beta are growing side by side they are in touch with each other. So therefore, the temperature must be continuous temperature must be continuous from alpha or beta to alpha to beta. You cannot develop a temperature gradient across the interface this interface between alpha and beta must have same temperature.

So, in order to make the temperature same, these lamely or lamella r actually curved So, that the curvature under cooling the under cooling because of curvature are tuned to make the lamely curved. So therefore, depending on the that is one aspect depending on the type melting temperatures of the these 2 phases, which are growing side by side the curvature can be changed ok.

Second important thing is that you know at the interface if I draw again other way vertical way bigger. At the contact point here if I draw the interfacial energies the way you have shown you earlier in case of, suppose this is the interfacial energy of alpha beta. Remember we have liquid in front of which. So therefore, this is the interfacial energy of this is your alpha central one these 2 are beta. So therefore, this is interfacial energy of beta liquid this is interfacial energy of beta liquid this is interfacial energy of alpha liquid. And if this angle which is which is subtended by these 2. So therefore, at this point these 3 interfacial energies must be balanced.

So, it is very simple, that if I draw a vertic normal vertical like this. Say as you clear see the angle will be subdivided by theta by pi by 2 pi by 2. So, I can write down gamma alpha beta must be equal to gamma beta l this is gamma bet l plus gamma alpha l cos pi by 2 the addition of these 2. You know, terms in the vertical direction must balance these.

Similarly, gamma beta l sin theta by sin pi by 2 must be equal to gamma alpha l sin pi by 2. These 2 are actually horizontal components. So, finally, balance of this interfacial energies. As well as the curvature under cooling determines the actual shape of that actual shape of the interface, that is very important. Because this shapes of the interface tells you what is the interfacial area. And remember the interfacial area multiply the interfacial energy that is what governs the driving force driving force for solidification.

Anyway this is basically happens in a eutectic lamellar eutectic growth. Things are of little bit different or not little bit quite a bit different in case of rod or in case of other eutectics. Because the complex micro studies the type of complexity is more, but for your purpose it is always more than enough to understand how a lamellar eutectic grows in the liquid. So, this is actually the mechanism of growth of the eutectic.

Now, question is the whether can we built a mathematical model around it, or not to do that let me just I know I just want to discuss I just discuss with you. So, as you can understand 2 important aspects which play a role in the eutectic growth. One the transport of this atoms from the tip of this lamely to the other right. So, one of the lamely alpha is rejected rejecting B atoms that needs to be transported to the beta and vice versa. That is beta lamely rejecting a needs to be transported to alpha. This that means, this is diffusional process.

So, because as if this atoms are not able to diffuse easily, the growth of this front eutectic front of liquid will be slowed down. So, growth rate will be distinctly dependent on how fast these atoms are transported or diffused rather are transported by diffusion across. This interface not perpendicular to the interface across the interface remember this way parallel to the interfacial ok.

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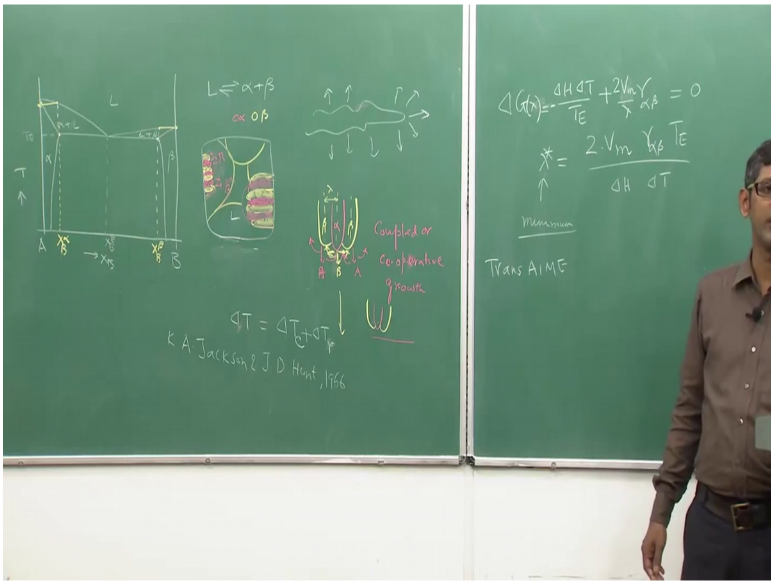

So therefore, we need to calculate what is the under cooling required to diffuse the transport, this atoms that is the first part. That is very important. Because this is will basically govern or rather it basically dictate, how fast is this eutectic lamellar or eutectic you know colony can grow in the liquid. Second important aspect just now I discussed is the under cooling required for the curvature. So that means what? The total under cooling required for the eutectic growth is basically equal to under cooling because of the curvature, that is I have given r you always write r because these are curves. So there is a radius of curvature and the compositional aspects delta T c. These 2 needs to be calculated separately then only we can develop a model.

Now, this once I know this delta T then I know what is a driving force delta G available right.

So therefore If I write down here delta G is basically because of this delta T that is can be easily written like delta H delta T by T E right. That we have already seen how to calculate that delta H is what is the latent heat of evolution because of the eutectic formation.

And delta is the total under cooling. If this is a total under cooling, this is total under cooling. Divided by the eutectic temperature, this is what is the driving force available now this driving force available is spent in 2 things. One for the interface to grow or for this whole things to move in the liquid faster, this liquid this whole thing will grow in the liquid.

Second thing is to create an alpha beta interface. Because there are 2 things here. One is the interface between alpha and beta the other one is the interface between the lamely and the liquid. So, I just need to add the energy required for that. So, this is minus as you know correct. So, if I write down this as a G when the inter lamellar spacing is equal to lambda, G is equal to minus delta H delta T by T E plus the energy because of interfacial energy that you always write down a gamma right.

So, what is A here? Remember A is basically proportional to lambda. Basically A is proportional to twice by lambda square. So, normally people write this is equal to 2 V m by lambda alpha beta where V m is the molar volume of average molar volume of alpha and beta. So, the actually the surface area of one meter cube of eutectic is equal to 2 by lambda square. That is what you see calculation source.

So now this is the delta G or the free energy for the transformation of the eutectic with the inter lamellar spacing equal to delta. Question is this at when the when you know when the total energy which is which has been obtained, because of the latent heat evolution or because of that is equivalent balanced by the formation of the interface.

Then I can write down this to be equal to 0; that means, there is no finite driving force available. So, this will give me a delta star the minimum value of del lambda sorry, lambda star minimum value of lambda. And that is equal to basically twice V m and gamma alpha beta that the surface energy T E divided by delta H into delta. T is very simple you just simply back calculate you will get it this is the minimum value of lambda you cannot have less than that. Because as we know that is the lambda it goes on decreasing surface area increases. So, if therefore, the this part because lambda is at the denominator. So, they because of it is it is increase of lambda sorry decrease of lambda; that means, when the lambda becomes smaller and smaller this part will increase the value will increase. So therefore, this is basically minimum value of lambda.

Now, is very simple actually mathematically. So that means, the whole energy which has been which was available to the system as you will spend on creating the interface between alpha and beta. That will never happen in a actual sense, because in that case eutectic has no energy available for is to grow. So, lambda will be always higher than lambda star, that is very simple ok.

So, we will stop here in the next lecture we will discuss how actually I can use total under cooling terms to formulate a theory to calculate what is the lambda, what is the velocity interface how they are related just like a dendritic growth. The velocity of the dendrite as well as the int tip radius are related by a single equation. So, we will also see that this is possible to develop a such a equation.

In fact, this theory useful formally developed by K. A. Jackson and J. D. Hunt in 1966. And classically this theory is known as Jackson and hunt theory. So, those of you are really interested to know how this theory was developed by Jackson, Jackson and hunt this paper was published in transaction of American institute of American metallurgical institute of engineers. Something like that AIME transaction of AIME American institute of metallurgical engineers. This was published in 1966 where the detail description of how this model was developed is provided.

So, in the next lecture we will start with that and describe although it is not possible for me to describe the whole model, but basic features of the model will be discussed. So, that you understand how the eutectic actually lamellar eutectic actually grows in to the liquid. So, we will stop today.