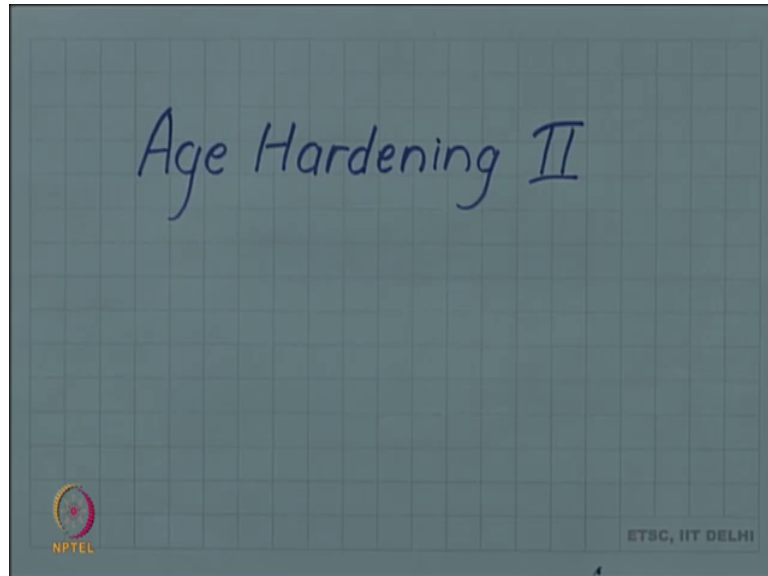


Introduction to Materials Science and Engineering
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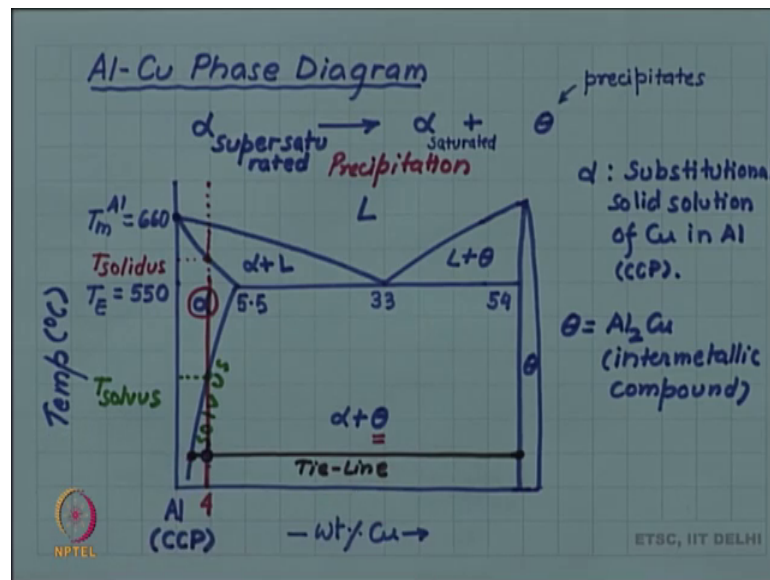
Lecture – 124
Age hardening II

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In the last video, we saw the process of Age hardening; how Wilm discovered age hardening in aluminium alloy. However, although, it was found that hardness is initially increasing and then subsequently decreasing, the reason for such increase or decrease in the hardness of aluminium alloy as a function of time after quenching was not known. So, let us now try but gradually with more discovery these regions were established and we will now discuss them.

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First of all look at the aluminium copper phase diagram; it is very important when discussing any alloy to look at its phase diagram. So, in an aluminium copper phase diagram, this left axis is the aluminium alloy, sorry, pure aluminium axis and the melting point of aluminium 660 degree Celsius is listed there, this is the temperature axis as you are now well familiar with a phase diagram.

Then the phase diagram has a eutectic reaction, this is the liquid phase, this is alpha which is the solid solution phase, aluminium is cubic close packed CCP. So, alpha is a solid solution substitutional solid solution of copper in aluminium, its structure will also be CCP, then you have liquid you will; obviously, have alpha plus liquid, this particular phase is theta which is an intermetallic compound; theta is Al_2Cu intermetallic compound, you can see by the formula that it has about one-third of copper. So, it is about 33 percent 33 atomic percent copper but since copper is heavier, it contributes more as weight percent, it is about 54 weight percent, this theta. So, you have liquid plus theta and alpha plus theta. So, this is the phase diagram of aluminium copper system.

Now, let us look at Wilm's alloy in this that was 4 percent. So, that is let us say this line represents this vertical line represents 4 weight percent copper. So, this is Wilm's alloy.

Now, you can see that in this alloy this is the solidus temperature and if I heat above solidus, liquid phase will form. In a heat treatment process usually the heat treatment is done for a shaped object in which we are trying to enhance the property. So, we will not

like it to melt. So, we will not like to go above the solidus temperature. Another critical temperature on this line is here where it hits this boundary; this boundary is called solvus. So, the corresponding temperature is called the solvus temperature; this temperature is the solvus temperature; this boundary is named solvus.

So, the idea for heating aluminium alloy is to take it into the single phase field alpha. So, you have to heat above solvus, but keep it below solidus. So, in this range you will form single phase solid solution alpha that is what you will like to subsequently quench.

Now, if this phase is cooled below the solvus, theta will start forming within alpha. So, alpha is already a solid phase is a solid CCP phase and in that a new phase the precipitate phase theta will form. So, and you can at any given temperature, you can find the composition of alpha in equilibrium with theta by using the Tie Line; let us say this is the tie line.

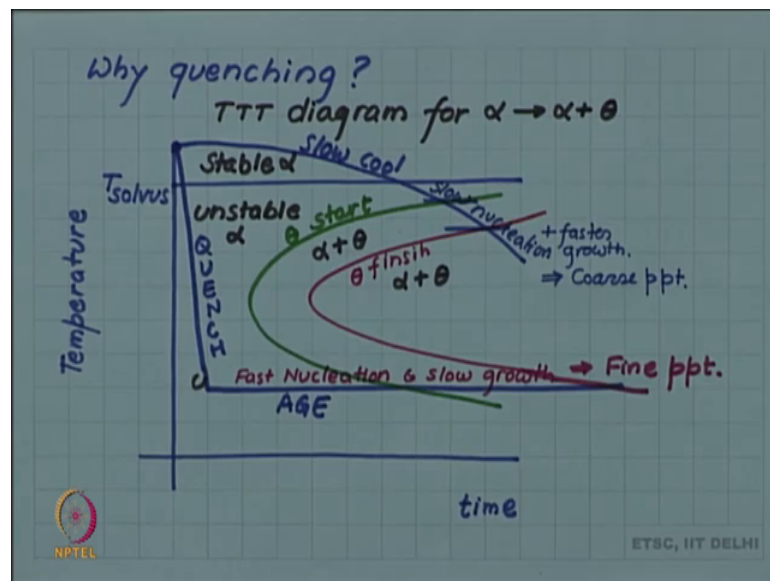
So, alpha if cooled below solvus will undergo this transformation to alpha plus theta, let me write that alpha undergoes a transformation to alpha plus theta, this alpha we will call a supersaturated alpha. Why? Suppose we have 4 percent copper and we brought it at this temperature, then at this temperature 4 percent alpha is having a very high concentration than the saturated alpha which is given by the solvus line.

So, this is a supersaturated alpha, this will give you a saturated alpha plus theta; theta in this case will be called precipitates. So, this is a solid state precipitation just like when you mix two liquid and if a solid comes out that is called precipitation. Here a single solid phase decomposes and gives you another new phase which is called the precipitate theta and the original phase adjust this composition and comes from supersaturated to saturated.

So, if we suddenly quench; if we suddenly quench the alpha phase to this temperature of the tie line, then initially the concentration will be 4 per weight percent, then, but the equilibrium concentration is much less than that let us say 0.58 percent. So, the extra copper in the alpha phase will start coming out of the matrix and that extra copper will concentrate in regions which will form theta. So, this is the so called precipitation reaction or a precipitation transformation.

So, when Wilm was heating his alloy and holding it, his whole temperature should be between solvus and solidus to form alpha and time should be long enough such that complete alpha forms. Then he when he quenches it, the temperature should be below solvus such that now alpha is unstable single phase alpha is unstable. So then, it gives you a new precipitation reaction and that is what is happening during the precipitation age hardening. So, these precipitates; these precipitates which are forming create an obstacle to dislocation motion and creates hardening.

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But why do we need to quench even if we slow cool? Even if we slow cool alpha theta will form in equilibrium, why do we need to quench? So let us look at the reason for quenching. So, now, we look at it instead of the phase diagram we look at the TTT diagram. So, this is this is the TTT diagram for the precipitation reaction. So, above solvus you can see above solvus alpha phase is stable.

So, nothing will happen to alpha phase. So, above solvus; you have a stable alpha, below solvus you will have unstable alpha which will like to decompose and form theta. So, the green curve gives you start of theta and the red curve gives you finish of theta. So, in between you will have alpha plus theta finally, also you will have alpha plus theta, but the amount of theta will keep increasing.

Now, in this diagram, even if we slow cool, even if we cool gradually and slowly. Suppose we have formed we have gone above solvus and we have formed a stable alpha

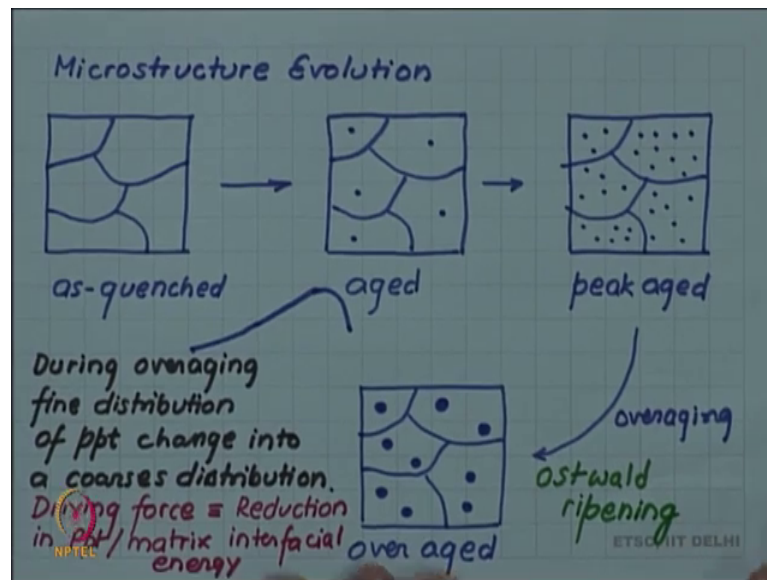
and then we are cooling that is stable alpha slowly, I will get alpha plus theta, I will still get the precipitate and if precipitates are supposed to be obstacle to dislocation motion, I have already created that obstacle and I should get hardening.

However, what Wilm is actually doing is to is to quench and then allow the transformation to happen. Why do we need to quench? Quench and then Age that is Wilm's procedure instead of gradually cooled. This is because you can see that during equilibrium cooling during slow cooling the temperature of transformation is much higher whereas, on quenching and then aging temperature of the transformation is much lower and recall that at lower temperature, you have faster nucleation and slower growth.

So, let us write that fast nucleation and slow growth whereas, at the higher temperature you will have slow nucleation and faster growth. So, you can now tell which will give you a fine structure and a course structure. Faster nucleation more nucleation centres and growing slowly still giving more time for more nucleation to form. So, there will be several nuclei forming here and each of them will grow to a limited extent.

So, this will give you a fine distribution of precipitate, the resulting distribution will be fine precipitates, whereas, here the resulting distribution will be course precipitate and it is the final precipitate fine distribution of precipitate always create more obstacle to dislocation motion than course precipitate. So, this will give you although both will give you the precipitate but quench and aging will give you finer precipitate and greater obstacle to the dislocation motion and thus higher hardness. So, this is the reason why we quench.

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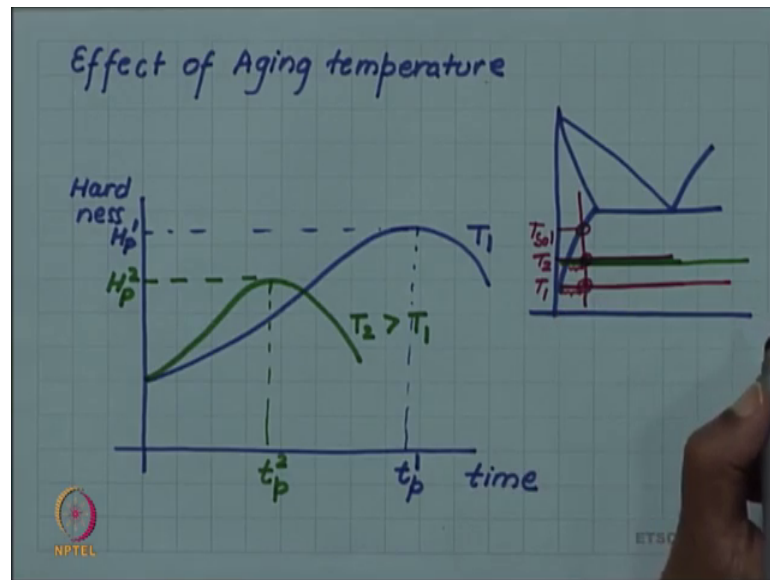
Let us look at pictorially the evolution of the microstructure. So, in as-quenched as soon as you quenched it, you have a single phase alpha no precipitate has formed. So, you have a single phase alpha but then as you age alpha precipitate will start forming. As aging continues, you will have more precipitates forming. So, you have a larger number density of precipitates in the peak age condition. So, there is each you can think of each precipitate as an obstacle centre for dislocation motion so; obviously, there will be more hindrance for a dislocation to be moving in the peak aged condition than in conditions before the peak aging.

But then so, hardness was increasing; you can see that in as-quenched, there was no precipitate, then in aging hardness increased and in peak age hardness has now reached a very high value. But then why after peak aging the hardness starts coming down as in our hard hardness versus time curve. So, during over aging, what happens? So, what really happens during overaging is that these fine precipitate distribution start transforming into a coarser precipitate distribution. And why so? The reason for course precipitate.

So, let us write that during overaging fine distribution of precipitates change into courses distribution. What is the driving force for such a change? The driving force for such a change is the precipitate matrix interfacial energy. Notice that if the same volume is distributed into finer particles, it will have larger interfacial energy and if it is distributed as coarser particle it will have a smaller area and a smaller interfacial energy because you

can think of fine distribution as being generated from a coarse distribution by breaking each of the coarser particle into finer particles and as you break the coarser particle into finer particle, you are generating new surface and correspondingly new surface energy. So, the driving force for this is reduction in precipitate matrix interfacial energy.

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So, now more or less we have seen the explanation for the aging curve. Initially as more and more precipitates form, more and more obstacle to dislocation motion is there. Finally, when all the precipitates have formed we have a fine distribution of precipitate fine and numerous precipitates are there.

So, we reach a peak hardness but beyond peak hardness to reduce the interfacial energy particles start to merge together and become larger particle which is called sometimes this process is called ripening. So, we should give that name this is also called Ostwald ripening and there will be a decrease in the hardness.

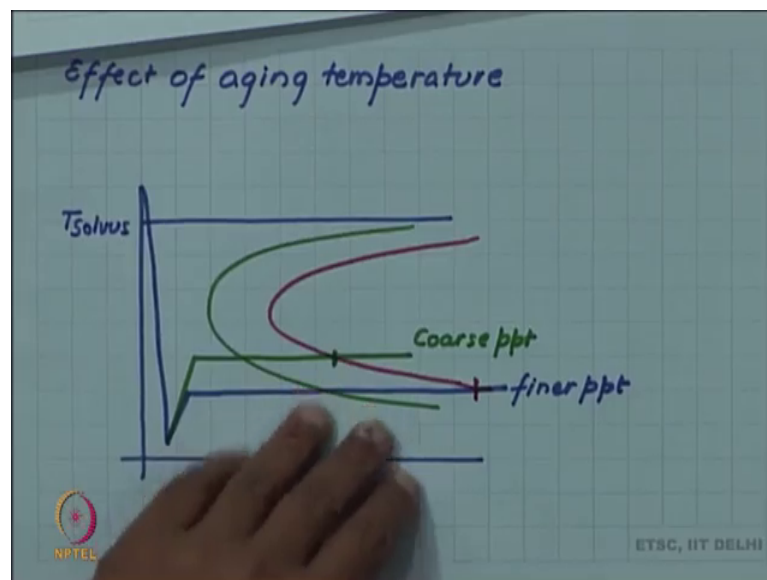
Now, let us look at what is the effect of aging temperature. So, let us say that this blue curve is at some aging temperature because you can do the aging at different temperatures. Remember I can draw the phase diagram for you again. So, you are below the solvus temperature an aging has to be done below the solvus temperature but you can choose different aging temperatures. So, I can choose a temperature T_1 or I can choose a temperature T_2 at which i is my alloy. Suppose I did the aging at temperature T_1 and

got this curve, what will be the effect on the aging curve if I age at a higher temperature? If I age at a higher temperature what do we get?

So, let us look at that. So, let us call this T_2 temperature the higher temperature. If I age at higher temperature you will find that you are reaching a peak hardness at a shorter time, I have T_2 greater than T_1 peak hardness is reached in a shorter time. But at the same time the value of peak hardness has also reduced. So, H_{p2} is less than H_{p1} , the time to achieve this hardness t_{p2} is also less than time to achieve the hardness at a lower temperature t_{p1} .

Now, why does the hardness decrease and the time also decrease? First of all you can see that at the higher aging temperature for the same time in the same two phase field, if I draw tie lines at higher temperature you have a smaller amount of precipitate forming. So, the amount of precipitate the total amount of precipitate will reduce, but more importantly the answer comes from again the TTT diagram because if you look at the phase diagram, where you look at the TTT diagram.

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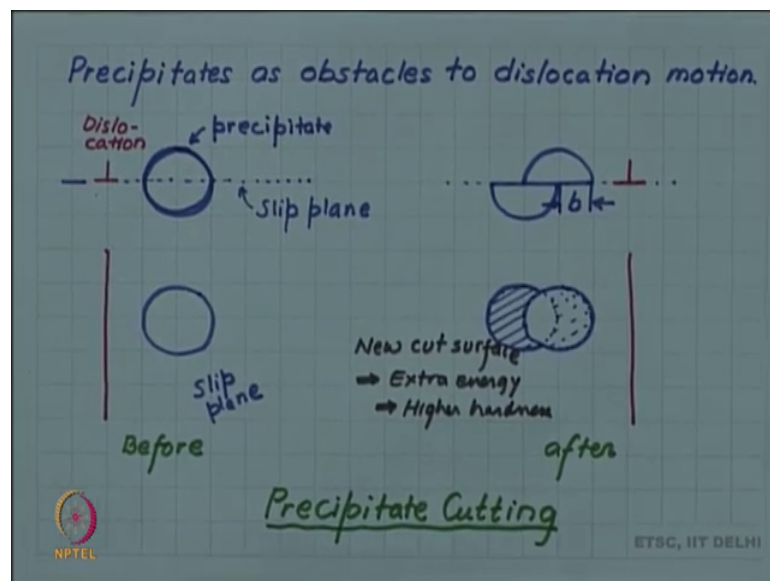


So, suppose you quench and then you aged at this temperature or you aged at a higher temperature. We have already seen that at the higher temperature, you will have coarser precipitate because of slower nucleation and faster growth whereas at a lower temperature you have finer precipitate. So, this fine precipitate will give you a higher hardness.

So, at lower temperature, you will have higher hardness but the time for completion you are seeing that the time for completion is more at the lower temperature than at the higher temperature. So, you will achieve lower hardness at higher temperature but you will achieve it in a shorter time. So, you can see that even designing the precipitation hardening sequence you have to take care of both these both these variables. If you if you go to higher temperature you will get a hardness in a very quick time but then the hardness value will be lower.

And if you try to achieve too much hardness, then you will have to do it at a much lower temperature where the time for hardness achievement will be much larger. So, you can optimize the two parameters and so that you have a reasonable hardness in a reasonable time.

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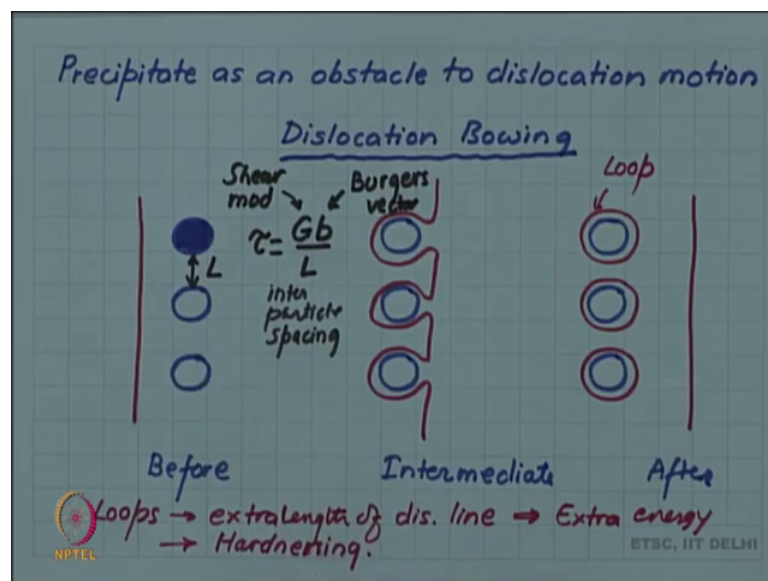
Now, let us look at the actual mechanism by which dislocation is obstructed due to precipitate. So, there are two mechanisms by which when a precipitate obstructs dislocation, the first one we are considering is what is called Precipitate Cutting. Let us imagine that we have a precipitate particle this is the precipitate particle and this precipitate particle is sitting on this slip plane on which this dislocation line is moving. So, this is an elevation view and below I have a plan view. So, you are looking down the slip plane you are looking down the slip plane on this and you are looking the slip plane age on here. So, here this whole thing is a slip plane and here the slip plane is age on.

So, suppose a dislocation line is now gradually approaching the precipitate as it is moving on its slip plane. If the precipitate is small and if the precipitate is coherent which means that the slip plane is continuous through the precipitate, then the dislocation line can simply move through the precipitate and come out. But then recall that if a dislocation line moves through any region one part of the crystal one side of the slip plane slips with respect to the other side by a Burgers vector.

So, a Burgers vector slip will be there this will be equal to the Burgers vector due to the movement of dislocation. So, this you can see that since the upper half has shifted with respect to the lower half, the upper half of the precipitate will also shift with respect to the lower half of the precipitate. So, it is as if slicing an apple in the middle and then sliding two halves of the apple.

In this cutting process, you can see from the plan view here that you will expose new surface area of the cut precipitate and this new surface area is associated with extra energy. So, extra energy is required to create new surface area and this will demand extra force for the dislocation to move. So, new cut surface implies extra energy which means higher hardening. This happens in the initial part of the precipitation hardening when precipitates are fine and coherent.

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When the precipitates have become much larger towards the later part of the hardening and during over aging, the precipitates become too large to be cut; so, it is not easy to cut

these precipitates, but the spacing between them is large enough recall that by Ostwald ripening, the spacing is becoming larger and larger. So, a spacing between them become large enough such that the dislocation can bow between them.

So, this is called Dislocation Bowing. So, we have shown a sequence of picture here. So, these are the precipitates and a dislocation line is coming we are looking down the slip plane. So, the dislocation line is moving in its slip plane. Because it is not able to cut through the precipitates, it will start bowing around the precipitate like this and you can see as it is bowing around the precipitate. On the other side of the precipitate two ends of the dislocation two ends of this loop will start coming close together and they are of opposite sign.

So, when they come close together finally, they will join and form a loop. A process is very similar, is reminiscent. You can remember of the process which we talked about in Frank Reid source.

So, it is something like the Frank Reid source there the dislocation was pinned and was bowing between the bowing between the precipitates. Here the dislocation the pinning is being done in a sense by the precipitate. But finally, when the dislocation most a crosses the precipitate and moves out, it will leave loops of dislocation loop around the precipitate particle.

Now, so, in a sense the length of the dislocation line the overall dislocation line has increased. So, these loops are extra lengths of dislocation line which requires extra energy you know that, but there is per unit length of line there is a energy $\frac{1}{2} \mu b^2$ which again leads to difficulty in the dislocation motion and hence hardness. So, these are two basic mechanism by which the precipitate cause increase in the hardness of the material.

Here we can also relate if the inter particle spacing. If the inter particle spacing is L , then we have a similar formula to what we had in the Frank Reed source that the shear stress required to move the dislocation through the precipitate particles is $G b / L$, where G is the shear modulus, b is the Burgers vector and L is the inter particle spacing.

So, this formula also can explain the decrease in hardness during over aging, has the particles become coarser and lesser in number their inter particle spacing starts

increasing. You can see from this microstructure here, if the same volume is distributed into smaller number of coarse particle the inter particle spacing is much more than the inter particle spacing in case of fine distribution. So, as L increases the stress required to move the dislocation will come down and you will have the decrease in the hardness during over aging.