metals 27 03 third cut

Here is where you have GP zones, and here is where you have Theta second and then Theta prime. Notice what happens in here, so the formation of GP zones, these are meant to be, right, essentially the aging time is in days, so this is in the first step, you keep the temperature constant, and you just keep it for one day, ten days, one hundred days, and you see what happens, you measure the hardness in this flow. So notice what happens in here.

Here we have the formation of GP zones, and this is always increasing, already increasing the hardness of the initial alloy. This depends on the composition, each cup is referred to a different cup composition. For a 4.5% cup here, you see that we go from 80 to almost 110 liters.

Then when we start precipitating Theta second, we get even higher hardness. We reach a maximum point here after a certain aging time, more or less 80 days, 70 days, something like that. And then here notice we start forming Theta prime, and you can see, I mean the curve stops here, but essentially you can notice that the beaker hardness starts decreasing.

Similarly for the other cloth. If the content of copper is too slow, the behavior of the hardness beakers is overall much less, but in general you see that there is a maximum, an optimal, that is somewhere in between, essentially when you have the precipitation of Theta second, and when you start having the precipitation of Theta prime. Similarly here, where we change the aging temperature, and in this case essentially notice that we are skipping the formation of GP zones here, because we are at a higher temperature.

So it just is very limited, you see in this case in reality, somewhat you might form some minor amounts of GP zones, but very minor. But again you have a maximum of the hardness, which is lower however than what you can get in there, and the maximum typically corresponds to essentially when you have this transition from Theta second to Theta prime. So the reasons for this are complex, because the effects, what happens at the microscopic level here, are several effects which justify the increase in hardness that we observe here.

There is always for example a solid solution hardening. It is already there after quenching. Solid solution hardening is typical essentially of all alloys.

Whenever you put an impurity in a pure metal, this impurity will somehow create some strange field around the impurity, and this will slow down again the dislocation function. So this is essentially an effect that is always there since the beginning. In this picture we put together essentially the different effects, and as a function of time, just to show that there is a correspondence between the sequence of precipitation and the different effects that I can get.

The formation of GP zones, and meaning essentially the formation of coherent interfaces, has another hardening effect, another strengthening effect. And this is essentially what you get

here. So when you, in this part of the curve, the hardness essentially increases.

You start from here because of the solid solution effect. Then you start hardening your material because of the formation of coherent interfaces which are linked to GP zones. The formation of theta second essentially causes another increase in the hardness, essentially because of the so-called cutting stress.

So essentially theta, this theta second precipitate, again hinders the motion of the dislocation because this dislocation, to move inside the material, they should cut through, they should essentially cut in the middle, this theta second precipitate. And this is again something which is not preventing completely, but essentially making it harder for dislocations to move. And finally, when you start forming essentially theta prime and theta later on, you would still have another effect which is called Orwan stress, which is somewhat related when you have many precipitates in your material, your dislocation, they are somehow pinned, they are blocked in between some of these precipitates.

So, bottom line, essentially there are several contributions, several explanations for why you get an increase in the hardness of your material, but obviously the effect is clear, is evident. I mean, you can see that you double, in some cases even more than double, the hardness of the material. And this is essentially what the industry, aluminum industry, for this alloy that can be age-hardened essentially, uses to improve the strength of metal.

The top-notch essentially aluminum alloys, which are used for, let's say, aeronautical application, space application, nowadays even in bikes and cars, but anyway, they are the most expensive and most, with the better mechanical properties among the aluminum alloys, are the ones that have undergone an agement, an aging, sorry, treatment, like something that you see here. Notice that, okay, you have to play the optimal industrial treatment, they are typically, many of them are still somehow industrial secret, because they are specific for more complex alloys than the one, the aluminum copper that you see here. The principles are what we're discussing here, but somehow some of these heat treatments are, again, tailored for a very specific complex alloy composition, and they are kept more or less secret.

They are the optimal combination of aging time, essentially in time, so all the steps are carefully crafted to optimize the entire process. This is also because, of course, you want somehow to do your treatment in the shortest amount of time, because, again, if your treatment takes one week or two weeks for the industry, it may be the cost of the production. Let me just very quickly, and then I will make a short break, so let me just conclude this, essentially, telling you that, okay, we can somehow, there are different factors that can be taken into account to tailor precisely this heat treatment.

The temperature in between the two solvents is at one point, which is, of course, modified by the composition of the alloy. Okay, this is something that I already essentially mentioned, so GP zones, essentially, if the aging treatment is done, evolved, the surface temperature of the GP zones, with solvus zones, do not appear, or they might dissolve if, for some reason, you had it

already in your material. In some cases, there are some heat treatments in which the first step is done in more stages to optimize the process, to make it faster.

Okay, so there might be a first step, a low temperature, where you have a high nucleation frequency, but low growth rate, and then you go to higher temperature to essentially improve the growth rate and to shorten the overall time of the heat treatment. One important point that I will mention, essentially, very quickly, is this risk, which is connected to this precipitation treatment, with this age hardening. The point is that you can have, at grain boundaries, you can have, essentially, what are called precipitation-free zones.

So if you look at the microscope, after the aging treatment, some of these aluminum alloys, you see an example here, with zinc and magnesium and copper, so you see that there are precipitates all around, bigger and smaller precipitates, but somehow this wider region here is depleted of precipitates. Okay, there are some bigger precipitates, but there are not the fine precipitates in here that are typically the best to enhance, essentially, the mechanical problems. This is another picture where you see the effect again.

You see this was a grain boundary. You see a lot of precipitates in here and there, but in the region in between, no precipitates. This is a problem because, as you notice, hardness and strength are connected to the presence of this precipitation.

So when you have a zone inside your material where there are no precipitates, this is a weak spot in your material, which can cause, essentially, failure. So you have somehow to prevent that, and here I do not want to go into detail because we are running out of time, essentially, but this is something which is related to the presence of vacancies, again, of excess vacancies, which typically concentrate on the grain boundary and they essentially prevent the formation of the right precipitate that you want. And there are some ways to reduce, essentially, the presence of excess vacancies that you can see here.

For example, one way would be to quench even faster your material. Okay, for example, this is a concentration profile of vacancies across this here is the position of the grain boundary. Here is the distance.

It could be the vertical, essentially, axis in this plot here in this microstructure. And if you do a slow quench, you get, essentially, more vacancies at the grain boundaries here. But if you do a faster quench, you see that the vacancies, the depletion, essentially, the zone where you have more vacancies, is much smaller than in the case of a slow quench.

Of course, you can also do some other possibility to somehow prevent the formation of this precipitate in the free zones. Okay, that was all for aluminum alloys. So for age hardening in particular in aluminum alloys, keep in mind, okay, this is mostly applied to aluminum alloys, but not only to this type of alloy.

This is somewhat a more general type of aluminum. Any questions? Okay, then I suggest we do

a 10-minute break, and we'll continue with the next topic later. Thank you very much.

in somewhat more detail. We'll start with a eutectoid phase transformation. As you've seen here, then we'll discuss massive spinodal decomposition and finally ordering.

Eutectoid is, as you hopefully know already, is essentially the transformation of a solid phase into two new different solid phases. If you look at the phase diagram, this is just an example of a possible phase diagram where you have a eutectoid phase transformation here. Essentially, at this point, for this specific composition, you go from a high temperature where you have only the alpha phase, you are in a single phase region, so you have alpha gamma here, and if you cool down your system, when you cross this temperature here, below this temperature, you enter the region of the phase diagram where you have both alpha and beta phases.

So basically, the reaction that happens here that corresponds to the eutectoid transformation is gamma, solid phase, that transforms into alpha plus beta, alpha and beta, two different phases. This typically happens via nucleation and growth, so the theory that we already studied, that we know now, and the growth mechanism in particular is cooperative. So the formation of alpha and beta at the eutectoid point happens, essentially, is concurrent, essentially.

So it happens at the same time, and also the growth process of both phases is essentially related to each other. There are different examples of eutectoid phase transformations. Please do not confuse the eutectoid with the eutectic phase transformation, because they are different.

The eutectic starting phase is the liquid, and here they are all solid phases. I'm emphasizing this because it's obvious, but at the exam, I consider wrong, and it has happened, that if I ask a eutectoid transformation, and you talk about the eutectic, this is wrong, and I do not accept it as a coherent transformation. So please just be careful of that.

The most studied case of a eutectoid transformation is the transformation of austenite to perlite. Perlite, this is a particular name that we use to refer to, essentially, a microstructure in which we have two phases, alpha, perlite, BCC, and cementite, a carbon, essentially a carbide, of iron, which has the formula iron-free carbon. I'm pretty sure that you know already that cementite is a somewhat hard compound that precipitates.

Alpha, on the contrary, is a matrix which is somewhat softer. The combination of perlite and cementite typically gives your material some good properties. It depends, I mean, the whole steel, essentially, the plain carbon steels, essentially the whole mechanical properties, the major factor is, essentially, the relative quantity that we have of perlite and cementite.

If we have too much cementite, the steel becomes very hard. But brittle, if we have, essentially, too few cementites, the steel is very soft, but more, essentially, easy to work, and somehow it has different properties. Going back, essentially, what we are interested in here now is to understand a little bit more about the mechanism, how this perlite essentially forms.

So, typically, the nucleation of perlite happens at grain boundaries. The growth, once after nucleation, essentially the growth happens in a radial way. You see, essentially, here a sketch of a possible colony of perlite, in which you see also the typical microstructure of perlite.

The microstructure of perlite is essentially a series of alternating lamella layers, these layers are typically called lamella, that are alternating between ferrite and cementite. So one layer is cementite, the next is ferrite, and so on and so forth. Here you see a real picture of a microstructure, a perlitic microstructure.

You see again the alternating layer of alpha and cementite. Cementite are the darker, essentially, layers that you see in this picture. Depending, of course, on the angle of cooling, so how low we go in temperature, we can have a different number of nuclei forming, we have learned that from the nucleation and growth theory, and also growth can be faster or slower.

So the final microstructure that we see here depends also, again, on the heat treatment that you apply. Basically, how fast you cool, how low in temperature you go, at which temperature you might keep your material for how long, and so on and so forth. Keep in mind that since saturation happens here at grain boundaries, if nucleation is very fast, at a certain point, you might not have any more grain boundaries where you can nucleate perlite.

So there can be site saturation, essentially, here. Let's consider now more in detail how the nucleation and the growth of this perlite happens. So obviously, there are two cases here that are forming.

You can either nucleate ferrite first, and then cementite later, or the other way around. It doesn't matter too much because whatever is the first phase that forms, as I already told you, they all form at the grain boundaries. So the initial situation is essentially you have two grains of gamma, austenite, gamma 1 and gamma 2. Here is a sketch, essentially, of the grain boundary, and here is the first, essentially, nucleus of either ferrite or cementite.

Depending on which phase nucleates first, there are two interfaces that are typically formed. So on one side, you form a semi-coherent interface. On the other side, you form an incoherent interface.

We already discussed, essentially, which are the advantages of this layout in general, essentially, in earlier lectures. The semi-coherent interface has, remember, to have a better matching at the interface to form something coherent or semi-coherent, typically this happens only when some orientational relationships are satisfied. In particular, if you nucleate ferrite, the orientational relationships are what we already discussed.

There are two general concepts of orientational relationships. If we form, if we nucleate cementite, we have different orientational relationships, which are essentially these two there. I'm not expecting you to remember, of course, all the details of these orientational relationships, but it is important to remember that they exist, essentially, they are there.

The other side, again, is essentially incoherent. Now, how the process goes on after, essentially, we nucleate the first small particle, the first nucleus. So, imagine that if we nucleate, essentially, the first nucleus is cementite, just as an example, but is similar to the other case, essentially, we nucleate first alpha.

So, imagine that we nucleate first cementite in here. So, we have now a small nucleus of cementite that has formed there, in between gamma 1 and gamma 2 at the grain boundary, and, of course, forming a semi-coherent interface on one side and an incoherent interface on the other side. Since cementite is richer in carbon atoms than the surrounding matrix, what happens here is that in order to form a small nucleus, again, this is something that we have seen already, there must be, essentially, carbon atoms from the surrounding atoms that have jumped inside the nucleus.

So, this means, essentially, that the region around nearby, essentially, the first nucleus of cementite is depleted of carbon atoms. But the depletion of carbon atoms in these surroundings make it more favorable, make it, essentially, the environment more favorable for the nucleation of an alpha nucleus, because ferrite is actually very low in carbon content. So, the content of carbon in the ferrite phase is much lower than both cementite and gamma.

So, the fact is, essentially, what is promoting the alternating nucleation of, essentially, cementite and alpha. So, when I have nucleated cementite in here, nearby, it is very favorable to nucleate alpha and to get to a configuration which is something like that. In turn, the nucleation of alpha here and here has created here an excess, now, an excessive concentration of carbon, which favors the nucleation of cementite again.

So, you see, essentially, the nucleation here will proceed along the grain boundary, alternating basically alpha and cementite. At the same time, growth will happen, as we have discussed under time, the incoherent interface is essentially more mobile, is more easy to grow. So, growth will happen, essentially, on this direction, as shown in the scheme here.

So, it will, essentially, grow to the right in this picture. So, this process is, essentially, the reiteration of this nucleation sequence and the growth, the lateral growth in this direction will create what we call a perilytic colony. Again, you see why you can have this alternating of, essentially, cementite and ferrite, and how the layer structure is actually originating.

Moreover, for the growth process to continue, there must be some diffusion of carbon atoms, essentially, in the gamma matrix in front of the advanced perilytic microstructure. What I mean by that is, essentially, that So, if I want this grain boundary, I have now a certain, this is alpha, this is cementite, this is ferrite, this is again alpha. So, imagine that, again, for the same reason that we discussed already, here we will be somehow low in carbon, here we will be somehow high in carbon content.

Okay? Sorry, it's the other way around, actually. Okay? So, if I want to grow laterally these crystals, I need, essentially, more carbon atoms in here, because then the carbon atoms must,

essentially, go at the interface for this taste, for this cementitic grain to grow. It's the other way around here.

I need to move away carbon atoms from here, from the, essentially, the region in front of the interface alpha-gamma, if I want to promote the growth of alpha, because alpha needs very few carbon atoms to grow. So, there must be, essentially, as you can see here, some diffusion of carbon in this direction, but also in this direction. So, there must be, somehow, diffusion of atoms from the region in front of alpha to the region in front of cementite.

So, there must be this type of lateral diffusion with a certain difference in the concentration that I can call, somehow, delta x zero. So, it can be shown that, basically, the growth rate here depends on, essentially, the diffusivity of the atoms, or the diffusion coefficient of carbon atoms in the gamma matrix. So, this is, essentially, how fast atoms diffuse in here, where we are in gamma.

Here, essentially, we have two grains of gamma, or the cementite. It depends on, essentially, the gradient of concentration we have in this direction, this region, essentially, here, and it depends on lambda. Lambda is, essentially, the spacing between, essentially, two layers of cementite and carbon.

So, it can be shown, essentially, that this is, essentially, the equation for the growth rate, which is proportional to d, to delta xc, and E. There is an inverse of proportionality, which is, essentially, to lambda, which is the interval level of space. In terms, as an approximation, somehow, we can, this is an empirical rule, essentially, this delta, this ratio, delta xc over lambda is proportional to delta t squared, and so I can recast, essentially, this equation into some quantities, which are a little bit easier. I mean, delta t is something that I can control in a much easier way than delta xc.

Actually, this is very difficult to measure, somehow. This can be measured, somehow, from microscopy, but they are essentially not as easy to measure as delta t, and they see gamma is something that you can find in tables, in handbooks, is the coefficient of diffusion of gamma in gamma. So, this is, essentially, the mechanism.

So, the mechanism is cooperative, because you see that they grow somehow in parallel, because it's the same process, this diffusion of carbon atoms in this direction, essentially, which is perpendicular to the direction of the growth, that is promoting the growth of the perihetic colony. Basically, the faster this mechanism is going on, the faster both sum and parity delta will grow, and they both can grow, essentially, more or less at the same rate. What you see in there, is the example in the case.