Thermo-Mechanical and Thermo-Chemical Processes

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Lecture-21
Processing Maps: Deformation Mechanism Maps

Hello friends, we will start with a new module now, we have already seen the constitutive equations. The next module is on the processing maps. So, for a practicing engineer who is on the shop floor, who is actually looking after the production, if I tell him all about this dynamic recrystallization, dynamic recovery, the flow stress, this will be the mechanism, in these temperature range or strain rate, you have to do the deformation or the processing.

He will not enjoy this particular idea that you are coming with all these flow stress because he has to look after the production. He does not have time for all these niceties and your enthusiasm for dynamic recrystallization and dynamic recovery. He wants to have a very clear answer that if he is designing a process which temperature, strain, strain rate he should be working in, what will be the flow stresses and which are the region where he will be able to get a good processing that means you will have maybe a recrystallized microstructure.

And which regions to avoid, maybe in some regions you will be getting some crack formation or some other defects which are going to come or which are going to be present in the material.

So, which regions to avoid and which regions are the regions for the processing. So, you must have seen large number of places we use these kind of maps to clearly bring out demark at ok this is my process processing region.

And usually graphical means are always better for example, in our stress analysis also we use Mohr circle, because a graphical representation very quickly bring out the main idea behind a particular aspect for example, in a stress analysis or as we are saying in case of processing maps. So, these maps are very convenient for a practising engineer to identify the processing conditions.

Now, as I was trying to tell you that what regions to do the processing and what regions to avoid, if you look at any plastic deformation or during a hot deformation or thermo-mechanical processing, our main objective is that I should be able to deform it without any difficulty. And I should be able to avoid any failure in the material, there should not be any defects in the material.

So, then, this is what we call as work ability that I should be able to work on my material. So, their work ability also can be kind of defined in two ways. One is called extrinsic work ability, which depends on the state of stress, that whether it is a uni-axial deformation, it is bi-axial deformation, it is plane strain deformation. So, what kind of deformation it is? Whether it is a shear deformation.

So one work ability depends on that, whether it is a tri-axial deformation. So, severity of the deformation increases as you go from uni-axial to bi-axial to tri-axial. And of course, you can also have more chances of introducing defects. Whereas, in shear process, you can go to very high strains without introducing defects, for example, surface cracks and so on. Whereas in compression, you can easily introduce surface cracks if you are doing a large deformation.

So, this is a extrinsic work ability of the material which depends on the state of stress, what type of stress system is there, plane strain, plane stress, compression, shear and so on. The intrinsic work ability is the inherent characteristic of a material.

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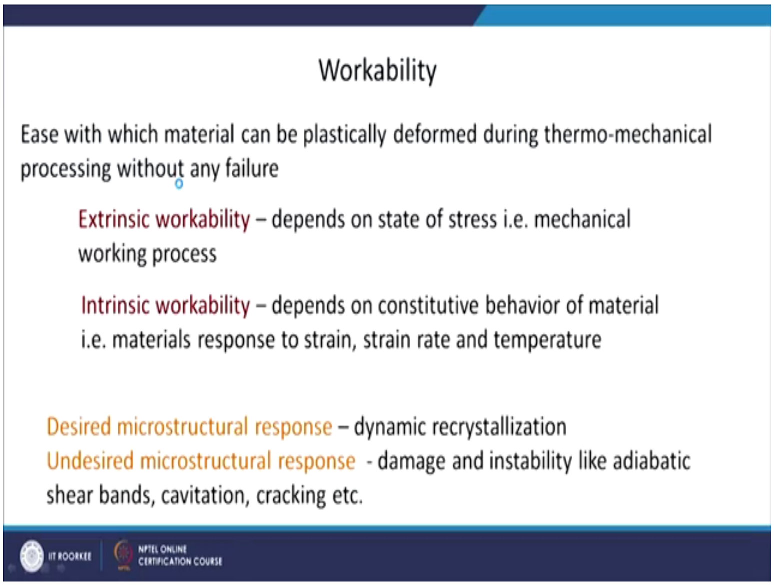

Workability

Ease with which material can be plastically deformed during thermo-mechanical processing without any failure

Extrinsic workability – depends on state of stress i.e. mechanical working process

Intrinsic workability – depends on constitutive behavior of material i.e. materials response to strain, strain rate and temperature

Desired microstructural response – dynamic recrystallization

Undesired microstructural response - damage and instability like adiabatic shear bands, cavitation, cracking etc.

And that depends on the constitutive behaviour of material that what is the materials response to in terms of flow stress, its response as a function of strain, strain rate and temperature. So, that is the intrinsic workability that is of course a material specific property, that how material behaves under certain set of conditions. And that will be intimately related with the deformation processes, at particular deformation conditions.

So, the flow stress response can be then also looked at as the microstructural response that what will be the response of the material. So, microstructural response also we can segregate the response in two categories. One is what we desire and one which is undesirable. So, dynamic recrystallization, dynamic recovery, these type of microstructural response is desirable because it enhances the workability of the material.

You are able to deform the material as you can see in dynamic recovery, dynamic recrystallization, if you reach the steady state, there is no change in the flow stress as a function of a strain. So, it is a steady state condition you are able to deform to larger strains, ductility will be more. So, these, this particular region we want to work in. Undesirable, microstructural responses are the introduction of defects.

So, damage instability like adiabatic shear band, cavitation, cracking this we do not want in the material because if crack is there in the material or cavity is there in the material it will bring down the strength of the material. As you know, in fracture mechanics, if a crack is there it when I am applying any tensile stress it will start propagating and your material will fail after some time.

So, there will always be a problem of failure of material if you have any defects in the material. So, again as we were discussing in the constitutive equation that the constitutive equation idea started from the creeped deformation. And creep already I have told you the creep is a very slow deformation as a function of time, time dependent deformation, in which the strain rate of deformation is very low 10^{-8} to I think 10^{-5} that is the window we decided for creep.

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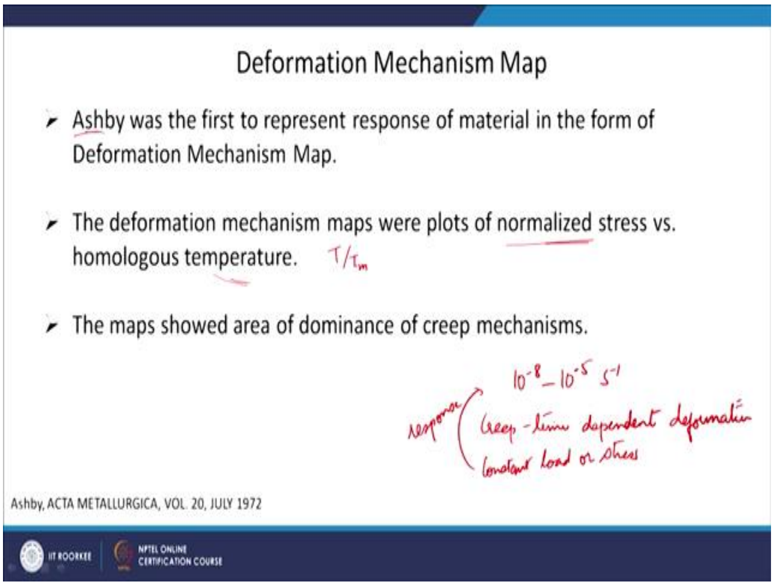

Deformation Mechanism Map

- Ashby was the first to represent response of material in the form of Deformation Mechanism Map.
- The deformation mechanism maps were plots of normalized stress vs. homologous temperature. T/T_m
- The maps showed area of dominance of creep mechanisms.

$10^{-8} - 10^{-5}\ s^{-1}$

response

Creep - time dependent deformation

constant load or stress

Ashby, ACTA METALLURGICA, VOL. 20, JULY 1972

Just to kind of recap it is the strain rate we reach. And creep is basically your time dependent deformation. And in this case, actually, you do not apply the strain rate, but you apply a constant load. So, you apply a constant load or you can say stress and the material response is seen in form of strain rate. So, slightly different than the hot deformation processes, where you apply a strain rate and you see the material response in form of stress.

Here we apply a constant load or stress and we see the material response in terms of strain rate, that was how fast the strain is being accumulated in the material as a function of time. So, constitutive equation also I told you at that time that the creep is the first phenomena which people looked at for developing constitutive equation. Similarly, this maps idea also started from the creep deformation only.

So, already we have discussed in creep that you have a dislocation creep, you have diffusional creep diffusional. Diffusional creep also we have Nabarro–Herring creep NH creep or you have Coble creep. NH creep is dependent on the diffusion through lattice whereas Coble creep is dependent on the diffusion through grain boundaries. So, you have these different type of creep processes.

So, I want to know that, at which temperature, stress condition which particular process will be the dominant process. So, M.F. Ashby was the first guy who proposed this kind of maps and he used to call it as deformation mechanism map. That what mechanism, which deformation mechanism is operating at particular temperature, stress condition. That they are trying to identify on a map.

And the deformation mechanism maps are plotted on a graph, where you have normalise stress and homologous the temperature. I do not know whether I have told you homologous temperatures if I express the temperature in the form i.e. the deformation temperature is divided by the melting point or temperature of melting of that particular material. So, you are actually normalising it. Maps show area of dominance of a particular creep mechanism. So, in particular area which mechanism is dominating that the map will be able to tell you.

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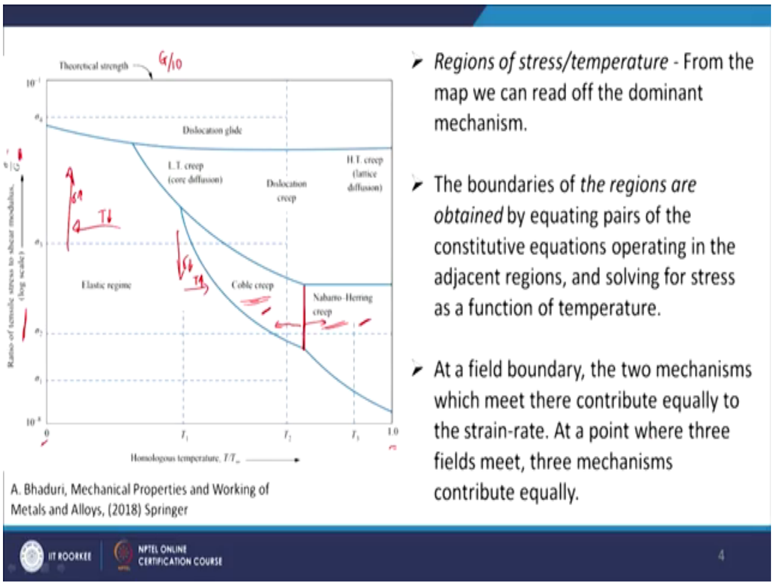

A. Bhaduri, Mechanical Properties and Working of Metals and Alloys, (2018) Springer

- *Regions of stress/temperature* - From the map we can read off the dominant mechanism.
- The boundaries of *the regions are obtained* by equating pairs of the constitutive equations operating in the adjacent regions, and solving for stress as a function of temperature.
- At a field boundary, the two mechanisms which meet there contribute equally to the strain-rate. At a point where three fields meet, three mechanisms contribute equally.

So, this map will look something like this (refer to above figure), where you on the x-axis you have homologous temperature $\frac{T}{Tm}$. So, now you can see, it is from zero to one obviously, so all the different materials can be clubbed together when you do something like this. And on the y-axis you have stress, which is normalised by the shear modulus. On the top you can see this is my theoretical strength.

So, if you have done in your mechanical behaviour course or strength of material course, theoretical strength you can calculate for a material, which usually scales with the shear modulus. So, if you see the usually I am just putting a parameter some number here. So, usually it is in this range $\frac{G}{10}$, that will be your theoretical strength.

So, that is my line 10^{-1}, because $\frac{G}{10}$ is normalised by G. So, it will be 10^{-1}. And then there are different mechanism as you can see are identified here. So, this is the higher strain rate, lower temperature. So, temperature is going down here and stress is going up here.

You can see that dislocation glide which is the normally deformation mechanism at lower temperature will dominate, up to a certain temperature. So, from very low temperature to a certain temperature your dislocation glide is the deformation mechanism. As you go to lower strain rate and higher temperatures, so in this case you will see that the creep deformation is starting to dominate. And in that also you have different type of creep mechanism. In this (refer to above figure) region you have a dislocation creep. This is your low temperature creep and this HT is your high temperature creep through diffusion mechanism and somewhere here you have a dislocation creep mechanism.

As you could go to even lower strain rates and of course, still at higher temperatures, your diffusional creep will start dominating. As you can see at lower stresses the Coble creep, which is a grain boundary diffusion process, and NH creep, which is the lattice diffusion. So, lattice diffusion will obviously be even at higher temperature, because for lattice diffusion, you need vacancies.

And vacancy concentration increases exponentially with temperature. So, you need more vacancies for diffusion. So, grain boundaries already have lot of disorder, you have a lot of open area where the diffusion can take place very easily without creation of vacancies. So, that dominates at lower temperature. At higher temperature when the vacancy concentration increases exponentially, you start having the lattice diffusion.

So, you can see that as you are going to lower stresses, higher temperature diffusional creep is taking place but slightly higher stresses you will start having dislocation creep. Even lower temperature and higher stresses you will have dislocation glide. So, you can see that all the different mechanisms are nicely shown on a single map.

So, what these (refer to above figure) regions are doing is from the map, we can read off the dominant deformation mechanism as we are doing it and these boundaries between two deformation mechanism are obtained by equating pairs of constitutive equations again you can see that constitutive equations are coming here. So, you have one constitutive equation for NH creep, we have already seen that we have one constitutive equation for coble creep.

So, you will see that when the strain rate predicted by these two constitutive equations when they have equal contribution, the strain rates are matching for both these processes, there we will say that a boundary is there between the two. So, at the boundary, you have equal contribution from coble creep and NH creep. So, strain rates are same for both the constitutive equation from both the constitutive equation.

But as you go to higher temperatures you will start seeing that the strain rate predicted by NH creep is higher than the strain rate predicted by coble creep. Whereas, if you go to lower temperature strain rate predicted by coble creep is higher than the strain rate predicted by the NH creep. So, that is how you can have the demarcation between the two processes. So, again you can see that constitutive equations are used to demarcate the region.

And of course, this kind of demarcation will be highly dependent on the accuracy of your constitutive equation. So, obviously at these boundaries where two different mechanism are operating their contribution will be equal to the strain rate. So, this is what I was trying to tell you. So, I can easily read out the deformation mechanism and I can easily find out that which deformation mechanism is operating in which particular area.

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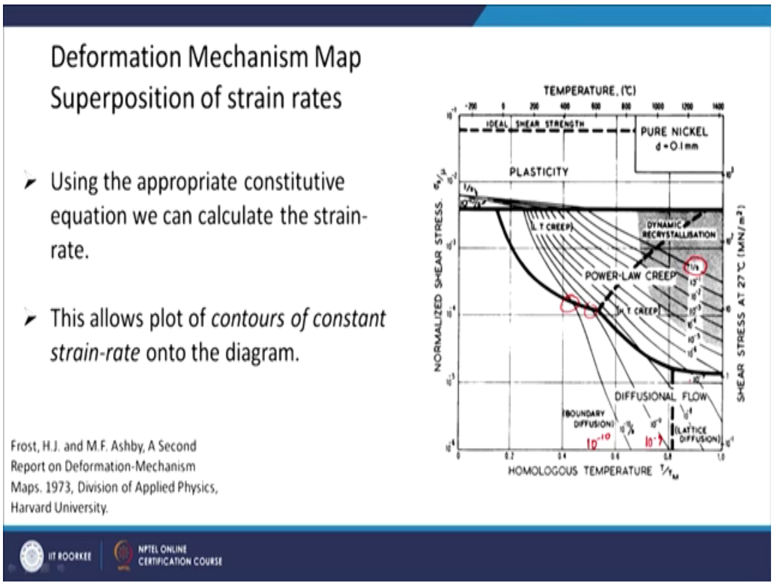

Deformation Mechanism Map
Superposition of strain rates

- Using the appropriate constitutive equation we can calculate the strain-rate.
- This allows plot of *contours of constant strain-rate* onto the diagram.

Frost, H.J. and M.F. Ashby, A Second Report on Deformation-Mechanism Maps. 1973, Division of Applied Physics, Harvard University.

Now, there was another addition to this deformation mechanism map. They started also superimposing the strain rate on these maps. So, you can see that the strain rates are very low for lower stresses. But as you are increasing the temperature, the strain rates are going towards higher values. So, if you are not able to see, this is 10^{-10}, 10^{-9}, 10^{-8} and as you can see that as I am increasing the applied stress, the strain rate is increasing (refer to above figure).

So, strain rates are superimposed on the deformation mechanism map. So, and of course, these are also plotted using only the constitutive equations. So, constitutive equation for different regions were used to develop these strain rate contours. You can see the effect of different deformation mechanism also.

So, wherever the boundary is, there is a change in the slope of this is strain rate contours. You can see there is a sharp change here, similarly a sharp change here (refer to above figure). So, wherever there is a change in the deformation mechanism, you see a change in the slope of this constant strain rate contours also.

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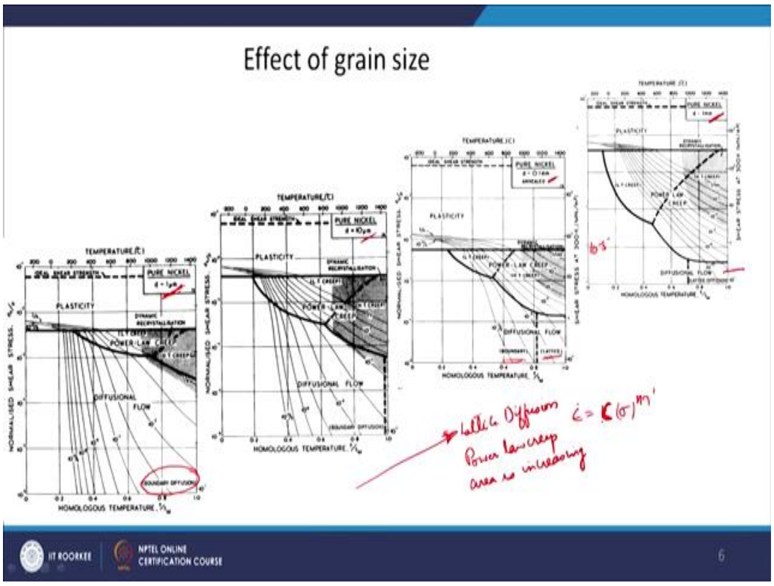

Effect of grain size

Now, what is the effect of grains size? You can also see very nicely that how the grain size affect the deformation mechanism map. So, this is for one micron (refer to above figure). These are all for FCC nickel. Nickel is an FCC material and this is for one micron, this is 10 micron, 0.1 mm means 100 micron and 1000 micron 1mm. So, grain sizes increasing in this direction.

So, how it affects the deformation mechanism map. You can see that when I compare with the two extreme one, you can see this is one micron and the boundary diffusion is the only one I am seeing in the diffusional flow and the power law creep, power law means where the stress and strain rate are dependent with some stress exponent. So, the equation will be something like this (refer to above figure).

So, you have a power law creep in that you have low temperature creep and high temperature creep and then, you have diffusional flow. In diffusional flow, only the boundary diffusion can be seen in this particular map.

For the same nickel of course all the temperature strain rates are same because these are all normalised if I see for one mm that is thousand micron I can see the lattice diffusion also here in diffusional flow and there is no region for grain boundary diffusion that means, as I told you that coble creep dominates in the material with finer grain size because you will have more grain boundary area.

So, grain boundary diffusion will be more obviously whereas NH creep that dominates in the coarse grained material because their grain boundaries are less. So, only the diffusion can take place through the lattice. So, you can see that the lattice diffusion field is coming here (refer to above figure), which is almost absent here and grain boundary diffusion is absent here, but if you say let us say for 0.1 mm, I can see both the lattice and the grain boundary diffusion in the diffusional flow where the diffusional creep is taking place and also the size of the power law creep area is increasing . Here it was very less in the fine grain size material, but in coarse grain material, the power law creep is extending up to a stress of I think of 10^{-5}.

Almost going up to there, whereas in this case, it is almost ending at between 10^{-4} to 10^{-3}. It is also shifting towards the lower temperatures. At lower temperature you can start having the creep process. So, very interesting that to see the effect of microstructure on the deformation mechanism map.

Of course, you should be seeing that it is only developed for pure nickel here. So, this is the effect of grain size. So, as grain size is increasing you are having lattice diffusion is coming as one of the field. Also, my power law creep area is increasing in this direction. Now, this is the difference between the two different crystal structure.

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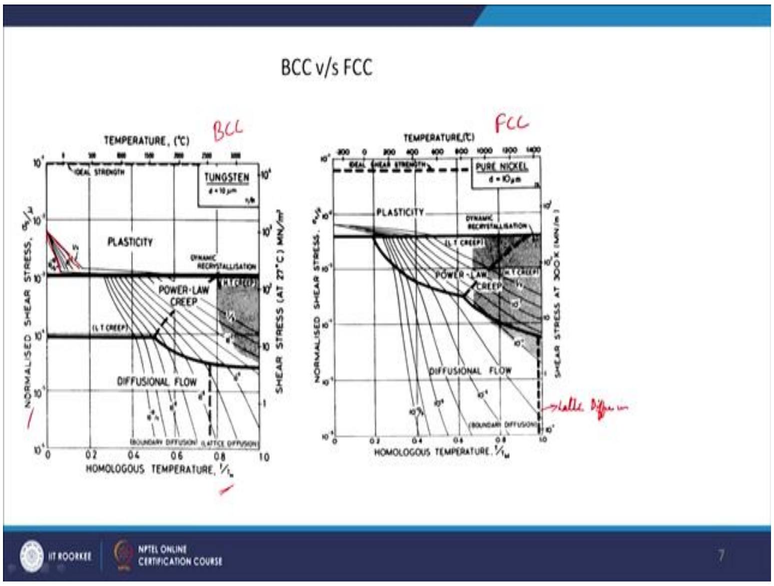

BCC v/s FCC

So, you have one tungsten which is BCC here whereas this is pure nickel, this is FCC (refer to above figure), and again because I am normalising with their melting point and will also normalise the stress. So, I can compare between the two. So, one thing you can see that at lower temperature, my yield stress is dependent on the temperature.

You can see that there is a sharp slope here at lower temperatures. This is because of the lattice resistance to dislocation movement i.e. pulse stress. Whereas in FCC material you do not see a very strong dependence, very shallow slope is there. So, in BCC material, that there is a strong temperature dependence on the flow stress or the yield stress of the material.

If you come to higher temperatures, again you have a power law creep region, where your low temperature and high temperature region are there. So, the area of power law creep is over a one order of magnitude. Difference is there between the strain rate. Here also almost it is one order of magnitude difference is there (refer to above figure). The interesting part here is about the diffusional flow.

You can see boundary diffusion as well as lattice diffusion in the BCC material and lattice diffusion is starting after homologous temperature of maybe around point 0.7, 0.8 or so, whereas in this case you do not see any lattice diffusion (refer to above figure). This is actually the lattice diffusion which is hardly having any field here. The whole thing is boundary diffusion at 10 micron.

That means, there is something in the crystal structure and why BCC has more diffusion through lattices because it has more open the structures, to diffusion through lattice is much easier in case of BCC than an FCC material. FCC is a more compact atomic arrangement so that effect you can see here. Also you can see there is one region of dynamic recrystallization is also shown here (refer to above figure).

Another interesting thing is that you can see this constant strain rate contours. So, in case of FCC material it is going 10^{-10} is going up to 0.4 homologous temperature whereas, in case of BCC material it is going only up to .5 homologous temperature. So, there is effect on the response of the material also as you are changing the crystal structure.

So, the mechanism map will change also as a function of microstructure, grain size, we have just seen and also as a function of the crystal structure.

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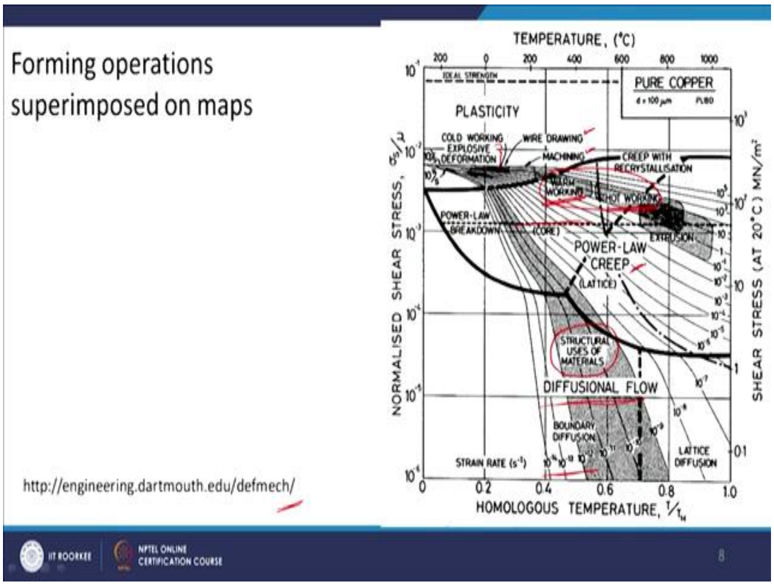

Forming operations superimposed on maps

http://engineering.dartmouth.edu/defmech/

Some more modifications were tried on deformation mechanism map. Very good source if you want on deformation mechanism map is this particular site you can go through the site also that you can superimpose the forming operation on a deformation mechanism map . So, you can see they have superimposed a forming operation like cold working so, explosive deformation very high strain rate, at low temperature. Then wire drawing, another low temperature deformation. So, all these are being done at lower temperatures. Then machining, machining also is can be considered as one of the deformation process only. So, by deformation only you take out the chip. Then you are coming to warm working here that means temperatures are increasing. Similarly, hot working is there.

So, these strain rates are more than the creep deformation. Temperatures are high, but the strain rate or the flow stress if you see here is more here whereas, the creep takes place at lower stresses. And if you come to creep, you have power law creep of course, there is a power law breakdown also. So, after certain strain rate or stress, there will be a power law breakdown, we have seen that power law equation was only valid up to a particular strain rate or stress range.

After that it was not a power law, we used an exponential equation for higher stresses. So, you can see there is a power law breakdown here below that it is power law creep and even below that it is a diffusional creep. So, the material which is used for high temperature structures, they are used in this range where only the diffusional flow will be the important one. That means, the stresses on the components are much lower.

So, that the other deformation mechanism should not operate, only diffusional flow you cannot stop, if you are working at a higher temperature at temperatures more than 0.5 T_m. But still you can see the strain rates are very low, the strain rate contours are 10^{-14} to 10^{-12} in that region. You will use the material for structural applications.

So, for example, a thermal power plant, the material which are used in thermal power plant or the material is used in gas turbine, so, what will be the temperature that material will be used in those structural application that particular region is this one whereas, deformation, warm working, hot working will be in this region (refer to above figure). Cold working will be even at lower temperature and higher stresses.

So, they were also trying to superimpose the deformation processes on these deformation mechanism map. But again please be careful we are doing it for pure copper. Now, there was another extension to this idea of deformation mechanism map which was proposed by Ashby. You can see that only the stable behaviours are shown there for example where there are no defects are identified in their processing map.

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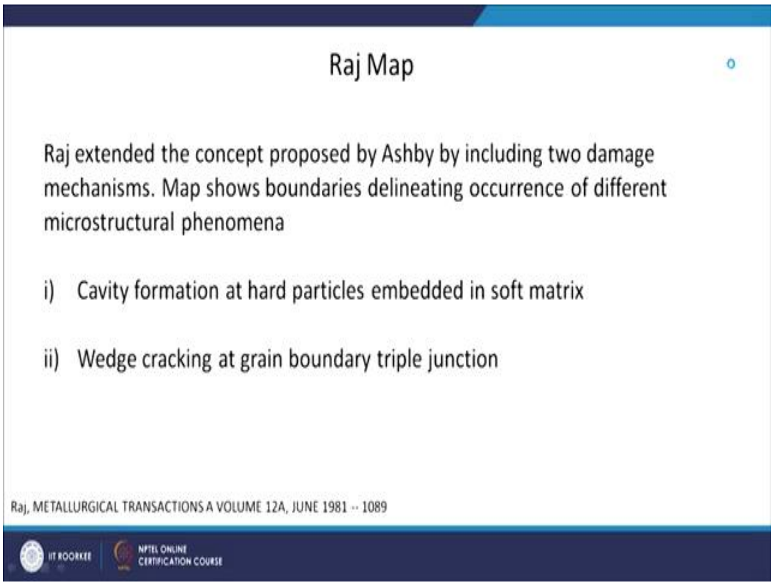

Raj Map

Raj extended the concept proposed by Ashby by including two damage mechanisms. Map shows boundaries delineating occurrence of different microstructural phenomena

i) Cavity formation at hard particles embedded in soft matrix

ii) Wedge cracking at grain boundary triple junction

Raj, METALLURGICAL TRANSACTIONS A VOLUME 12A, JUNE 1981 -- 1089

So, R.Raj, another researcher extended this concept of Ashby by including the defects or damage mechanism also in the deformation mechanism maps. For example, he introduced the idea of cavity formation during the deformation at high temperature. Cavity formation is a very important defect which can take place. So, this Cavity forms at hard particle which are embedded in a soft matrix.

Or there can be a wedge cracking at the grain boundary, grain boundary becomes weak at higher temperature. So, grain boundary separation can takes place. So, these different microstructural phenomena can be which are related to defect can be superimposed on the processing map or deformation mechanics map . So, this was an extension to that idea.

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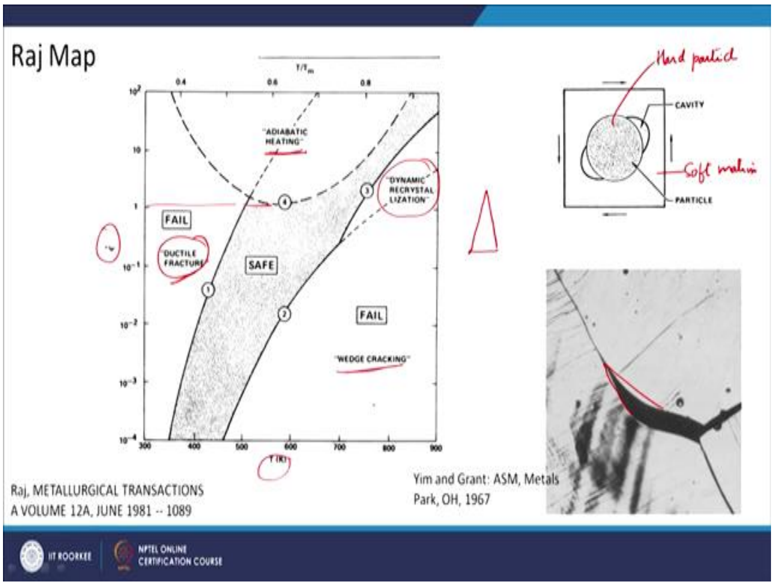

Raj Map

Raj, METALLURGICAL TRANSACTIONS A VOLUME 12A, JUNE 1981 -- 1089

Yim and Grant: ASM, Metals Park, OH, 1967

So, this is what they were trying to bring out (refer to above figure). So, you have strain rate on the y-axis and temperature on the x-axis. So, different defects are identified for example, wedge cracking a ductile fracture of course, at low temperature at sufficiently high strain rate you will have a ductile failure. Very high strain rate as I have already told you that you can have adiabatic heating because you are not giving enough time for heat to dissipate.

So, again you can see around strain rate of one above that the adiabatic heating will start dominating or it will be an important factor. And we also did stress correction in the constitutive analysis only above the strain rate of one. Then you can have dynamic recrystallization which is the desired microstructural change, which will be at higher temperature and sufficiently at intermediate strain rate range.

So, you have failure at different level and this is my safe region (refer to above figure). The dashed area is the safe region for my processing where you will not introduce any defects. So, there are couple of schematic is shown for the formation of cavity. This is my hard particle in a soft matrix. So, when you are deforming what will happen? The deformation, because matrix is soft, it will be able to deform but the particle is hard it is not going to deform.

So, because of that there will be the interface between the particle and matrix will have a breakdown and you will create cavities on both the side of the particle. So, that can happen as one of the defect. Another one is this wedge. So, wedge is a shape like a wedge. So, when you want to create for example, when you are cutting wood, you put a wedge and then you hammer it.

So, wood will open up. So, this is what you can see a shape of a wedge here on the grain boundary and that happens because of the separation of the grain boundary. So, you can see it happens at very high temperature, but relatively lower strain rates or lower stresses. So, at high temperature the grain boundaries become weak and even a smallest stress will be able to separate the two grains at the grain boundary. And you will have a defect called wedge cracking. So, these are the different defects he superimposed on the deformation mechanism map.

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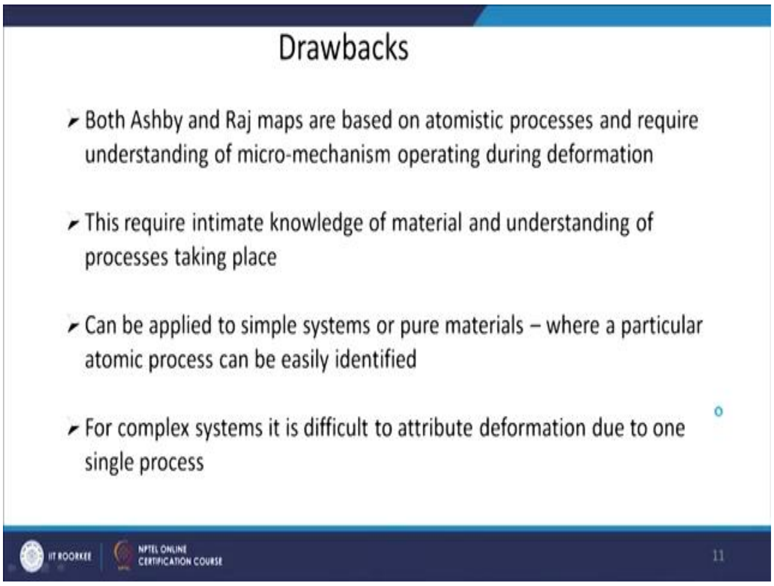

Drawbacks

- Both Ashby and Raj maps are based on atomistic processes and require understanding of micro-mechanism operating during deformation
- This require intimate knowledge of material and understanding of processes taking place
- Can be applied to simple systems or pure materials – where a particular atomic process can be easily identified
- For complex systems it is difficult to attribute deformation due to one single process

Now, the problem with deformation mechanism map is that you have a very good understanding of the atomistic processes. Like what is the creep, where the creep is taking place diffusional creep, dislocation creep. So, for every processing condition you have to do a very good microstructural analysis. And you should have a very well and good understanding of the microstructures to understand that what type of process is taking place.

So, you should have a very good knowledge of all these microstructural changes. And again for a practising engineer, doing all these things will be too much to ask because he has to also look at the production and also as I have told you at different places that these maps are developed only for very simple system, pure materials, pure copper, pure nickel and so on.

Because there only you can attribute a certain deformation mechanism for a particular microstructural change. Whereas, if you have a complex material you have two phases, you have precipitate, you have salute materials, salute atoms then clearly identifying that which particular constituent is responsible for a particular mechanism is very difficult .

So, for complex system it is difficult to attribute deformation due to one single process because there are multiple processes taking place. Dislocation is also there, diffusion is also taking place, solutes are diffusing and precipitates are doing their own business. So, these deformation mechanism maps are very useful to understand or to develop the understanding, but it will be very difficult to apply it to main engineering alloys.

And also it will be very difficult to predict any processing conditions from these maps for processing of a complex alloy. So, we will come to the next lecture that how it was solved, that this deformation mechanism map idea was extended and how these particular problems were solved in the processing map, which is used for hot deformation processes. So, thank you for your attention.

Key words - Deformation Mechanism Maps, Creep.