Surface Engineering for Corrosion and Wear Resistance Application

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Lecture- 18
Strengthening of metals

Hello, welcome to the 18th ha lecture of this particular course on Surface Engineering. Though it is a course on surface engineering, but this one and the very next one these two lectures will be devoted to the strengthening mechanism which had not necessarily only mean for surface engineering, but generally is applicable to the bulk as well.

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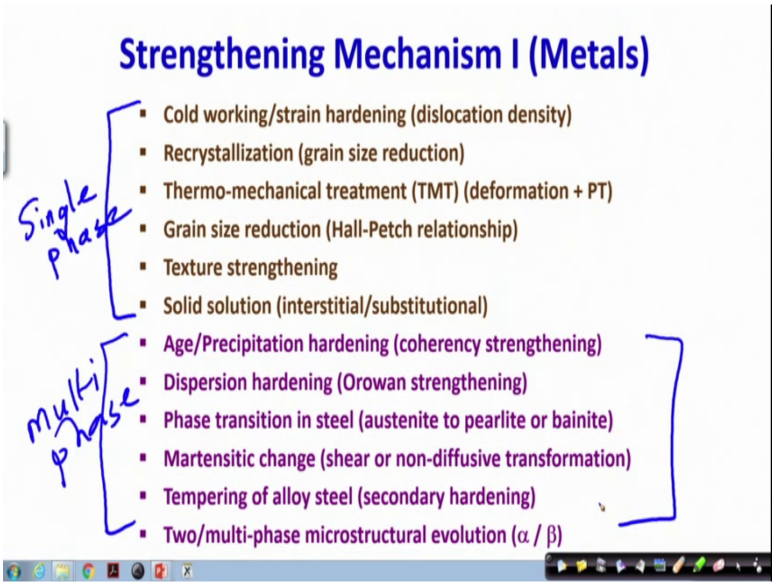

Strengthening Mechanism I (Metals)

- Cold working/strain hardening (dislocation density)
- Recrystallization (grain size reduction)
- Thermo-mechanical treatment (TMT) (deformation + PT)
- Grain size reduction (Hall-Petch relationship)
- Texture strengthening
- Solid solution (interstitial/substitutional)
- Age/Precipitation hardening (coherency strengthening)
- Dispersion hardening (Orowan strengthening)
- Phase transition in steel (austenite to pearlite or bainite)
- Martensitic change (shear or non-diffusive transformation)
- Tempering of alloy steel (secondary hardening)
- Two/multi-phase microstructural evolution (α / β)

But it is important that we understand these strengthening mechanisms so that we are in a better position to follow the possible interaction of the surfaces with various kinds of mechanical forces. So, for example, we begin; we would also like to divide this whole strengthening mechanism related discussion into two parts. The first part today is about metallic materials, where the strengthening or deformability both are primarily related to the ease or otherwise of dislocation movement on the slip planes and tomorrow we will discuss in the next lecture on strengthening mechanism applicable to non metallic materials.

Now, talking about metals and alloys ha we are already aware what we are talking about. We are talking about essentially an aggregate, where the cations are permitted; cations are arranged in three dimension, in regular and repeated manner with a three dimensional periodicity and this periodic array is permitted by free electron cloud. So, this is exactly the definition which allows us to explain all possible properties of metallic aggregates.

Now, the two color codes here essentially mean that for example, this first part is for the; let us say this set of strengthening mechanisms, they are typically applicable to single phase materials. So, metals and alloys which essentially are single phase whatever is a composition, they remain single phase and they do not undergo any typical phase transformations possible in other alloys for example, no in variant transformations; whereas, the remaining set of transformations are meant for two or multi phase material.

Of course, it does not mean that these kind of strengthening mechanisms of this side cannot be used at all. So, whatever is applicable to the single phase strengthening you can also be applied to two phase or multi phase materials to some extent but let us get into the details of it.

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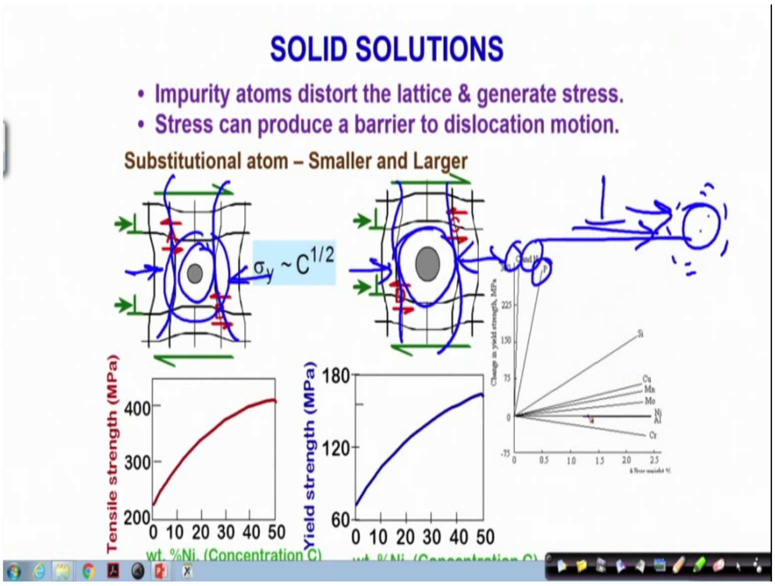

SOLID SOLUTIONS

- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

Substitutional atom – Smaller and Larger

So, the first one is about solid solution strengthening. So, just imagine that if you are able to pack certain amount of sugar in water or salt in water, they dissolve up to a certain extent and when you dissolve then, the taste changes. So, over here in metallic systems which we assume are all crystalline substances. If you pack in materials which could either be for example, a bigger in size, a smaller in size or bigger in size. So, if this is smaller than the usual lattice atoms then, these lattice planes they tend to collapse and move towards the smaller atom.

Yet you create a stress field around this region. So, this is the stress field that you create, but this stress field essentially will be tensile in nature; because they are essentially the atoms are dilated. On the other hand, if you actually have an atom which is bigger in size so, obviously due to the bigger size, the lattice planes will be moved away and hence, the pushing tendency will be towards the right and the reaction to that the residual stress of that will be towards the for an atom. So, you create essentially a compressive stress field around that. Now, in other cases since you create a stress field around this. So, when you have a dislocation which is trying to move along a particular plane; then, it encounters a certain obstacle because this is the foreign atom, which is either smaller or bigger, but it has a certain stress field around it.

So, while trying to negotiate this particular dislocation, will have to face or need a different kind of a shear stress to be able to overcome this. So, as a result the motion of this or the speed or the velocity of this dislocation is different and as a result the strength may actually increase.

So, there is a limit up to which, of course, you can back in solute atoms into the material and that is dictated by the equilibrium solubility. But here you can see for example, if you back; if you are able to introduce certain amount of these interstitial elements like carbon nitrogen or and so on. So, here in this case even with very small amount of solute atoms, the strength very drastically can increase. But for most of the other elements actually the strengthening occurs because of this solid solution strengthening.

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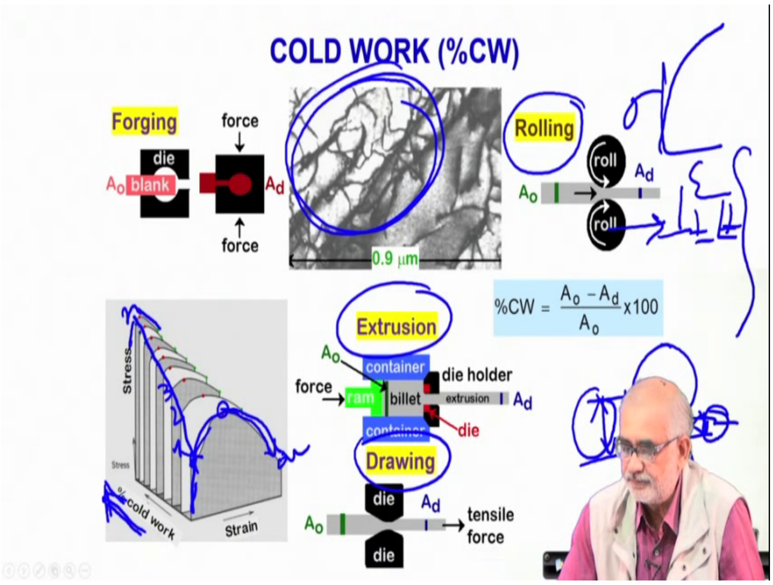

COLD WORK (%CW)

$$\%CW = \frac{A_0 - A_d}{A_0} \times 100$$

Now, the other possibility could be for example, if you introduce deformation. So, if you say for example, you take a roll and in this between the two rolls if you are allowing this stock to be rolled in between. So, you squeeze and you deform and what comes out actually is of smaller thickness compared to this thickness.

So, in this situation, when such a huge amount of deformation takes place, this is essentially made possible through again the dislocation movement. So, if this material here before deformation has a certain density of dislocation after the deformation this side, the material will have lot more dislocation density. And these dislocation densities will actually also create certain impediment against movement of other dislocations. So, if you have a particular boundary and if this is; these are the set of dislocations already piled up.

So, next time a new dislocation arrives, these dislocations will come in the way and as a result the strength of the material will go higher as we introduce more and more amount of dislocations. So, this is what is exactly explained here that at very low. So, this is how the amount of cold work is increasing. Of course, these deformations are necessarily below the recrystallization temperature; otherwise, they will be dynamic recrystallization or emulation of dislocations. But if the deformation is done below the recrystallization temperature so, for example, at a given in a given condition as we deform. So, this is the typical stress strain diagram; this is this yield stress; this is the tensile strength and then, the stress drops and eventually material fails here.

So, this, if this is the stress strain diagram for a particular level of dislocation density or state of stress, internals strain and as you keep increasing the amount of strain in this direction what we see is that the amount the yield strength increases from this level to this level to this level and eventually to very high level. So, this increase in yield strength, gradually increase in yield strength is made possible purely because of increasing dislocation density as we introduce more and more deformation and as we know that these deformations can be essentially done through such kind of processes like rolling or extrusion or drawing or various other kinds of mechanical processing techniques.

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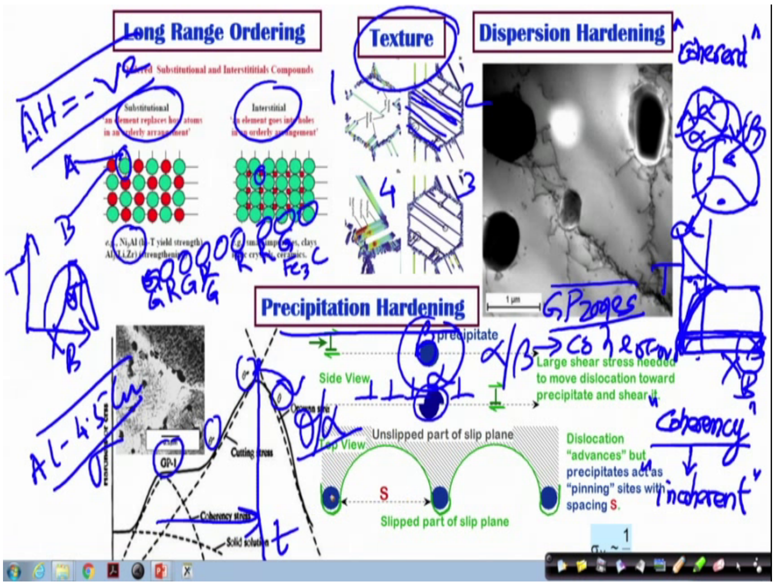

Long Range Ordering

Texture

Dispersion Hardening

Ordered Substitutional and Interstititials Compounds

Substitutional
'an element replaces host atoms in an orderly arrangement'

Interstitial
'an element goes into holes in an orderly arrangement'

Precipitation Hardening

Large shear stress needed to move dislocation toward precipitate and shear it.

Dislocation "advances" but precipitates act as "pinning" sites with spacing S.

Now, as we go to other possibilities, for example, in an alloy if you have at least two components the solute and the solvent, let us say this the green ones are; the green ones are one type of atom, let us say A and the red one is B. So, we are dealing with two kinds of atoms A and B. If they are arranged in a very ordered manner; very just like the way the military is I mean they behave very in a disciplined manner. So, for example, if we impose a particular discipline that the red guy has to be next only to a green guy and likewise; so, we will always see an alternate sequence of red green red green and so on.

But this is very very not very usual situation this can be made possible only when in a given condition where delta H is highly negative and this enthalpy of the transformation is so negative that below in the phase diagram, below a certain temperature we see if this is the temperature axis and if this is the composition axis.

Then, maybe there is a particular region, where we see a dome like this which essentially says that this is the critical temperature and below which you actually have completely ordered solid solution. And this ordered solid solution can be substitutional or interstitial in nature depending upon there is relative size of the solute atoms. So, here for example, you are seeing that the solute atom is tiny little and is able to go into the interstices of the material. So, we can end up getting an ordered interstitial solid solution or interstitial compound; otherwise, we can have an ordered interstitial alloy. For example, Ni 3 AL or in case of for example, here we can have an interstitial compound like Fe 3 C and so on.

So, in all these cases when, we have such an ordered array; then, the stress field undergoes a periodic or cyclic change. And as a result of that when any dislocation is trying to negotiate this field, it has to actually; it sees a very different kind of a situation than what it normally sees when you have random.

A random means that essentially I have this is, if these are the arrays of atoms in a given plane then, there is no necessity that this has to be green; this has to be green and this has to be red. In an ordered fashion we always see like that; but in a random situation this can very well be green and this can be red, the next one can be red again; it can be green so, these are all random sequences. You can also have a situation where, the crystallite arranges themselves in a particular crystallographic orientation. In other words, these are the planes which actually are arranged parallel to the surface and they are of a particular crystallographic type.

So that means, the density of atoms, planar density of atoms on these planes is of a particular type. And majority of the crystallites in a polycrystalline aggregate are so arranged that these set of planes are parallel to the surface. So, in such a situation as you have multiple grains, let us say 1, 2, 3, 4; in all these cases if these crystallites are so arranged that the dislocations will see one set of planes for negotiation and if these planes have relatively higher shear strength then, the dislocations will face more difficulty to move there. So, bringing in a particular preferred crystallographic orientation whereby, the crystallographic planes which actually pose problems for dislocation movement can actually raise the strength of the material and that is called texture strengthening.

Now, one of the most effective and most I would say widely applied strengthening mechanism is called precipitation hard. Now, if you imagine any alloy where, this is let us say a binary alloy and if we have a situation where, the solid solubility decreases with temperature very significantly and if you take an alloy like this of this particular composition and if you equilibrate at a temperature like this which is going to give you a single phase microstructure. So, in the microstructure, you will have a single phase all are alpha. And as you bring it to lower temperature, you are going to see the precipitation of the second phase, let us say beta. So, this microstructure will now convert into a situation where, you have precipitates. And these are so called beta precipitates in alpha matrix.

So, in a situation where, you have this alpha and beta; beta precipitates appearing into the matrix of alpha. Usually, this is nothing unusual, this is most usual but a special subset of these kind of precipitates which also are able to maintain coherency or the precipitate which are coherent with the matrix, they actually pose; they actually can offer a very high strengthening as a function of time in this kind of an aging treatment. So, if you consider this to be a particular alloy; typically this is very well known in aluminum 4.5 percent copper alloy or the durable alloy. In this alloy, what we know is that as we age at a single phase region and then, bring it to lower temperature; either bring to room temperature and then, again heat up artificially to hold at this temperature or we directly transfer to this temperature. In either case, when we see appearance of these beta precipitates into the matrix, if this precipitates not only undergo precipitation due to decrease in solid solubility.

But they are also able to maintain coherency then, these precipitates are bound to provide very high resistance to dislocation movement. In a situation like this, the dislocation while trying to negotiate a precipitate like this will move up. And then, we will have to encounter a region of this precipitate so called zones which actually can have very high or very different elastic modulus and as a result the precipitate will offer a great deal of strengthening to the matrix. But when you overage; that means, if this is the time axis and if this is the strength axis then, if you overage; that means, if you aged for longer than this peak aging period then, beyond this period the precipitates which earlier on where coherent will lose their coherency and will convert into in coherent precipitates.

So, when they are incoherent; then, what it means is that, this precipitate for example, did not have any clear cut boundary with the matrix. So, that is why, if this is the matrix and if this is the precipitate; this alpha beta inter phase was completely coherent. So, a dislocation cannot make out any difference between alpha and beta. Of course, I must clarify that the precipitate, when you say beta it cannot be considered as a coherent precipitate anymore; it has to be an inquiring bird.

So, convention wise they are called zones. Typically, in aluminum silicon, aluminum copper alloys they are called the GP zones. So, whether they are GP zones or theta prime or theta double prime precipitates; they are still able to maintain coherency or semi coherency. But when, they move across for longer ageing period and convert themselves into equilibrium precipitates which is theta. So, when theta forms then, these theta; theta alpha matrix is no longer coherent, but incoherent. And as a result you lose the coherency strengthening.

But you enter into a different regime which is called orowan strengthening regime; that also offers move impede impediment to dislocation movement. But here the obstruction is slightly of different type that dislocations tend to bow and when, they tend to bow like this eventually there could be possibilities of annihilation at this point. And then, you leave behind the loop and this loop is going to further provide hindrance to dislocation movement. So, this is in the nutshell various possibilities of strengthening mechanisms in the alloys.

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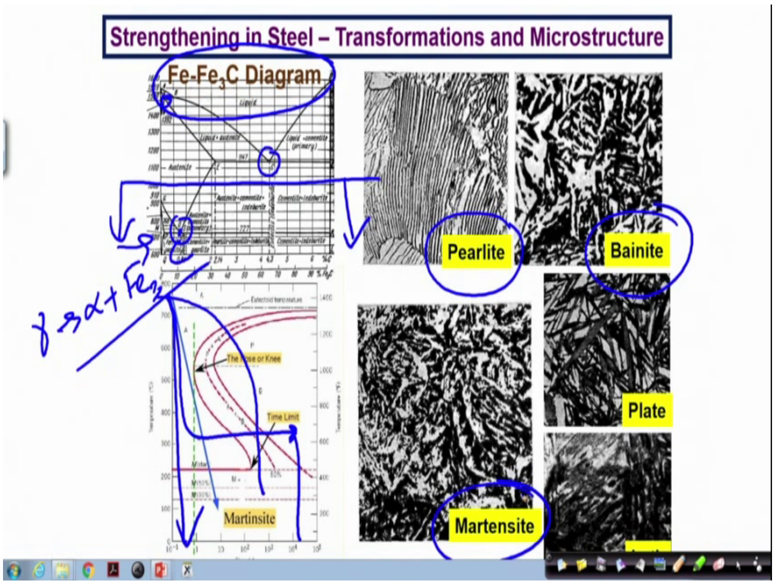
Strengthening in Steel – Transformations and Microstructure

We also need to learn a little bit more in details about steel the very; the one of the most widely used and utilized structural material.

But this is a subject by itself all we need to understand at this moment is something very simple that this is the so called iron cementite diagram. I am very specifically mentioning this as iron cementite because there is a metastable diagram. And we essentially need to understand about three possible invariant transformations the peritectic, the eutectic and eutectoid. Out of all these ah; these are involving liquid states. So, most of our activities for structural applications will be confined only to the region below this temperature zone. And which means we will be concerned with this so called eutectoid transformations which involves transformation of austenite into ferrite and cementite.

Now, this can be made use of or utilized for various purposes. So, when this eutectoid transformation state place at slightly higher temperature or slightly at a slightly slower rate for example, somewhat like this then, you are likely to see pearlite. If you have the possibility of holding and then cooling like this then, you are likely to see pay night and instead if you quench very fast then, you are likely to see martensite.

So, these two are physically get whereas, martensite per se is an extended solid solution, a supersaturated solid solution, but differs from the other two in the fact that it is a shear transformation product. So, first you know at this stage that martensite gives you the hard; it is the hardest possible solid solution in iron carbonyl and cementite system because of which you get the maximum amount of hardening.

So, even on surface depending on whether we give a pearlite or bainite or martensite the mechanical properties at the surface is going to be vastly different.

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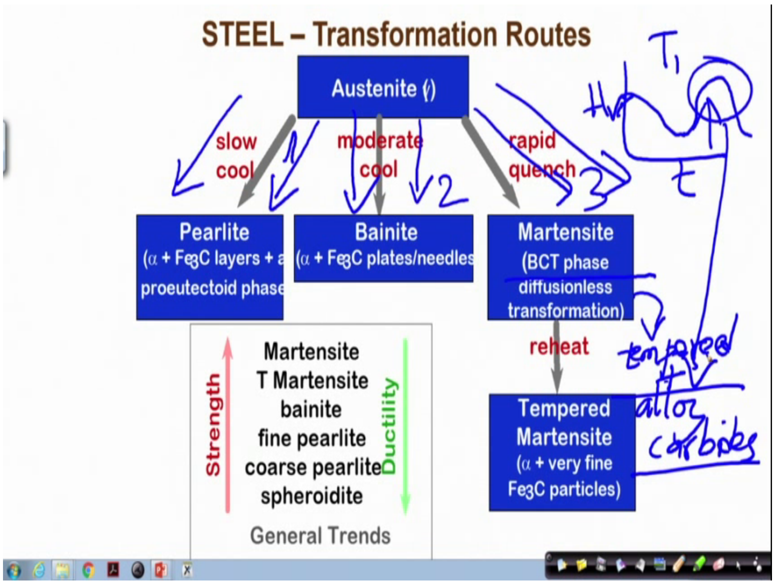

STEEL – Transformation Routes

Austenite (γ)

slow cool

moderate cool

rapid quench

Pearlite (α + Fe_3C layers + a proeutectoid phas

Bainite (α + Fe_3C plates/needles

Martensite (BCT phase diffusionless transformation)

reheat

Tempered Martensite (α + very fine Fe_3C particles)

Strength

Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite

Ductility

General Trends

And in fact, taking advantage of this situation typically one can actually think of adopting a possibility of this so that you have pearlite, the second possibility is to have bainite and as I said the third possibility is martensite. So, in terms of severity of quench this is rather slow process, this is moderately fast and this is the fastest. So, as a result of formation of martensite, which is a non cubic product so called tetragonal product. There are many other reasons as to why martensite is the hardest solid solution you actually can convert the surface of steel to very high to make it very very strong and very resistant and so on.

You may also like to bring in certain changes in the temp; in the as hardened condition and particularly for alloy steel you may actually like to convert this martensite into what is known as the tempered martensite. And most importantly apart from tempered martensite what you also can bring in also are called the alloy carbides. So, when you bring in this alloy carbides you actually see a further strengthening possibility. So, if this is the so called vickers hardness and this is the time at an isothermal temperature T1. So, typically after martensitic hardness hardening, you will see that the hardness actually will constantly decrease; but then, there could be a possibility of another hump coming. And this is the so called fourth stage of tempering which gives rise to this alloy carbides. And this is called secondary hardening also, but then this is ha prerogative of the alloy steels not generally any kind of steel.

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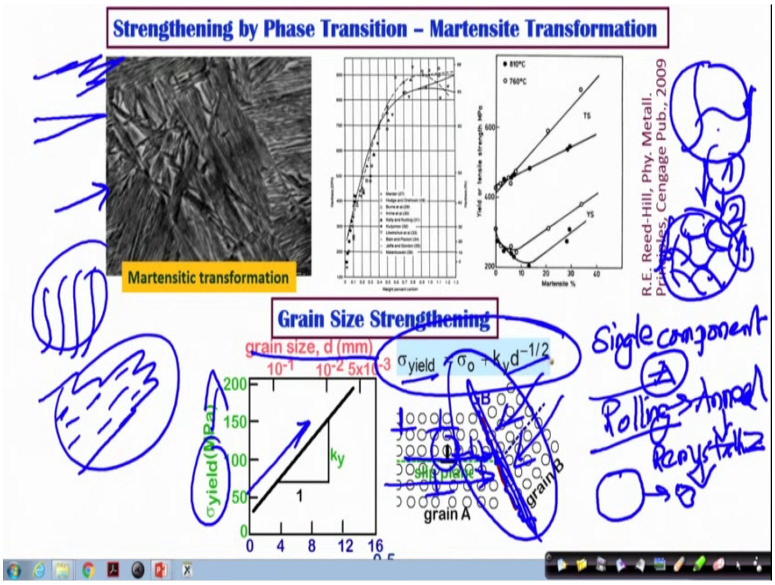

Strengthening by Phase Transition – Martensite Transformation

Martensitic transformation

R.E. Reed-Hill, Phy. Metall. Principles, Cengage Pub., 2009

Grain Size Strengthening

$\sigma_{yield} = \sigma_0 + k_y d^{-1/2}$

Now, we need to; now go to the other possibilities; for example, martensitic transformation is something which we have already discussed. At this point I just would like to mention that the when you talk of pearlites, you are talking about lamellar structure like this. When you are talking of bainite; then, you are talking about a ferritic steel with carbide strangers decorated like this. But when you are talking about martensite then, you actually are talking about either the acicular or the martensitic log structures because of these sharp boundaries and ultrafine size, martensite always is much harder and much stronger than either pearlite or bainite.

Now, this is something which we will discuss in greater details very soon but at the moment let me also tell you that if you do not have these alloying elements present; for example, hypothetically speaking if we have something which is a single component and a single phase. So, when you are talking about something which is not only single phase, but also single component; that means, you are talking about a pure element A. How do you strengthen this pure a metal, which is pure metal? So, there are a few possibilities, one which we saw already in the beginning which is strain hardening; that means, if you deform this material you certainly introduce higher density of dislocations and this is higher dislocation density can actually provide you strengthening. And this is exactly the strategy adopted in for example, shock pinning or any amount of surface deformation procedures.

When you; but when you have, when you cannot do this for example, when you cannot shot pin another possibility is that you simply roll. So, when you do rolling either skin pass or slightly higher level of deformation, when you roll and then, subsequently when you anneal these rolled structures then, these structure is going to give you what is known as recylization or recylized structures. And in the process the grain average grain size if this was so big; now, could be much smaller.

So, when the crystallite size is refined to this small level significantly refined then, the amount of grain boundary area. So, essentially we are talking about a situation where, earlier the grain size average, grain size was so big and from this because of recylization if we make it much smaller for example, very very small grains like this. Then; obviously, the total area of boundaries in this particular situation the specific surface area per unit volume would be much higher here that compared to this situation.

So, if we convert this coarse grain structure into this fine grain structure, the specific boundary area per unit volume is going to go up significantly high. And we all know that this boundary is actually nothing, but a barrier or a wall for against the movement of this dislocation. So, when you try to move this dislocation it merely moves until this particular boundary then, sees a barrier and stops.

So, all dislocation if these are the parallel slip planes, all dislocations which are trying to move will certainly face a barrier here and stop. And this can happen also for dislocations moving from the other sides. So, if you increase such barrier or walls more and more then obviously, the amount of resistance or dislocation movement should go up.

And as a result the yield strength goes up as a function of decreasing crystallite size and because of which we actually see a very significant strengthening. And this strengthening is known by this famous relationship proposed independently by a hall and pitch and which clearly shows that the yield strength is inversely related to the average diameter of the grain.

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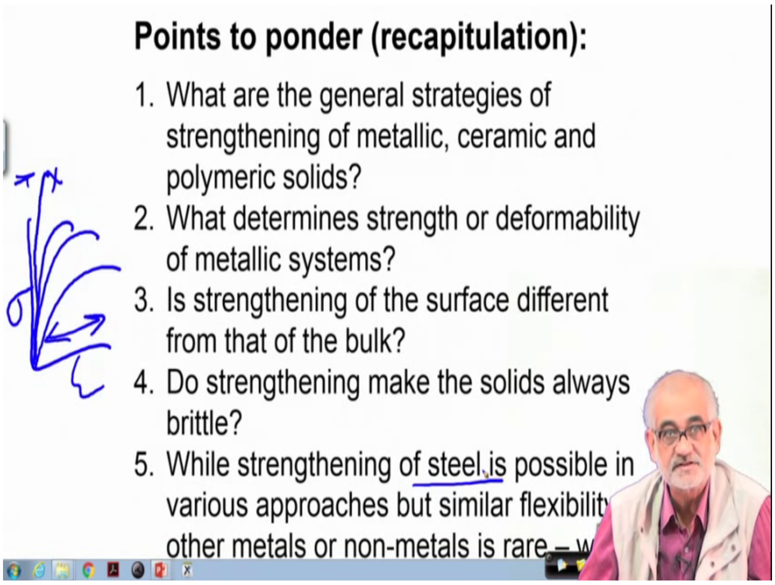

Points to ponder (recapitulation):

1. What are the general strategies of strengthening of metallic, ceramic and polymeric solids?
2. What determines strength or deformability of metallic systems?
3. Is strengthening of the surface different from that of the bulk?
4. Do strengthening make the solids always brittle?
5. While strengthening of steel is possible in various approaches but similar flexibilit other metals or non-metals is rare – w

Now So, this possible strengthening mechanism certainly is all these possible strengthening mechanisms they are very useful to us not only when we are trying to negotiate with the bulk, but also trying to tailor the micro structure and composition of the surface; so that the structural properties the mechanical properties of the surface is improved. So, let us try and recapture let some of the points that we have discussed in this particular lecture.

The first thing I would like to draw your attention is that what we have discussed here is that the general strategies of strengthening for metallic ceramic and polymeric actually are different they are not one and the same. But since, we have discussed only about metals in this particular discourse let us not worry much about ceramic and polymeric. And what we must take away from today’s lecture is that most of the structural properties namely this strength or hardness and various other strength properties. They are somewhere or other related to the ease or difficulty of dislocation movement in the crystallite.

So, metals are predominantly or 99 percent crystalline; except for the boundary regions, the rest of the areas or volume is all crystalline having three dimensional periodicity and whatever strength if you want to deform this metal without having any dislocation then, you require to overcome the theoretical shear strength. If you have a dislocation then, these dislocations can actually help you deform the material plastic deformation, permanent deformation at a shear stress level which is easily thousand times or more, less than a one thousand or ten thousand of the theoretical shear strength.

So, whenever you deform essentially the presence of dislocations help. So, by the same logic if you make movement of dislocation difficult then, you strengthen and this is exactly the strategy that is adopted. Now, this opposition or so called resistance to dislocation movement can be brought in by either by bringing in precipitates which are; which could be coherent initially and then subsequently become incoherent.

So, whether they are coherent or incoherent they offer a resistance to dislocation movement you can increase the grain boundary area that is how you can strengthen the material you can pack in more and more amount of solute atoms either smaller or bigger than the matrix atom and create either compressive or tensile stress field around them and as a result the strength or the dislocation movements would be impeded.

There is another question that when we make materials strong, when we make it too strong there is a possibility that the material will not be able to take deformation anymore. For example, if a material is normally showing a stress strain diagram like this; you make it stronger it will go like that, but when you make it ultra strong it might not show any plastic region at all and might fail at this very point itself. So, it is not enough that we only increase the yield strength or so, called tensile strength. We also have to make sure that there is sufficient amount of plasticity involved or plasticity or plastic deformation possible.

So, we have to play sort of look for a compromise between strengthening and sacrificing ductility or deform ability. There are techniques where, you actually can have a very good compromise between both strength and toughness. We did briefly mention about possibilities of strengthening of steel, but I promise that we will very soon go into another lecture well, discuss in greater details about strengthening mechanisms of steel and nonmetals will be discussed; the strengthening of nonmetals will be discussed in the very next lecture.

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Thank you very much.