Welding Metallurgy

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Lecture - 13
Precipitation Hardening and Martensite Strengthening

Welcome to the lecture on precipitation hardening and martensite strengthening. So in this lecture towards discussing the strengthening mechanism of metals we are going to have the discussion on these 2 mechanisms that is precipitation hardening and martensite strengthening. So coming to the precipitation hardening you know first.

So what we know that many a times we try to make the ductile matrix or the material you know having more strength by reinforcing by having the presence of you know the second phase particles and it is one of the you know adopted method. So you know that way we do the alloy strengthening. So one of the method is that the dispersant strengthening in which we normally have 2 different type of materials.

You have one hard particle and that will be mixed with the matrix powder and then they are consolidated using the powder metallurgy route. So that is one of the method you know that is known as dispersant strengthening; however, many a times we take you know what we do is that we adopt the method of precipitation hardening.

Now the precipitation hardening means the precipitates are formed because of certain conditions we have studied about the phase diagrams and we also know that in many cases when there is solubility limit and when the solubility is low at room temperature so in that case you get the supersaturated solution and then slowly by some mechanism you know the precipitates are coming up when the material after being quenched will be aged to certain temperature.

So that basically leads to giving the you know resistance to the motion of dislocation and making the material stronger. So that is the concept of precipitation hardening. So many alloy system can be strengthened by precipitation hardening mechanism produced by solution treating and quenching the alloy.

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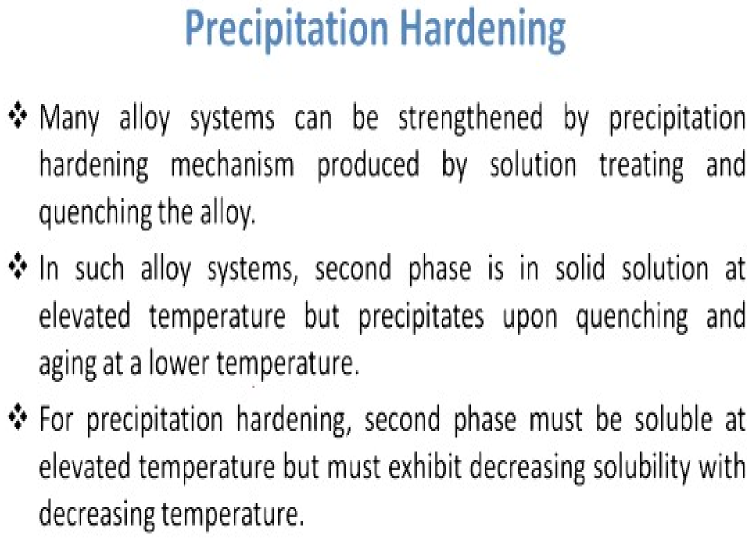

Precipitation Hardening

- Many alloy systems can be strengthened by precipitation hardening mechanism produced by solution treating and quenching the alloy.
- In such alloy systems, second phase is in solid solution at elevated temperature but precipitates upon quenching and aging at a lower temperature.
- For precipitation hardening, second phase must be soluble at elevated temperature but must exhibit decreasing solubility with decreasing temperature.

So you know what we do first is we first solutionize and then we quench the alloy. So you know after quenching what happens that we are aging at a lower temperature. So in such alloy systems the second phase in solid solution at elevated temperatures. So you know this condition comes because the second phase solubility will be higher at higher temperature, but once you go to the lower temperature, it is solubility is decreased.

Now when we do the aging further at you know somewhat lower temperature then there is precipitation. So for precipitation hardening the second phase must be soluble at elevated temperature, but must exhibit decreasing solubility with the decreasing temperature. So the thing is that in this case that should be the condition. Now if you know, so that is why what happens that when you are quenching at a fast rate or you are, you know making you know the second phase get trapped into the solidified structure.

And then further you are when you are aging in that case the precipitates start coming up. So basically you have you know parallely you have also dispersant strengthened you know mechanism dispersion strengthening where basically the condition is that even at the elevated temperature they are having very limited solubility.

So but in this case you should have good solubility at elevated temperature, but the solubility is low at the lower temperature. So that is the difference between these 2 systems.

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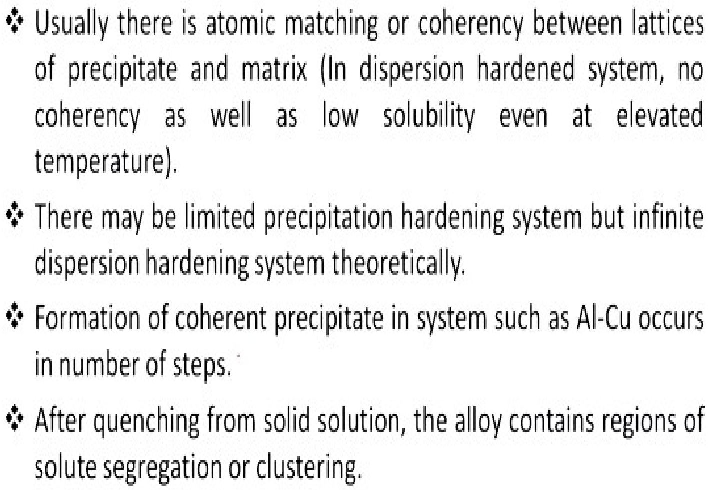

- Usually there is atomic matching or coherency between lattices of precipitate and matrix (In dispersion hardened system, no coherency as well as low solubility even at elevated temperature).
- There may be limited precipitation hardening system but infinite dispersion hardening system theoretically.
- Formation of coherent precipitate in system such as Al-Cu occurs in number of steps.
- After quenching from solid solution, the alloy contains regions of solute segregation or clustering.

So usually there is atomic matching or coherency between lattices of precipitated matrix. So that is again there is some difference between the dispersal hardened and the you know precipitation hardened material. In this case you will have the coherency between the lattices of precipitate and the matrix and in that case there will not be coherency and also as we discussed that you know there will be in dispersion hardening system there will be very low solubility even at higher temperature.

So you are basically having the powders of different materials and then ultimately you are you know fusing them together and applying pressure and all that, so that is what is happening they, basically they are the distinct phases and then you are basically getting the required properties by doing the processing.

So what happens the basic difference between the precipitation hardening system and the dispersion hardening system is that as we have understood that in the case of precipitation hardening system you must have this property that when your temperature is higher the solute has to be more soluble and the solubility has to decrease as the temperature comes down whereas there is no such condition in the case of dispersion hardening.

And also we discussed that there is coherency also, coherency has to be there. So if you talk theoretically you may have infinite number of dispersion hardening system because there is no such you know condition you can have any material their powders are to be used and they are to be dispersion hardened, you know so that matrix is to be made. So that is dispersion hardened matrix, say dispersion hardened.

But in the case of precipitation hardening system certainly you have some limitation on the number of such systems because that condition has to be met. So one of the very you know example which is live example will be the aluminium copper system we have studied about the aluminium copper phase diagram also where we have seen that you know for a certain copper percentage.

And you know I mean solubility of copper will be up to certain percent around 5, if you increase the temperature and if you decrease the temperature that decreases to a very low value. So in such cases you know you have the formation of coherent precipitate in the system such as so in that case of aluminum copper system. So what happens that when you quench from the solid solution the alloy contains reasons of solid segregation or clustering.

So basically what happens that when you are quenching the solid solution and then you will have further ageing, so you will have different stages in which these precipitates are formed and basically one of the very renowned scientist has worked in this direction.

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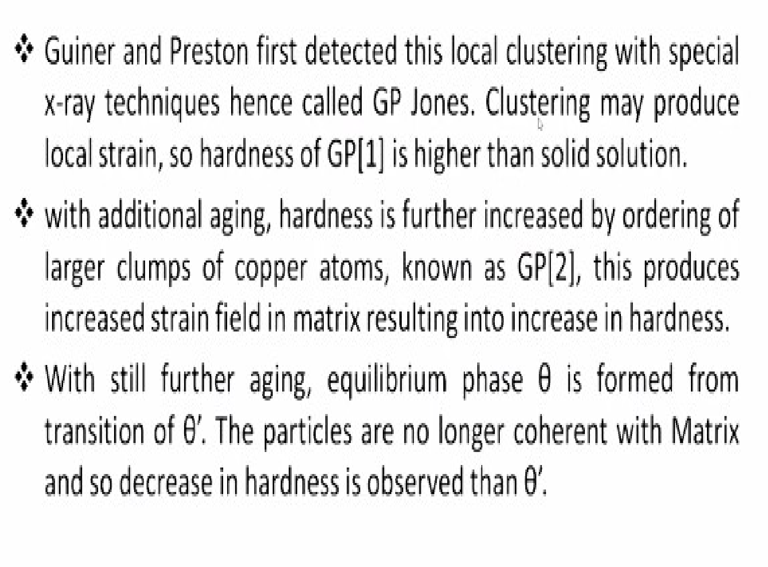

- Guiner and Preston first detected this local clustering with special x-ray techniques hence called GP Jones. Clustering may produce local strain, so hardness of GP[1] is higher than solid solution.
- with additional aging, hardness is further increased by ordering of larger clumps of copper atoms, known as GP[2], this produces increased strain field in matrix resulting into increase in hardness.
- With still further aging, equilibrium phase θ is formed from transition of θ'. The particles are no longer coherent with Matrix and so decrease in hardness is observed than θ'.

And he has seen the you know the variation of yield stress with ageing time. So what he saw so that is Guiner and Preston that is known as GP. So that is GP zones, in fact this has to be Z. So GP you know that zone has to be there.

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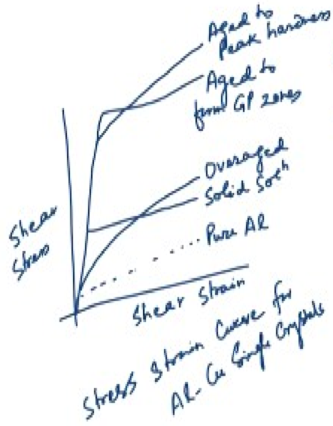

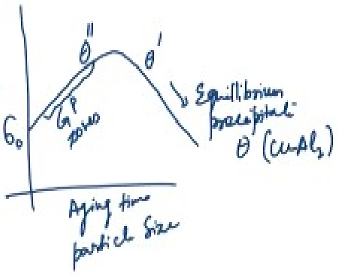

So what you can see that when he you know did for this aluminium copper system then what he saw that when you know this was with ageing time and particle size with ageing time and particle size, so it was seen that how you know the yield stress is varying and he found certain you know curve. So what he saw that you have you know he quenched from the solid solution and it was found that there is you know reason of solute segregation.

So then what he saw that this clustering basically initial clustering was seen and that basically you know that clustering produces local strain and in that case so what he has found the zones so that is why this is known as GP zones, now in that basically he has come to different stages so initially he found this θ''phase that is GP[1] zone and then you have the θ'zone that is GP[2] zone.

And then finally he got the equilibrium you know precipitate so towards the end he is getting the equilibrium precipitate that is theta. So that is $CuAl_2$, so this is theta is nothing but $CuAl_2$, now what is seen that in this case so this is your σnot and this way there is the variation of this σ not, it goes from sigma not to θ'' and then from there it goes to θ'.

And then further it comes to the you know the equilibrium phase that is theta. Now you know this coherency which is there so after if you age for larger time then what happens that the particle size goes on increasing and then you know after certain stage you have this coherency is basically lost. So basically that was the observation and then this is known as the over aged condition.

So in the case of overage condition the property you know basically deteriorates. So hardness of GP[1] will be higher than the solid solution that is the first zone, θ''. Now if you do further aging then hardness is further increased by ordering of these larger clumps of copper atoms and this produces increased strain fill in the matrix resulting to increase in hardness.

So you have θ' stage coming and then if you do the further aging then equilibrium phase $\theta$is formed from the transition of θ'so that is what you are getting the $CuAl_2$ phase and this is no longer coherent you know with the matrix and so there will be a decrease in hardness that is observed. So if you know if you look at the variation in the mechanical properties then such type of variation was seen.

Now if you draw the stress-strain curve for this aluminium copper you know a single crystal so this was the stress-strain curve for aluminium copper single crystal. So that experimental results have indicated that when you have a pure aluminium you know this goes like so this way it goes, so this is the you know so this is your shear stress and this is shear strain. So what is seen that so for the pure aluminium this is the curve.

And for the different you know aging so if you go for aging and you have different conditions so what is seen is that for the if you go to you know peak hardness, the peak hardness line goes like this and for the you know when the formation of the GP zones and then in that case it goes like that and if you are doing the over aging then it has you know curve like this and in the solid solution you have such is the shear stress strain diagram.

So this is for the aging to peak hardness and this is for the aging to form GP zones and this will be for the you know over aged condition and this line will be basically once you are coming here and this is so this is for the solid solution and this line is for pure aluminium. Now in these curves basically we are interested basically how this stress strain diagram looks like especially you know this reason that is this reason when we are looking at the increase in these stress values that reason is basically the reason of strain hardening.

So what we see that the strain hardening rate basically so this is smaller in this case and it is quite high in the case of overaged solid solution, over aged condition. Now in the case of solid solution also it is quite flat and when you are having the aging to form GP zones certainly you are getting quite high yield stress value yielding is occurring at this point and then you have you know this is the strain hardening rate.

And if you go to peak hardness in that case you know what you see that this is the maximum what you see the strain hardening rate is basically it is of continuously increasing. So basically this is for the shear stress and shear strain curve for the aluminium copper single crystal and it shows how there is difference you know in that property once you age you know once you are going to aging for forming the GP zones or to peak hardness or to overage you know conditions.

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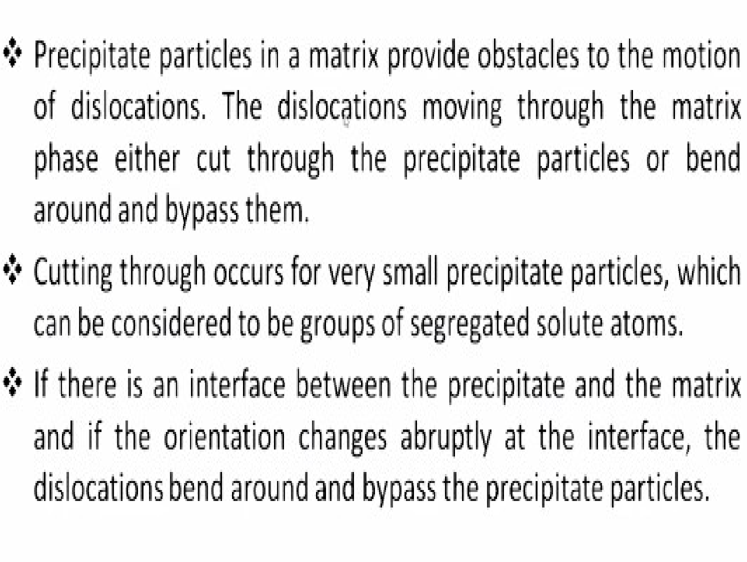

❖ Precipitate particles in a matrix provide obstacles to the motion of dislocations. The dislocations moving through the matrix phase either cut through the precipitate particles or bend around and bypass them.

❖ Cutting through occurs for very small precipitate particles, which can be considered to be groups of segregated solute atoms.

❖ If there is an interface between the precipitate and the matrix and if the orientation changes abruptly at the interface, the dislocations bend around and bypass the precipitate particles.

So precipitate particles in a matrix that is providing the obstacles to the motion of dislocations now these dislocations moving through the matrix phase either cut through the precipitate particle or bend around and bypass them. Basically when there is formation of precipitate particles then either they have to cut them or they have to bend and bypass them.

So cutting through occurs for very small precipitate particles which can be considered to be groups of segregated solute atoms. So in those cases it can cut through it and if there is interface between the precipitate and the matrix and if the orientation changes abruptly at the interface in that case the dislocations bend around and bypass the interface particles. So there are 2 situations either they are going to you know cut through it or they are going to bypass.

So these are the 2 mechanisms by which the dislocation so these dislocation lines when they are moving they are having the obstruction and this way once you have the obstruction of the movement to dislocation lines it means you have basically the strengthening developed, so that is a mechanism of you know the development of strength in the case of precipitation hardening system.

Now we are coming to the another kind of you know strengthening mechanism that is martensite strengthening. So now in fact before that we must have the understanding about this you know graph where you have the you know different type of properties we are looking into. Now in this case when the you know copper is in supersaturated solution in that case the yield stress is increased significantly as compared to these pure aluminium.

So if you look at this graph this is pure aluminium curve and when there is solid solution then what you see that the yield stress has increased from this value to this value. So there is significant increase in the you know yield stress value and you know but the rate of strain hardening is basically low. So that is you know the characteristic of easy glide or easy slip and in this case the slip bands are quite wide, broad and widely spaced.

Now if you go to the GP zone formation when is to form these GP zones, now in this case the yield stress if you look at this is the one where this is the form for the easy to form GP zones. Now in this case what you see that your yield stress has increased significantly, it has reached to this point and then there is yield drop is observed. So from here it is basically there is some drop and then it is coming.

So you find the yield drop and also what you see that this you know this is strain hardening rate is quite small in this case. It is not very high. So this suggest that the dislocations are cut through these zones, so we discussed that when the dislocations are cutting through so in these cases basically that is likely to happen and that's why you know they are cutting the zones and so because once that stress reaches high enough value then they are basically cut.

So that way you have the low strain hardening you know rate. Now if you are basically aging to the peak hardness in this case you are getting the peak hardness. Now in this case you know there will be you know a small decrease so as compared to this there will be small decrease in the yield strength, but there is large increase in the rate of strain hardening, so that is what is seen in this case.

And in this case slip lines were found to be very sort and distinct. So that you know this suggests that dislocation are no longer now they are cutting through okay and they are basically this is the indicative of the situation where dislocations tend to bypass and have a bend type of movement in such cases. So that is what you know the situation look like in that case.

Now comes the situation where you are doing the further aging and then you are coming to the overaged condition. Now in the case of overaged condition this graph goes like this. So what you see that again your strain hardening rate is high, you know, but the particles become noncoherent and the particles become basically rather coarse. So what you see that these yield strength is low but strain hardening rate is very high.

And in this case the dislocation basically will be accumulate entangles around the particles you know in the process of passing between them. So in that case they promote the slip on secondary slip systems. So you know continuously the hardness goes on increasing and you see a good rate of you know increasing the rate of strain hardening.

So that is how you know that tells that how you know with the different aging time you know the different type of strengthening can be achieved and that is what is suggested from this you know graph. So next will be so we were discussing about the martensite strengthening.

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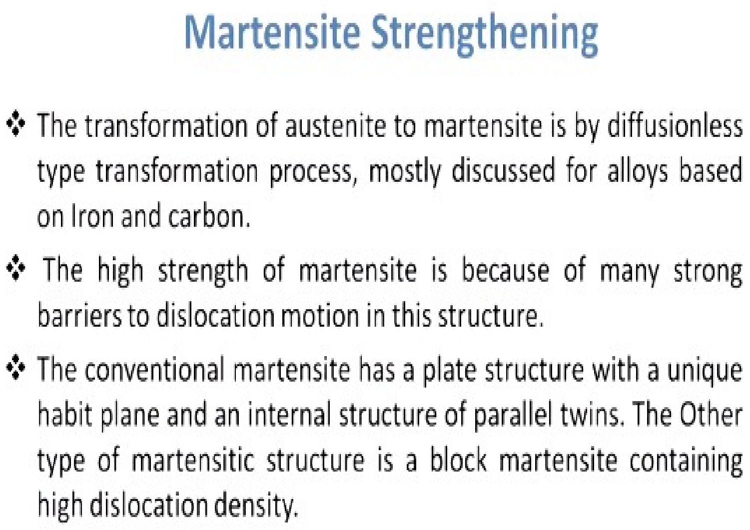

Martensite Strengthening

- The transformation of austenite to martensite is by diffusionless type transformation process, mostly discussed for alloys based on Iron and carbon.
- The high strength of martensite is because of many strong barriers to dislocation motion in this structure.
- The conventional martensite has a plate structure with a unique habit plane and an internal structure of parallel twins. The Other type of martensitic structure is a block martensite containing high dislocation density.

And we know very much about the term martensite whenever martensite word comes into we know that we are talking about a very extremely hard phase. So it is basically you know for many systems this martensite phase, martensitic transformation you know is dealt with, but mostly it is discussed for alloy based on iron and carbon. So basically the transformation of austenite to martensite it is a diffusion less type of transformation process.

And in this case the high strength of martensite is basically because of many strong barriers to dislocation motion in this structure. So you know what happens that you know the conventional martensite, so the thing is that as we know if you recall the iron carbon diagram, So in that case you have these structure will be.

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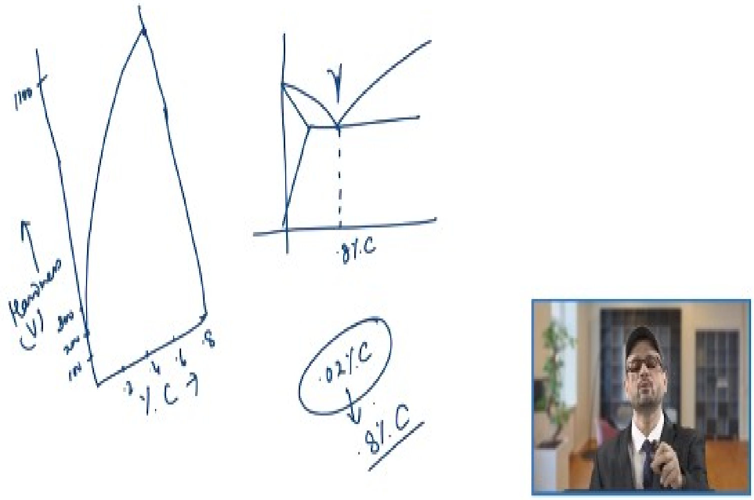

So you have lower critical temperature, so as we know that this is you know 0.8% of carbon is there. So the thing is that at this point the austenite which is there, this will be converting to ferrite and cementite. Now the thing is that if you are cooling at a fast rate then this austenite has the chance to transform to martensite about that also we have discussed a little bit. Now we know that this is basically diffusionless type of transformation where shear is occurring and you are getting you know.

So there is large, I mean, we have again to talk about how there is interaction and how there is dislocation coming into picture dislocation lines and that way you know the hardness is going to increase. So this austenite is converted to martensite. So if you talked about you know the conventional martensite, so basically you have 2 types of you know structures that is plate type of structure and block type of structure.

So conventional martensite has a plate structure with a unique habit plane and internal structure of parallel twins, so you will have you know the parallel twins which can be seen and other type of martensite structure is a block martensite which is containing very high, the dislocation density. So basically what you see is that you have you know, so in this case when you have the you know twins.

So when you are parallel twins basically they are about 0.1 micron meter thick within the plates so they are very you know so that is the dimension of that and then you know this block martensite so they are containing a very high value of you know dislocation density may be of the order of 10^9 to 10^{10} per meter square. So per mm^2 in fact.

So that is a very high value of dislocation density and that is corresponding to a very highly deformed material where you know the dislocation density basically because with the change in the dislocation density that yield stress value will be changing. So that way this basically so these 2, one is the conventional martensite, another is you know because of the so very high you know dislocation density, so that is you have the block type of martensite.

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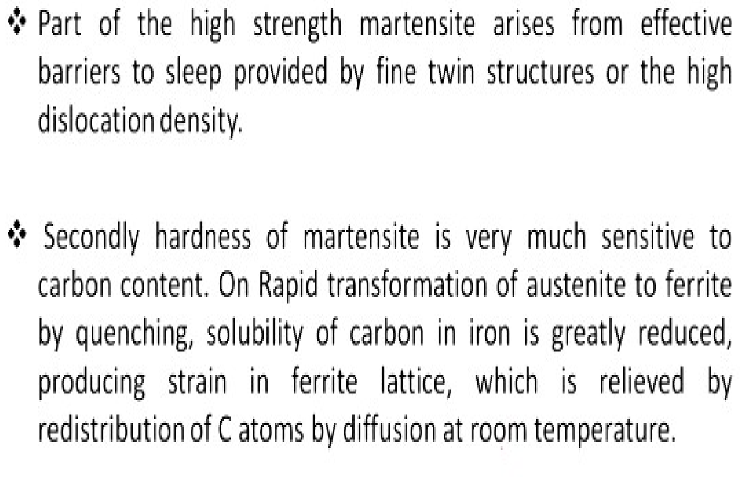

- Part of the high strength martensite arises from effective barriers to sleep provided by fine twin structures or the high dislocation density.
- Secondly hardness of martensite is very much sensitive to carbon content. On Rapid transformation of austenite to ferrite by quenching, solubility of carbon in iron is greatly reduced, producing strain in ferrite lattice, which is relieved by redistribution of C atoms by diffusion at room temperature.

Now the part of this high-strength martensite arises from effective barriers to sleep provided by the fine-tuned structures or the high dislocation density. So as we have seen that either you have the barriers to the slip that is, so barrier to that slip which is provided by the fine twin structures or you know high dislocation density, so that way you know your high strength is coming into.

And secondly the hardness of martensite is also very much sensitive to the carbon content so basically what happens that when we do the rapid transformation of austenite to martensite by quenching then solubility of carbon in iron is greatly reduced that will produce the strain in ferrite lattice which is relieved by redistribution of carbon atoms by diffusion at room temperature.

So if you look at the you know solubility if you look at the hardness of martensite with respect to carbon what you see that you know there is if it is more than you know 0.4% carbon then there is steep increase, even so the graph suggests. So if you look at the variation of you know the graph of hardness versus the carbon percentage. So this is hardness Vicker and if this is the percentage carbon.

And if you take say 0.2, 0.4, 0.6 and 0.8 so in that case if you, you know look at the martensitic structure which is quenched and if you say this is 100, 200, so that way, if the value is going. So if your value goes up to say you know 1100, now what is seen that in the case of you know when there is a change in the carbon content then the martensitic structure so that that has hardness you know increased and which has 200 Vickers at.

So say suppose 0% of carbon and it goes to about you know about the value of 10, 50 or so at you know 0.8% of you know carbon. So this way it goes like this. So basically you say so after this what you see that there is an increase, so with the increase in the carbon content the hardness is increasing. So this is basically that you know hardness or strength which is coming because of the steep increase.

So because you are you know you are quenching from austenite and transforming to martensite which otherwise you know in normal case there could have been 0.02% carbon, but then you are retaining 0.8% carbon, suppose so it is about 40 times you know. So about 40 times increase of the carbon concentration is there and because of that you have you know increased hardness and so you know once you are you know.

So as we discussed that when you are doing the rapid transformation of austenite to ferrite, so this carbon solubility will be greatly reduced as the temperatures will come down. So that will produce a strain in the ferrite lattice and then it will be relieved by the redistribution of carbon atoms by diffusion at you know the room temperature and so that there will be a strong binding. So that binding is set up between the you know dislocations and the carbon atoms and that you know binding.

So that will be you know that will basically restrict the movement of the dislocation and that way the strengthening is achieved. So ultimately you know what see that because of these you know interaction, because of the binding the movement of dislocation is hampered and you are you know strengthening is achieved. So this is about you know the martensite strengthening mechanism. We will talk about the other you know strengthening mechanism in our coming lectures. Thank you.