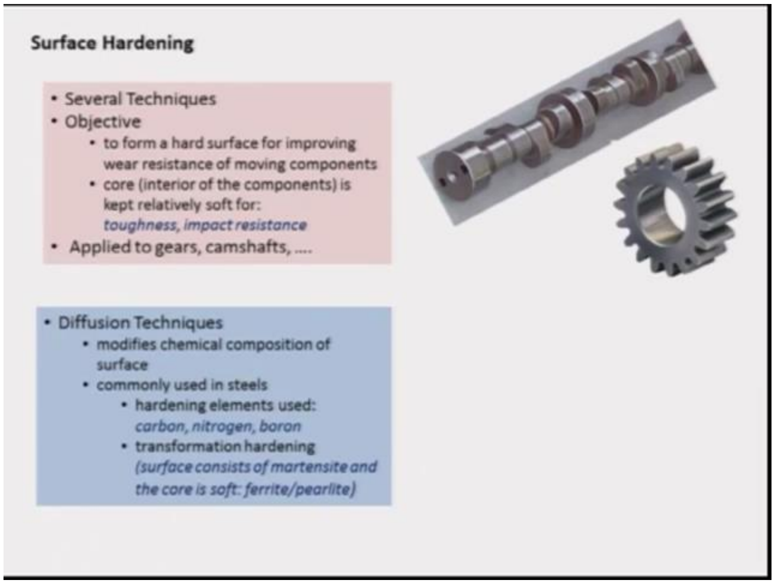
Heat Treatment and Surface Hardening (Part–1)
Professor Kallol Mondal
Professor Sandeep Sangal
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur
Lecture Number 40
Application of heat treatment

Ok so this is the forty eighth lecture and the last lecture of this course, here in this lecture whatever fundamentals that we have done so far we look at the applications of those fundamentals. So the first Martensite very important application is how to hardened surfaces of materials where particularly the components made out of that materials may be, may be involved with a lot of wear and how to increase the wear resistance basically involves hardening of surfaces.

(Refer Slide Time: 01:10)



Surface Hardening

- Several Techniques
- Objective
  - to form a hard surface for improving wear resistance of moving components
  - core (interior of the components) is kept relatively soft for: *toughness, impact resistance*
- Applied to gears, camshafts, ...

- Diffusion Techniques
  - modifies chemical composition of surface
  - commonly used in steels
    - hardening elements used: *carbon, nitrogen, boron*
    - transformation hardening *(surface consists of martensite and the core is soft: ferrite/pearlite)*

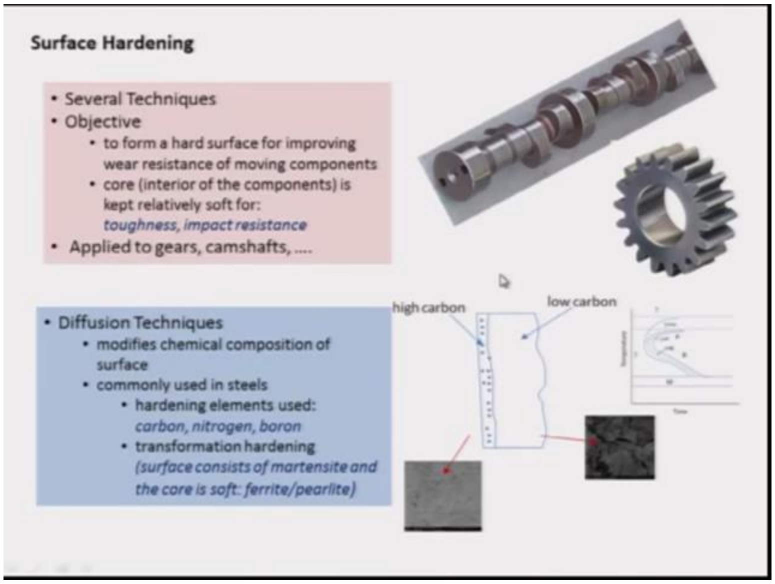
So surface hardening is a first application let us look at and in surface hardening there are many techniques and we are not going to in this lecture going to go into several techniques but we will look at one particular technique of surface hardening and what is the objective of surface hardening is to form a hard surface for improving wear resistance of moving components, and you just want to hardened the surface while the interior of the component or the core of the component is kept relatively soft so that overall the component has a high toughness and high impact resistance.

This is particularly useful for applications in the automobile industry where gears are involved, camshaft are involved and also in many many other applications as you can see couple of illustration here. This is a picture of a cam shaft which is subjected to a lot of wear during its operation because it is used in timing of the engine and here is a gear which in which there is a lot of wear that could take place.

So you want to hardened the surface of the teeth of the gear so that you can improve the life of the gear. Now as I said there are many ways of doing this one specific method of doing this is using diffusion in through a process of diffusion one modifies the chemical composition of the surface so that the surface becomes harder. It is very commonly used in steels, in fact one of the first hardening technique was this only for steels.

So what you what you do is through diffusion you introduce some hardening elements like carbon, nitrogen and boron in the surface layer. So what you have done is you have changed the chemistry of the surface layer while at the same time keeping the core at the same composition, so for example if you have introduced carbon in the higher carbon content in the surface then one can use transformation hardening heat treatment through which on the surface you get Martensite while the core is kept soft with a structure like ferrite and perlite.

(Refer Slide Time: 03:50)



Surface Hardening

- Several Techniques
- Objective
    - to form a hard surface for improving wear resistance of moving components
    - core (interior of the components) is kept relatively soft for: *toughness, impact resistance*
- Applied to gears, camshafts, ….

- Diffusion Techniques
    - modifies chemical composition of surface
    - commonly used in steels
        - hardening elements used: *carbon, nitrogen, boron*
        - transformation hardening *(surface consists of martensite and the core is soft: ferrite/pearlite)*

This is illustrated here as follows that here is a component. The surface of this component here is exposed to an atmosphere of high carbon concentration and of course this component is kept at an high enough temperature so that diffusion of carbon can take place from that atmosphere into the material in the surface layers. So what you see eventually a high carbon content surface layer is formed while the rest of the material is kept at low carbon.

Now as a result the transformation kinetics have been altered at the surface as compared to the interior. How was it altered well if you look at the transformation diagram a small transformation diagram that I have schematically shown here the temperature versus time cct or a TTT diagram here.

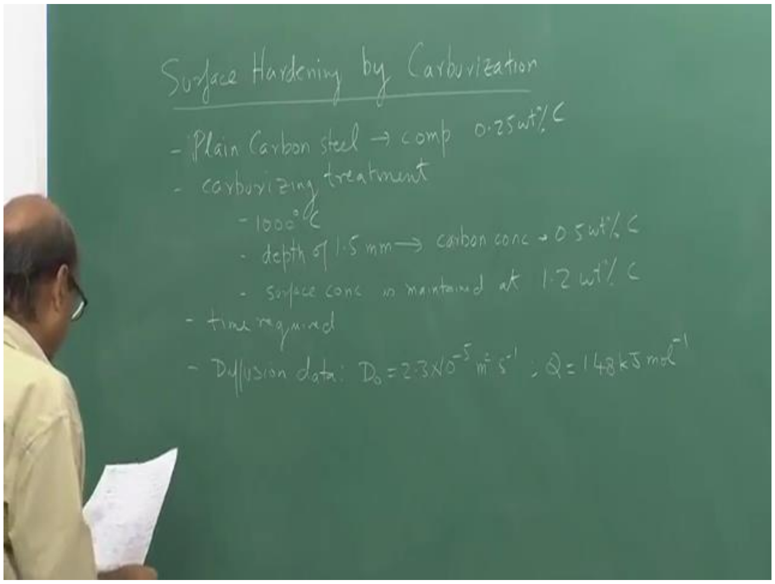
As you increase the carbon content the kinetics of the transformation or to ferrite or perlite slows down as a result the c curves of the transformation diagram these c curves that you see here. They are shifted to the right, so what happens is for if you now heat treat this component by taking this component to the austenite region where now everything has becomes austenite and then you cool this component.

In one case in the interior part the cooling rate that is produced intersects the ferrite-perlite curve. So this is the ferrite curve and this is the perlite curve. As a result the micro structure that you would get in the core would be ferrite and perlite. On the other hand, the surface layer which have a higher carbon content there transformation diagram would have been shifted to the right then for the same cooling rate. There those cooling rates may not intersect the ferrite or the perlite c cruves they would directly cool down into the Martensite region producing a hard surface consisting of a martensitic structure as illustrated here.

So in the core you have a ferrite-perlite structure and in the surface layer you a martensitic structure a hard surface is produced so you have a hard surface in the end with overall toughness of the component being still kept still high without losing the toughness or the impact resistance of the component. So for example camshaft and the gears come under a lot of impact loading so they can still sustain those while at the same time the wear resistance has been increased through surface hardening.

Now what I will do is, I will take up a specific case of a surface hardening in a steel where we will look at a problem and see how we can estimate how much time at what temperature we should we should subject this component so that we get a certain thickness of the hardened layer. So let us look look at this on the board.

(Refer Slide Time: 07:35)



Surface Hardening by Carburization

- Plain Carbon steel → comp 0.25 wt% C
- carburizing treatment
  - 1000°C
  - depth of 1.5 mm ⟶ carbon conc → 0.5 wt% C
  - surface conc is maintained at 1.2 wt% C
- time required
- Diffusion data: $D_0 = 2.3 \times 10^{-5}\ m^2 s^{-1}$; $Q = 148\ kJ\ mol^{-1}$

So surface hardening is specifically by a process called carburization. In this as I have already explained that you subject the, steel in this specific case to an atmosphere containing a high carbon concentration. So let me first outline the problem and then solve it. So there is a plane carbon steel out of which some components has been made whose composition is 0.25 weight percent carbon.

Now this is the carbon content in the surface of this component has to be increased or this has to be subjected to a carburizing treatment and what is involved I this carburizing treatment the system that will do carburization at 1000 degrees centigrade so that at a depth of 1.5 millimetres, the carbon concentration should be increased to 0.5 weight percent carbon.

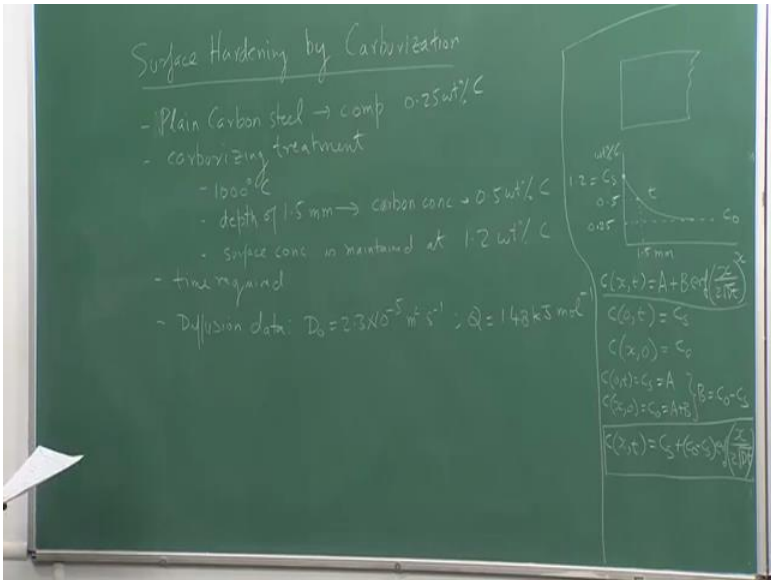
So what we want to do is at the depth of 1.5 millimetres we want to double the carbon concentration from 0.25 to 0.5 weight percent. In order to do this the surface concentration through that carburizing atmosphere is maintained at 1.2 weight percent carbon, so typically a carburizing atmosphere would be a gaseous atmosphere kept at a1000 degree centigrade.

So that the surface concentration throughout the carburizing treatment is kept at 1.2 weight percent carbon and what do we want to find out well we want to find out the time required for this treatment that is the time required to increase the carbon content at a depth of 1.5 millimetres from.25 weight percent to 0.5 weight percent.

So this is a simple diffusion problem of carbon of carbon atoms diffusing into the steel. One would also require in order to solve this problem the data for diffusion so one can keep diffusion data so at 1000 degrees centigrade the steel will be in austenite. So we require diffusion data for carbon diffusing in the austenite structure, so for that D0 the frequency factor is 2.3 into 10 to power minus 5 metre square per second.

The activation energy for diffusion is 148 Kilo Joules per mole inverse. So let us let me Martensite illustrate this problem by drawing a diagram.

(Refer Slide Time: 12:20)



Surface Hardening by Carburization

- Plain Carbon steel → comp 0.25 wt% C
- carburizing treatment
  - 1000 °C
  - depth of 1.5 mm → carbon conc → 0.5 wt% C
  - surface conc is maintained at 1.2 wt% C
- time required
- Diffusion data: $D_0 = 2.3\times10^{-5}\ m^2 s^{-1}$; $Q = 148\ kJ\ mol^{-1}$

$C(x,t) = A + B\,\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$

$C(0,t) = C_s$

$C(x,0) = C_0$

$\left.\begin{array}{l} C(0,t) = C_s = A \\ C(x,0) = C_0 = A+B \end{array}\right\} B = C_0 - C_s$

$\boxed{C(x,t) = C_s + (C_0 - C_s)\,\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)}$

So I have a component made out of this steel of 0.258 percent carbon the surface of this is exposed to an atmosphere of high carbon concentration such that the surface concentration cs is kept at 1.2 weight percent carbon.

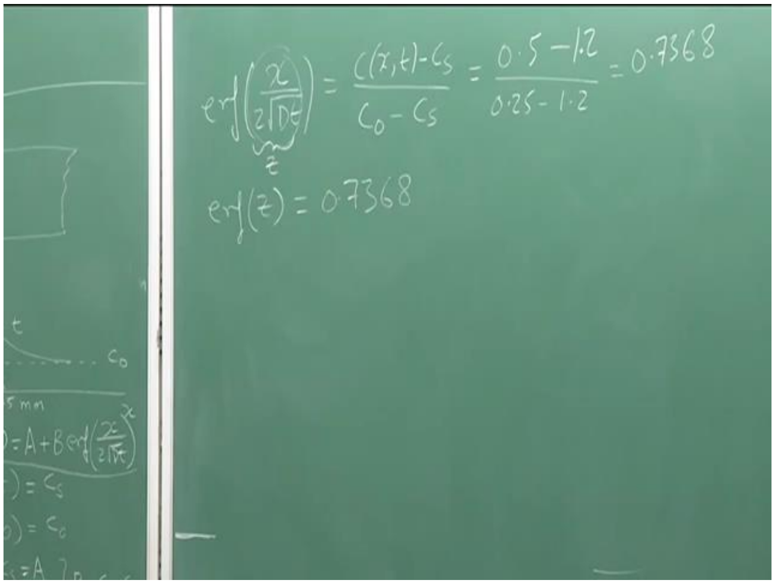
The initial concentration of carbon we call it as C0 is kept at 0.25 weight percent carbon so at time t is equal to 0 everywhere it is 0.25 weight percent carbon. After sometime t we will have carbon diffusion into the material and we will get a profile something like this, so this is at some time t and in fact I want to find the time t for which at a depth of 1.5 millimetres the concentration becomes 0.5. So I want to basically find the profile at time t which gives me a particular concentration at this particular depth.

Now if you recall from the last lecture I can write the concentration profile cxt concentration as a function of distance and time as a constant A plus another constant B times the error function x divided by 2 root dt. Let me put a boundary condition that at x is equal to zero at any time t the concentration is cs the surface concentration fixed by the atmosphere then there is an initial condition I can put at t is equal to 0 cx 0 or x greater than 0 the concentration everywhere is the initial concentration of the steel C0 which is 0.25 weight percent.

If I put these the boundary conditions and the initial conditions well if I put the boundary condition C0t equals cs into this expression well when I put x is equal to 0 error function of 0 is 0, so hence the constant A is simply cs. I put the initial condition cx0 this should be C0. So when I substitute in this t is equal to 0 I get error function of infinity. Error function of infinity is 1, hence C0 is equal to A plus B.

From this I will get B is equal to C0 minus cs, substituting A and B into this expression I will get cxt is equal to cs plus C0 minus cs times error function x divided by 2 root dt. So this should enable me to solve the concentration profile for any x and for any t and let us see how we can do this for the specific problem at hand.

(Refer Slide Time: 16:50)

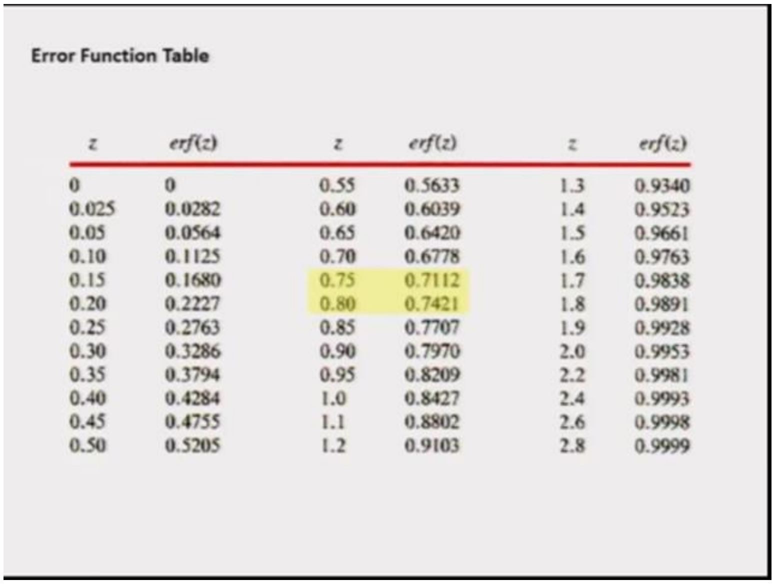


So let us look at rewriting this expression as error function x divided by 2 square root dt equal cxt minus cs divided by C0 minus cs. Now let me substitute that I want at some depth at a depth of 1.5 mm. I want a carbon concentration of 0.5 weight percent, so therefore for cxt I will put 0.5 minus the surface concentration is fixed at 1.28 percent so I will write 0.5 minus 1.2 for the numerator and in the denominator C0 is a initial concentration of the steel which is 0.25 minus cs which is 1.2.

So on solving this I will get 0.7368, so error function of x upon 2 square root of dt should be equal to 0.7368. In this if I know x and I can find D from the data given from D0 and Q, I should be able to find time. Such that the error function of this quantity should be equal to 0.7368. Now how to do this we will have to go to what is called as the error function table where the table of values given and from that table one should get one should be able to obtain that for error function to be equal to this what should be this quantity, and let me call this quantity as z.

So I can write error function of z is equal to 0.7368 and I need to find what is z, so if I go to error function table let me just do this.

(Refer Slide Time: 19:45)

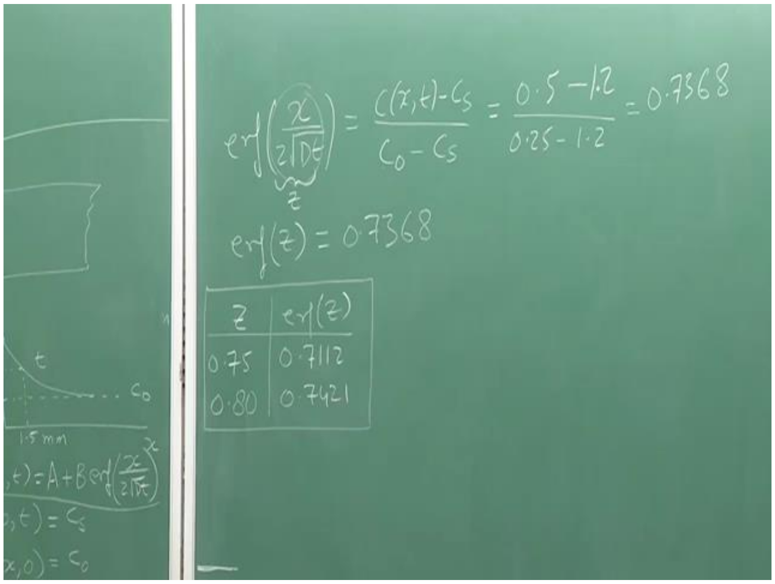


Error Function Table

z	*erf*(*z*)	*z*	*erf*(*z*)	*z*	*erf*(*z*)
0	0	0.55	0.5633	1.3	0.9340
0.025	0.0282	0.60	0.6039	1.4	0.9523
0.05	0.0564	0.65	0.6420	1.5	0.9661
0.10	0.1125	0.70	0.6778	1.6	0.9763
0.15	0.1680	0.75	0.7112	1.7	0.9838
0.20	0.2227	0.80	0.7421	1.8	0.9891
0.25	0.2763	0.85	0.7707	1.9	0.9928
0.30	0.3286	0.90	0.7970	2.0	0.9953
0.35	0.3794	0.95	0.8209	2.2	0.9981
0.40	0.4284	1.0	0.8427	2.4	0.9993
0.45	0.4755	1.1	0.8802	2.6	0.9998
0.50	0.5205	1.2	0.9103	2.8	0.9999

What you see here are for different values of z I get what is an error function of z. So for 0 it is 0 for 0.1 it is 0.1125 for 0.5 it is 0.5205 and so on and as you can see that sz is increasing the error functions values are also increasing and obviously for large values of Z it will be very close to 1.

(Refer Slide Time: 20:40)



$$\mathrm{erf}\Big(\underbrace{\frac{x}{2\sqrt{Dt}}}_{z}\Big) = \frac{C(x,t)-C_s}{C_0-C_s} = \frac{0.5-1.2}{0.25-1.2} = 0.7368$$

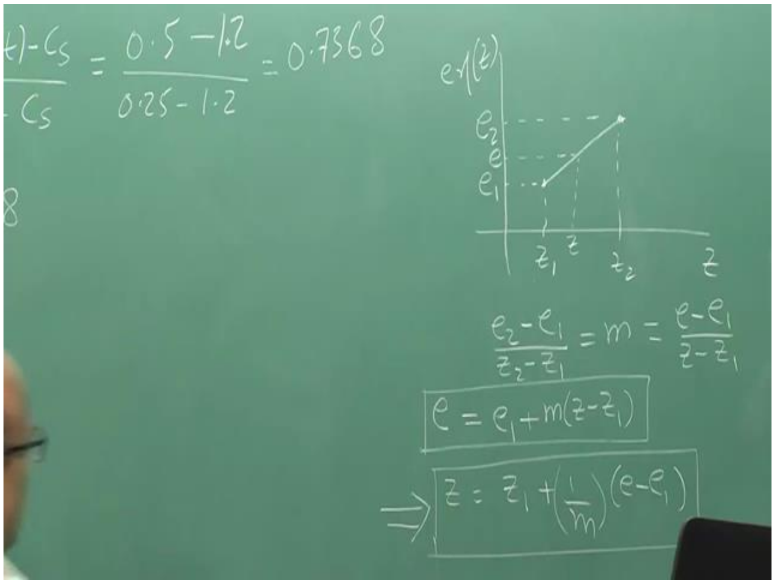
$$\mathrm{erf}(z) = 0.7368$$

z	$\mathrm{erf}(z)$
0.75	0.7112
0.80	0.7421

Now for the specific value in hand of 0.7368 if I locate this I will come here that 0.7368 lies between these two values as highlighted here. Therefore z would be in between 0.75 and 0.80 so what we need to do is we need to do a linear interpolation. So what I have is essentially a value of z and error function of z, so I have for 0.75 from the error function table it is 0.7112 and for a value of z 0.80 I have an error function value of 0.7421. From the error function table.

So this I have obtained from the error function table and 0.7368 lies in between these two and hence z should also lie between 0.75 and 0.80. So I need to then do a linear interpolation to get the value of z.

(Refer Slide Time: 21:40)

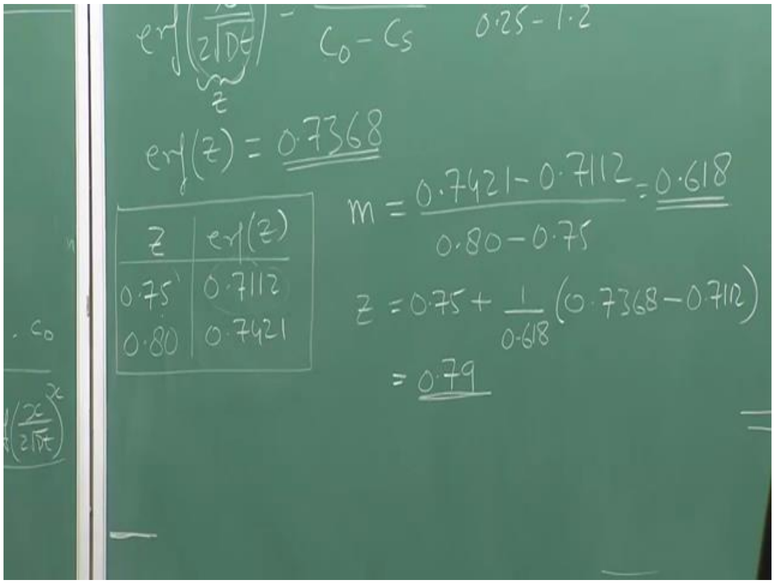


How to do this linear interpolation well let me just do this little exercise that let me take these two values of z and error function of z Martensite let me say this is a z and this is error function of z.

So I have for z1 I have the error function value to be, let me call it as e1 for z2 I have an error function value let me denote it as e2 and I join these two points with a straight line somewhere now if I want to find an error function value in between designated as e for a given z. So knowing z1, z2, e1, e2 if I know z from linear interpolation I should be able to get e. If I know e from linear interpolation I should be able to get z.

So this we can write, so the slope of this line can be written as e2 minus e1 divided by z2 minus z1 and let me call that as m, the slope. This is also equal to e minus e1 upon z minus z1. Hence I can write e is equal to e1 plus m times z minus z1. So if I want to find at some z in between z1 and z2 what should be the error function value. So I first get the slope from here put the value of z in this e1 z1 and the slope value I will get e or I can also write for z as z is equal to z1. Rearranging these terms1 upon m times e minus e1.

(Refer Slide Time: 24:50)



$\mathrm{erf}\left(\underbrace{\frac{}{2\sqrt{Dt}}}_{z}\right) = \frac{}{C_0 - C_s}$ 0.25 − 1.2

$\mathrm{erf}(z) = \underline{\underline{0.7368}}$

z	erf(z)
0.75	0.7112
0.80	0.7421

$$m = \frac{0.7421 - 0.7112}{0.80 - 0.75} = \underline{\underline{0.618}}$$

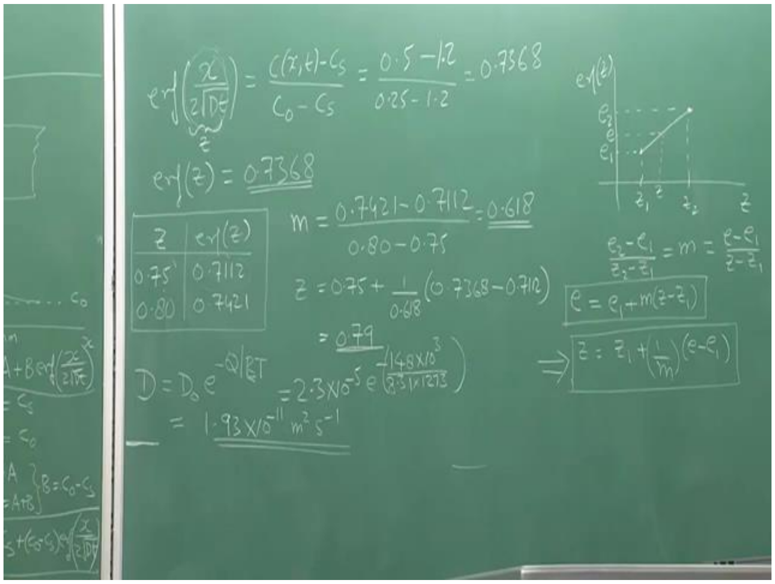
$$z = 0.75 + \frac{1}{0.618}(0.7368 - 0.7112)$$

$$= \underline{0.79}$$

Now if I know e the error function value in between e1 and e2 then I would be able to compute what should be the z value. So using this particular relation I have this data and I know error function value in between these two so I should be able to get a corresponding z value. Which turns out to be, so first let me calculate the slope m which is simply e2 minus e1 so it is 0.7421 minus 0.7112 divided by 0.80 minus 0.75 and the slope turns out to be 0.618.

From this slope then I can get the z value as z1 which is 0.75 plus 1 upon the slope, so 1 upon 0.618 multiplied by e minus e1 so e is this the error function for which I want to find z 0.7368 minus e1 which is 0.7112. This gives me a value of z as 0.79. So now I know what is z and z itself is equal to x upon 2 square root of dt. x I know given in the problem at the depth of 1.5 millimetres. I need to find what is the diffusion co-efficient D at 1000 degree centigrade at which I am doing carburizing so now let me also calculate what is D.

(Refer Slide Time: 26:15)



$$\underbrace{\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)}_{z} = \frac{C(x,t)-C_s}{C_0-C_s} = \frac{0.5-1.2}{0.25-1.2} = 0.7368$$

$$\mathrm{erf}(z) = \underline{\underline{0.7368}}$$

z	erf(z)
0.75	0.7112
0.80	0.7421

$$m = \frac{0.7421-0.7112}{0.80-0.75} = \underline{\underline{0.618}}$$

$$z = 0.75 + \frac{1}{0.618}(0.7368-0.7112)$$

$$= \underline{0.79}$$

$$D = D_0 e^{-Q/RT} = 2.3\times10^{-5} e^{\left(-\frac{148\times10^3}{8.31\times1273}\right)}$$

$$= \underline{\underline{1.93\times10^{-11}\ m^2 s^{-1}}}$$

$$\frac{e_2-e_1}{z_2-z_1} = m = \frac{e-e_1}{z-z_1}$$

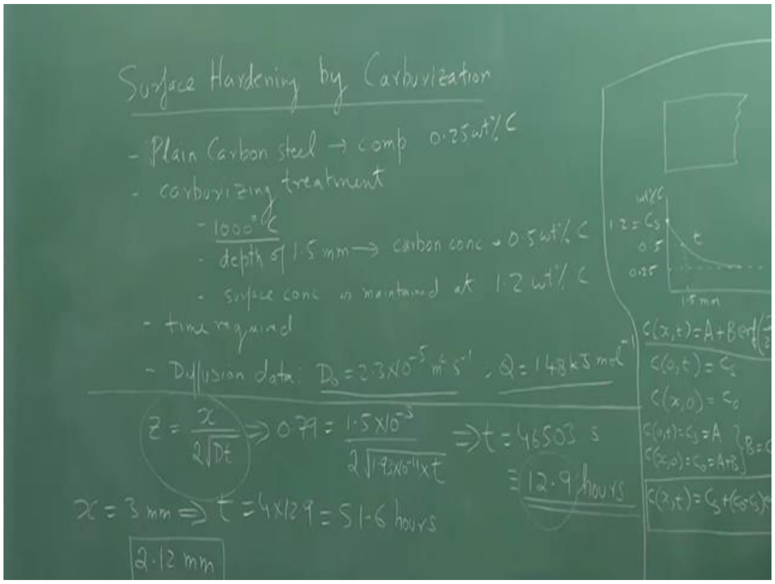
$$\boxed{e = e_1 + m(z-z_1)}$$

$$\Rightarrow \boxed{z = z_1 + \left(\frac{1}{m}\right)(e-e_1)}$$

So diffusion co-efficient D is equal to D0 e to power minus Q divided by RT. Now let me write down what is D0, D0 is 2.3 into 10 to power minus 5 meter square per second multiplied by exponential e minus what is Q, Q is 148 Kilo Joules per mole convert the Kilo Joules into Joules. So it is 148 into 10 cube divided by, divided by R the Gauss constant which is 8.31 Joules per kelvin per mole multiplied by the temperature at which I am doing the carburizing and I am doing it at 1000 degree centigrade.

I need to convert these 1000 degrees to kelvin and so I will write it 1000 plus 273 so 1273 becomes the temperature this gives me the value of the diffusion co–efficient as 1.93 into 10 to power minus 11 metres square second inverse. Now with this value, so I now know in this I know this whole quantity is equal to z which is 0.79. X is 1.5mm now I know what is the diffusion co-efficient so I should be able to find the time.

(Refer Slide Time: 28:30)



Surface Hardening by Carburization

- Plain Carbon steel → comp 0.25 wt% C
- carburizing treatment
  - 1000°C
  - depth of 1.5 mm → carbon conc = 0.5 wt% C
  - surface conc is maintained at 1.2 wt% C
- time required
- Diffusion data: $D_0 = 2.3\times10^{-5}\ \mathrm{m^2\,s^{-1}}$, $Q = 148\ \mathrm{kJ\,mol^{-1}}$

$$\boxed{z = \frac{x}{2\sqrt{Dt}}} \Rightarrow 0.79 = \frac{1.5\times10^{-3}}{2\sqrt{1.93\times10^{-11}\times t}} \Rightarrow t = 46503\ \mathrm{s} = 12.9\ \text{hours}$$

$$x = 3\ \mathrm{mm} \Rightarrow t = 4\times12.9 = 51.6\ \text{hours}$$

$\boxed{2.12\ \mathrm{mm}}$

$C(x,t) = A + B\,\mathrm{erf}($

$C(0,t) = C_s$

$C(x,0) = C_0$

$C(0,t) = C_s = A$

$C(\infty,0) = C_0 = A+B$

$C(x,t) = C_s + (C_0 - C_s)$

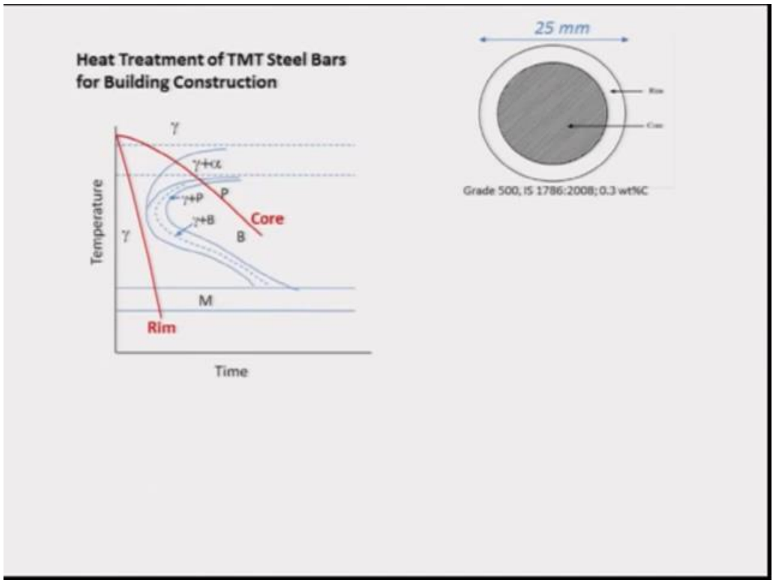
So let us find this, so z is equal to x divided by 2 square root of dt. I will substitute for z as 0.79, substitute for x 1.5 mm convert this to metres so 1.5 times 10 to power minus 3 divided by 2 divided by square root of D. D we have calculated just now as 1.93 into 10 to power minus 11 multiplied by time t. From here I will get a time off 46503 seconds convert this into hours, so divide this by 3600.

This gives me that I require a carburization time of 12.9 hours of almost 13 hours. So in order to get the carbon concentration of up to 0.5 weight percent at a depth of 1.5 mm. I will need to carburize this component for almost 13 hours. Now suppose I were to get the same, I wanted to get the same depth not at 1 I wanted to get the same concentration of.5 weight percent not at a depth of 1.5 mm but a double the depth at 3 mm.

So if I double the depth how much time it would require. Well I just have to look at this if I double the depth that means x is becoming 3 and in order to get the same concentration of 0.58 percent the value of z would still remain as 0.79. Hence if I double this depth that time will have to be increased by a factor of 4, which would mean time would become 4 times 12.9 hours and it would become so far, if x is equal to 3 mm time required x is equal to 3 mm at which the concentration should be 0.58 percent, time will become 4 times 4 into 12.9 and that would take me to almost 52 hours more than 2 days of carburizing.

Similarly I leave it to you that if I double the time then at what distance x I will get a carbon concentration of 0.5 weight percent. I will give you the answer to this the answer to this is 2.12 milimeters and you can work it out just the way we have worked this out that if I double the time what is going to happen to x for the same z valve of 0.79.

(Refer Slide Time: 32:05)



Heat Treatment of TMT Steel Bars for Building Construction

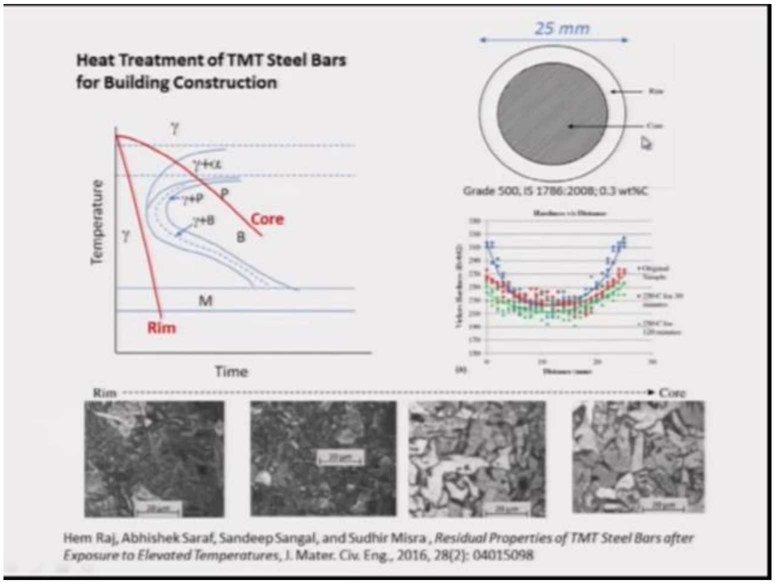
So with this I will close discussion on surface hardening very important application and let us move to another application. This thermo-mechanically treated steel bar for building construction, so they come in various diameters. One particular diameter that is used is 25 millimetres and they come in also various grades, this particular grade which is grade 500 it has a carbon content of 0.3 weight percent.

Now in this if I look at the transformation diagram then this is the transformation just a schematic this is not a specifically drawn for this particular composition where this is the ferrite seeker these are the perlite seekers and out here you will have a bainite. Now what you want to do is you want to create a hard surface outside while a soft core inside but in this we will not do any carburizing.

What we will do is or what is actually done in the industry is that these steel bars are are heated into to the austenite region and then they are quenched, the surface is quenched in such a way that you have different cooling rates on the surface and core obviously cooling if I spray water on the surface of these bars the cooling on the outer surface region would be much faster than the cooling in the interior region and in fact the cooling is so controlled that in the rim region or the surface region the cooling curve is given by this while in the core the cooling is lot slower.

As a result you can very clearly see that in the surface layer the cooling does not intersect any of the seekers hence no ferrite no perlite is formed on the surface, only Martensitic is formed while on the core it cuts the ferrite curve so you get some ferrite it also cuts a perlite seeker so you also get perlite. So you get a ferrite-perlite structure.

(Refer Slide Time: 34:15)



Heat Treatment of TMT Steel Bars for Building Construction

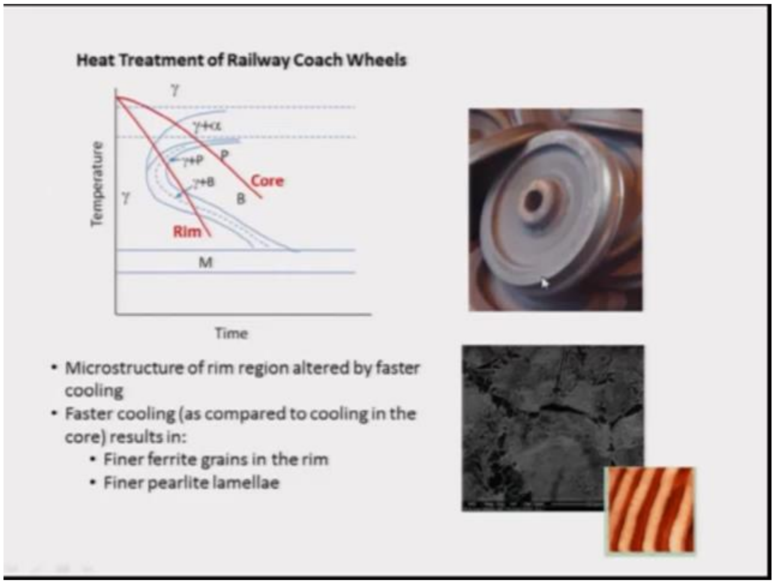
Hem Raj, Abhishek Saraf, Sandeep Sangal, and Sudhir Misra , *Residual Properties of TMT Steel Bars after Exposure to Elevated Temperatures*, J. Mater. Civ. Eng., 2016, 28(2): 04015098

In fact if you look at you will get a gradation of structure right from the surface to the core and these are the kind of micro structures you get right at the rim it is a Martensitic kind of structure and towards the core it is a ferrite-perlite structure.

So as a result you have a hard surface outside and you have a soft core inside and if you measure the hardness of this right from the rim to the core this is the kind of hardness data you will see. You can ignore the just look only at the blue curve and ignore the others curve because they are those are curves that are drawn for other treatments. So just the blue curve which is after this kind of treatment is given to the steel bar.

You have high hardness towards a surface than the hardness drops becomes minimum in the centre and then it starts to increase again. So this is another example of modifying the surface but in this no chemistry is altered.

(Refer Slide Time: 35:30)



Heat Treatment of Railway Coach Wheels

- Microstructure of rim region altered by faster cooling
- Faster cooling (as compared to cooling in the core) results in:
    - Finer ferrite grains in the rim
    - Finer pearlite lamellae

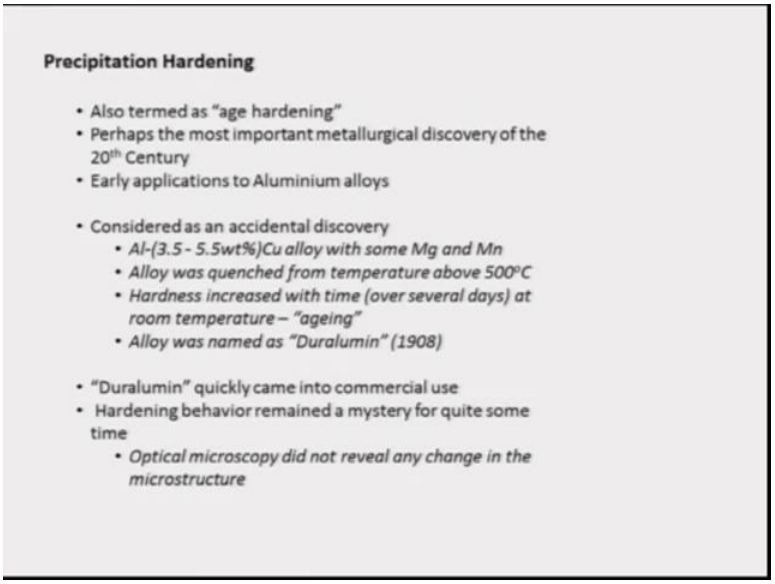
Another example is heat treatment of wheels for the railways coaches so these are photographs of photographs of some real wheels and here again we tried to make some modification to the surface, so that the rim has a somewhat different structure compared to the core but here we do not produce any Martensite side.

In fact so in this the hot wheel which is in the austenite region is subjected to water spray all around the rim as a result the cooling curves that you get are this kind. This wheels are very massive so the even at the surface the cooling is not as fast as it was shown in the earlier case for steel bars for construction.

So both the rim as well as the core cut the ferrite as well as the perlite seekers but the rim has a lot faster cooling as a result what you get is finer micro-structure in the rim as compared to the core remember that In one of the lectures we have discussed that if you go down relatively low in under cooling than you can get high nucleation rate but small very small growth rate as a result you will get a much finer structure.

So you end up with finer ferrite grains in the rim and a finer perlite lamellae and you again get a ferrite-perlite structure everywhere so but then the perlite lamellae, if they are very very fine then they can produce a very high wear resistance and this is what you want for these railway wheels.

(Refer Slide Time: 37:40)



Precipitation Hardening

- Also termed as "age hardening"
- Perhaps the most important metallurgical discovery of the 20th Century
- Early applications to Aluminium alloys

- Considered as an accidental discovery
  - *Al-(3.5 - 5.5wt%)Cu alloy with some Mg and Mn*
  - *Alloy was quenched from temperature above 500°C*
  - *Hardness increased with time (over several days) at room temperature – "ageing"*
  - *Alloy was named as "Duralumin" (1908)*

- "Duralumin" quickly came into commercial use
- Hardening behavior remained a mystery for quite some time
  - *Optical microscopy did not reveal any change in the microstructure*

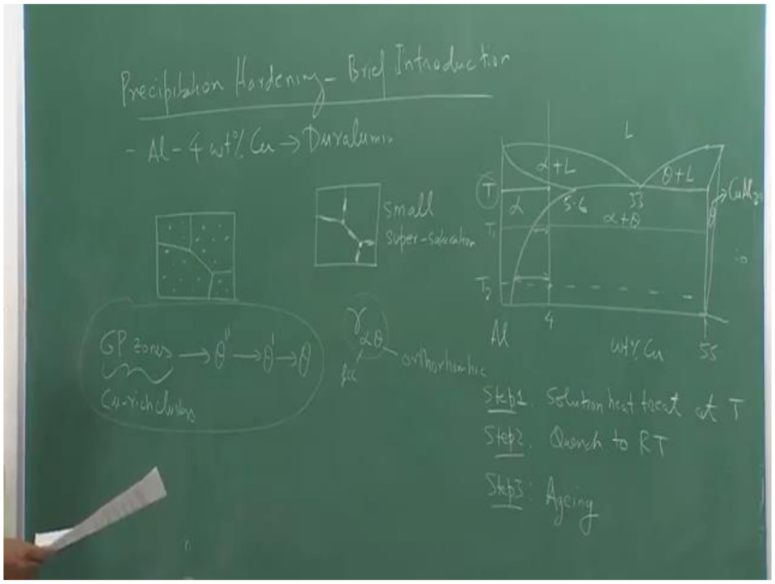
Now one final application and an extremely important application is precipitation hardening. In precipitation hardening it is also termed as age hardening and it is perhaps one of the most important metrological discovery of twentieth century and which changed the way material got used and in fact it enabled aluminium alloys to become very useful engineering materials.

So early applications of precipitation hardening was in the aluminium alloys and it is considered as an accidental discovery, so there was some work going on with aluminium-copper alloys of a certain composition with some magnesium and manganese. This alloy was quenched from a temperature above 500 degrees centigrade. Above 500 degrees centigrade this particular alloy is a single phase alpha which has a face centred cubic structure.

It was then quenched from that and as a result the high temperature micro structure was retained but then it was noticed that the hardness continued to increase with time off course it took several days for the hardness to increase and in fact the material was ageing and getting harder and in fact it was such an amazing discovery that immediately it had commercial applications and the particular alloy was named as Duralumin.

Even today this particular alloy is used extensively. So Duralumin quickly came into commercial use of course hardening behaviour remained a mystery for quite some time as the micro-structure and the optical micro structure showed no change. So people did not know for quite some time what was happening to the material and now just very briefly we will discuss what is happening in precipitation hardening.

(Refer Slide Time: 40:10)



So this is going to be a brief introduction to precipitation hardening in fact very very brief. So let us consider this aluminium–copper alloy and specifically consider aluminium 4 weight percent copper alloy which is called as Duralumin. If I look at the face diagram for aluminium-copper a part of the face diagram, so this is aluminium weight percent copper. So this is about approximately 55 weight percent copper here this point is about 5.6 weight percent copper out here is 33 weight percent copper.

Label the phases this is liquid this is alpha, this is alpha plus liquid. This is the phase called theta plus liquid, this is theta out here is alpha plus theta. Theta specifically is CuAl2 intermetallic. If I take 4 weight percent alloy which may be somewhere here and take this alloy at some temperature t inside the alpha phase. So I start with a single phase copper 4weight percent alloy.

If I start to cool down then what should I get well I start off with with an alpha grains and if i kept cooling down may be I just cool down to let us say some temperature t1 which is high enough temperature for easy diffusion to take place then what would happen is that theta phase would start to precipitate on the grain boundaries.

And eventually I will get alpha and theta in equilibrium as dictated by the phase diagram at that temperature t1. So this is for small under cooling but if I or I can also say that at t1 if I take this then there is a super saturation of alpha of a certain amount and this super saturation than has to dissociate and form the theta phase. So this is for small super saturation of alpha. However if I go down to a much lower temperature, say like t2 the super saturation is much much larger but the temperature is also very large.

sorry the temperature is also very very low as a result now I have a much larger super saturation but the material cannot directly, the theta phase cannot directly precipitate because the energy hill that is there for nucleation of theta to occur is very large or delta g star is very large and why is it very large particularly also because gamma alpha theta the sub-interface energy between alpha and theta is very large because of the very different crystal structures of alpha and theta.

Alpha is face centred cubic while theta is ortho-rhombic hence direct precipitation of theta does not become possible so what happens in this material first clusters form of copper rich clusters form and the sequence of precipitation of theta these as follows. These clusters copper rich clusters or what are called as GP zones so these are copper rich clusters. Eventually they transform to another metastable phase theta double prime and this theta double prime decomposes to theta prime and eventually it forms a equilibrium theta phase.

So theta forms in these steps but the whole idea of this over here is that when you go down to such a low temperature you have very fine precipitation everywhere because of the high driving force not just at the grain boundaries. These are very very fine particles which are not cannot be observed in an optical microscope. One way have to go to a transmission electroscope to see this precipitation.

These very fine particles become obstacle for dislocation movement as a result you have a very significant increase in strength and that is what is called as precipitation hardening. These kind of transient phases forming before the final equilibrium phase formed is also observed in many other age hardenable alloys in many of the aluminium alloys themselves. They are also observer in iron-copper, copper-iron, copper-titanium etc.

So this is quite a general general sequence where a metastable phases form during precipitation which give you precipitation hardening and finally what would be the particle steps involved to produce precipitation hardening is actually very very simple. Three steps that are required to produce precipitation hardening you do not have to take the alloy to this temperature and then quench to t2.

What you do is step one, you solution heat treat at T so that everything is single phase everything is solutionized then step two quench to room temperature as a result the high temperature alpha phase is retained with a very high super saturation of copper in aluminium and the last step, step three is the ageing step that you age at a specific but low enough temperature so that you get fine precipitation.

Many of these alloys will actually even precipitate at room temperature but they may take a long time for that precipitation to occur. With this very brief introduction to precipitation hardening which is an important very very important application of what we have done. I bring this lecture to a close an as well as this course to a close. Thank you.