Introduction to Materials Science and Engineering
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Lecture - 92
Nucleation, growth and overall transformation

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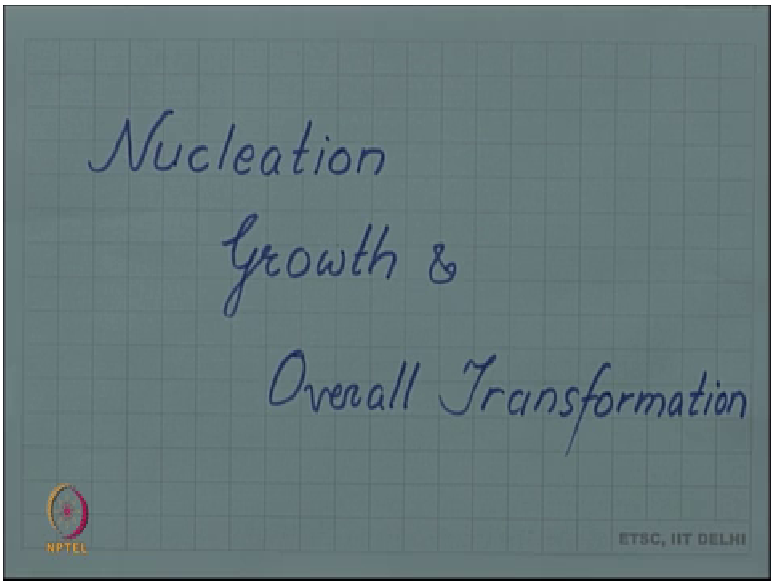

So, let us continue the discussion of phase transformation. Let us look at nucleation, growth and overall transformation.

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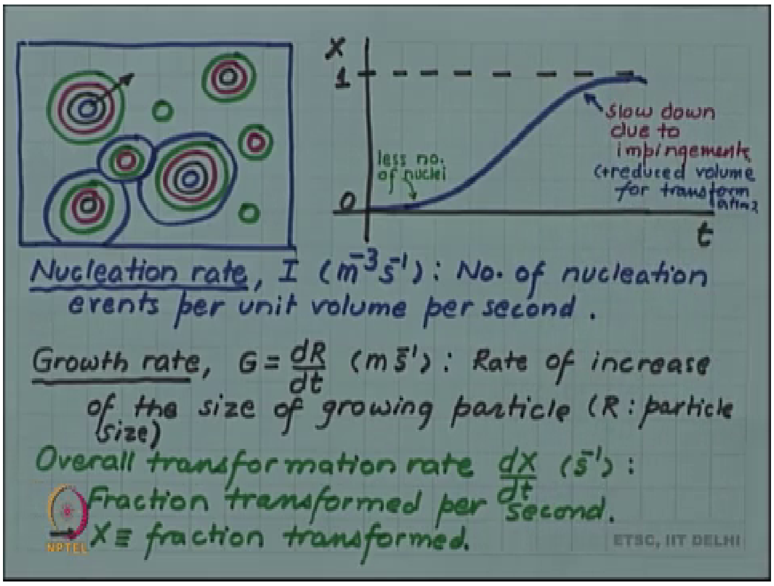

So, we let us imagine that we have a volume of material which is going to transform. Let us say that this box represents an untransformed material and gradually is going to transform. So, the transformation as we have seen will begin with some nucleation event so some nuclei of critical size will form in a given time interval.

As the time passes these nuclei will grow to a larger size, as well as new nucleation event will happen. Then in the next time interval already nucleated regions will keep growing and further new nuclei will get added to the system. So, in still next event all these existing particles which are growing will keep growing and still new nuclei will form. So, one can see that gradually with this process of nucleation and growth new nuclei are forming and already existing particles are growing.

So, the overall transformation rate will depend upon both the nucleation rate and the growth rate. So, let us define nucleation rate you will use the symbol I and its units will be per meter cube per second. So this will be the number of nucleation events per unit volume per second so that will be the nucleation rate.

Then we also have the growth rate we give the symbol G, we can also call it dR by Dt, where R is the particle size. So, the units will be meters per second so this will be rate of increase of the size of the particle, so that is at what rate this interfaces moving.

So, that will be the growth rate the nucleation rate will be at what rate new particles are forming per unit volume, per second the growth rate is a given particles at what rate it is increasing its size so that is growth rate. Then we have an overall transformation rate, which we represent dx by dt and the unit is only per second, where x is the fraction transformed.

So, overall transformation rate in fraction transformed per second x is the fraction transformed, and here R is the particle size. So, if we now show these quantities as a function of time let us say x axis is time, and y axis is the fraction transformed x. So, as you can see the fraction transform can take a maximum value of 1, which means transformation is complete 100 percent transformation has happened and the minimum value will be 0 at the beginning.

So, initially since nucleation has to happen and initially they are no nuclei. So, there will be a 0 overall transformation rate, and 0 transformation has happened. Then as nuclei begin to appear the transformation rate will pick up and since as you saw now at this moment of time I have 1, 2, 3, 4, 5, 6, 7, 8 particles growing, but in the beginning I was having only 1 or 2 particles growing.

So, the number of particles which are growing will increase as a function of time so the growth rate be the overall transformation rate will pick up. But gradually towards the end of the transformation it will again slow down when it reaches the value of 1.

So, this slowing down you can see from appreciate from here if we allow further growth if we allow further growth here you can see that particles will start impinging. And the region where they impinge further growth is not possible they can impinge among each other or they can impinge from the external surface also.

So, there wherever this impingement takes place the transformation will end and further growth is not possible at that interface. So, this will slow down the rate towards the later part. So, this part is slowing down due to impingement. The initial part and also the slowing down is due to impingement and also the remaining volume in which transformation can happen also will be reducing.

So, for the say even if the nucleation rate is same for the same nucleation rate the number of nuclei which will appear will be less because the volume is less this will also lead to the slowing down, plus reduced volume available for transformation. The initial part is slow as I have already told is because of less number of nuclei.

So, this s curve is generally what is observed for any transformation that the fraction transformed is initially grows slowly, but as nuclei build up it picks up in the rate. And finally, as towards the end impingement starts taking place and the volume remaining to be transformed is less. So, the fraction transformed again slows down in terms of its time rate. Let us now look at the temperature dependence of these rates.

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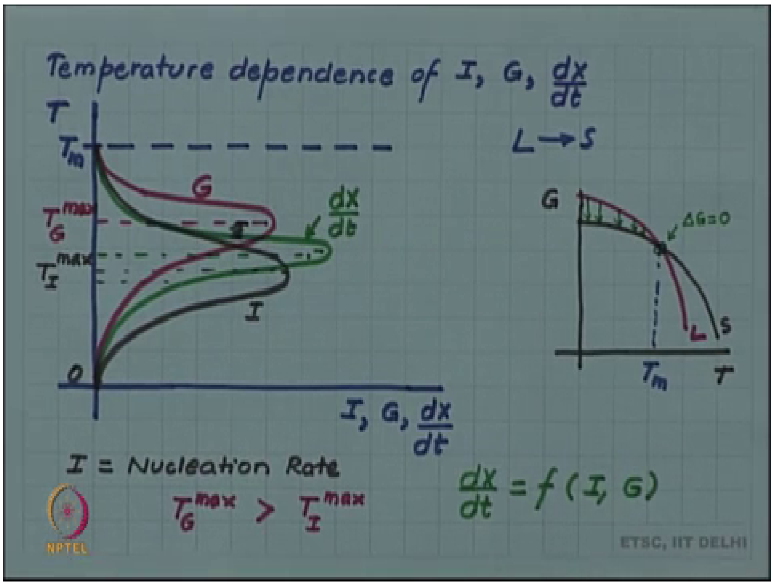

Breaking dependence, of the nucleation rate the growth rate and the overall transformation rate. Let us have y axis as the temperature, and x axis we represent for either of these rates, y axis is temperature and this is rate let us say the nuclei I, G or dx by dt.

Of course, as you have seen they have different units. So, you really have 3 different scales here, but we are drawing schematically and we are not worried about the different units and scales at the moment and let us for example, let us think of solidification.

So, we are talking of liquid to solid transformation. So, there is the critical temperature for this is the melting temperature Tm, and so below above the melting temperature there will be no freezing no solid will be forming. So, all these rates will be 0 above the melting temperature there is no question of any transformation from liquid to solid above the melting.

So, so all these rates exist below this melting temperature. So, we can draw line at Tm, and we have seen that the nucleation rate I let us say I is the nucleation rate. So, nucleation depends upon a driving force recall that diagram of the free energy versus temperature.

So, this is free energy and this is temperature we saw that if solid has this free energy as a function of temperature, and the liquid has this free energy as a function of temperature in the intersection of solid and liquid free energy is the melting point and the driving force is the difference between the liquid free energy and the solid free energy.

This is the reduction in free energy if liquid transforms into solid and you can see that this reduction at the melting point is 0. So, at melting point there is no driving force because the two free energies are equal so delta G is equal to 0 there. So, at the thermodynamic equilibrium melting point the nucleation rate will be 0, because there is no driving force and it above that is anyway 0 because there will be no transformation possible.

So, at Tm we have a 0 nucleation rate, and then as the temperature falls the driving force increases and this will try to increase the nucleation rate. So, nucleation rate we will keep increasing as a function of temperature as we lower the temperature because of this increase in driving force, but this is not the only factor the other factor for nucleation is the atomic mobility. If we have no atomic mobility because nucleation even requires formation of a new phase which means atoms have to rearrange themselves into a new organization.

So, for example, liquid is a disordered phase and solid has a nice unit cell. So, it is a periodic organized structure so from disordered phase to organized structure requires atomic mobility. And as we lower the temperature as we lower the temperature although the driving force is increasing you know that atomic mobility keeps decreasing in particular at absolute 0, if this is absolute 0 there will be no atomic mobility and then no transformation is possible even though the driving force is very high.

So, because of a reduction in atomic mobility at very low temperature the rates will again fall. So, at the melting point rate is 0, because you are having no driving force then the rate builds up and then it again falls 0 to 0 value as a temperature falls because of the atomic mobility. So, finally, the nucleation rate I will look something like this and will have a maximum at some temperature.

So, at this temperature sorry at this temperature it is having a maximum value. The same in competition between driving force and atomic mobility is proof or the growth also, growth require also requires both the driving force and atomic mobility. So, growth rate also shows a similar pattern, but the maximum the temperature at which it will attain maximum is a different temperature and I draw it like this this is for growth rate.

Let me write it here so that there is no confusion and generally it is found that the growth rate, the temperature at which the growth rate maximum happens. So, let me call that temperate temperature for growth rate maximum t G max, and let me call this temperature for nucleation rate maximum t I max. And we will not get into details of this, but for most system it is found that t G max, the growth rate maximum happens at a higher temperature than the nucleation rate maximum.

So, this we will take it with this we will take for granted that our system has this property. Now the overall transformation as we have seen in this at what rate the overall transformation is happening will depend not only on at what rate the nucleus is forming, but also at what rate the particles are growing.

So, the overall transformation rate dx by dt, the overall transformation rate dx by dt is a function both of the nucleation rate and the growth rate. So; obviously, if at Tm were both nucleation and growth rate are 0 the overall transformation rate also will be 0. Similarly at very low temperatures where both of them are small and close to 0, the transformation rate also will be 0.

However, at the intermediate temperature where they have significant value the growth rate will also the overall transformation rate will also maximize. So, if we now plot the overall transformation rate, it will also have the same pattern and will have a maximum somewhere between t G max and t I max. So, this is the overall transformation rate.

So, essentially all these rates are 0 at the melting point and above will be 0 again a very close to a 0 Kelvin, and at lower temperature and in between they reach a maximum. So, we will develop this, an idea now into in the next video into something called time temperature transformation diagram which is a very useful diagram in phase transformations.