Structural Geology
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Lecture 15
Deformation Mechanism Part 3 Intracrystalline Deformation

Hello everyone! Welcome back again to this online structural geology in NPTEL course and we are learning the formation mechanism in this week and today we are in our lecture number 15, Part 3 and we will learn intra crystalline deformation. Before this lecture at the very beginning of this week we learned Crystal defects. Then we learned a cataclastic deformation and today particularly in this lecture we will be using the concepts that we have learned from our first lecture of Crystal defects.

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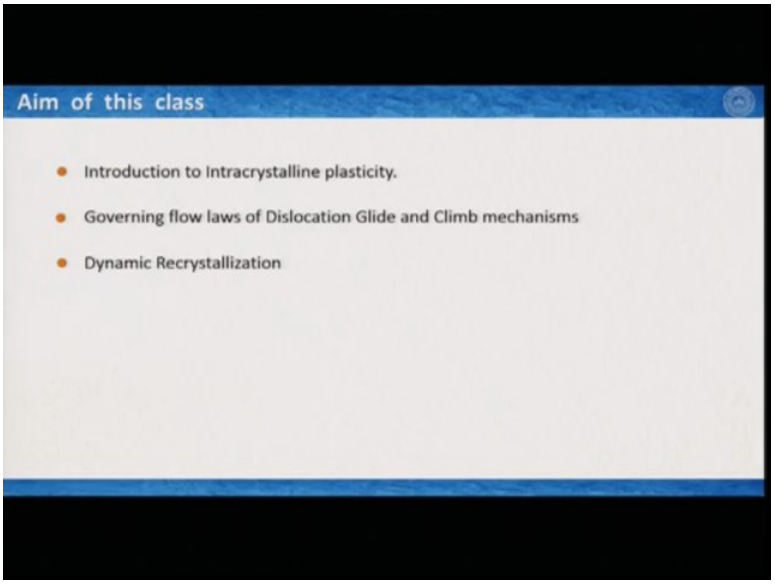

Aim of this class

- Introduction to Intracrystalline plasticity.
- Governing flow laws of Dislocation Glide and Climb mechanisms
- Dynamic Recrystallization

So in this lecture will mostly cover intra crystalline plasticity as I told a few seconds before what we are going to do with this subject we will very briefly go into this topic and introduce the different processes which are involved in this and then will slowly see the different governing laws for particularly dislocation glide and dislocation climb mechanisms. We learned about these two terms in the first lecture and finally will conclude this lecture with dynamic re-crystallization. And in the next lecture we will learn about diffusion creep or diffusive mass transfer.

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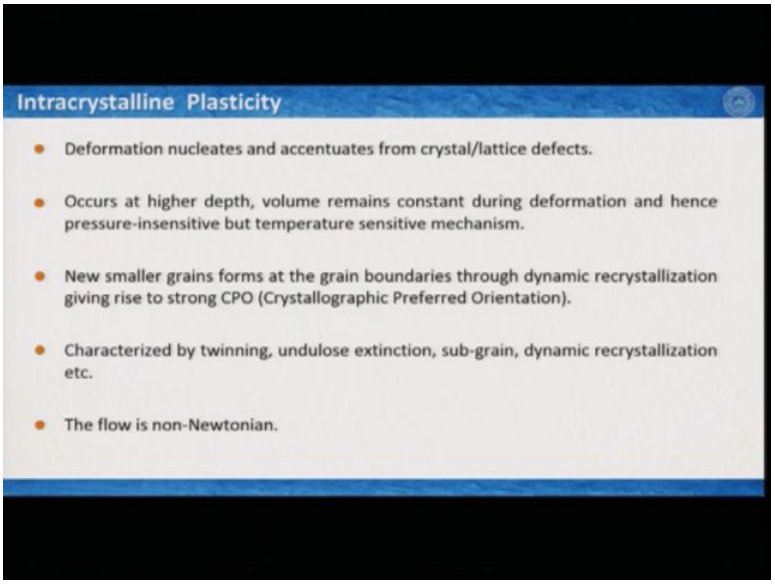

Intracrystalline Plasticity

- Deformation nucleates and accentuates from crystal/lattice defects.
- Occurs at higher depth, volume remains constant during deformation and hence pressure-insensitive but temperature sensitive mechanism.
- New smaller grains forms at the grain boundaries through dynamic recrystallization giving rise to strong CPO (Crystallographic Preferred Orientation).
- Characterized by twinning, undulose extinction, sub-grain, dynamic recrystallization etc.
- The flow is non-Newtonian.

So here are some basics of intra crystalline plasticity. Unlike cataclastic deformation in the domain or in the mechanism of intra crystalline plasticity the deformation generally nucleotides and then accentuates from the crystal or lattice defects. So we learned about what are these crystal and lattice defects and we will see how they help us to understand better the intra crystalline plasticity. Now because this is mostly governed by Crystal defects so it occurs at a higher depth.

That means that the temperature is high because of it is at higher depths of volume remains constant during deformation and therefore it is pressure insensitive deformation. But essentially it is highly temperature sensitive mechanism and we will see how temperature greatly influences this process. We develop a very characteristic micro structure when we see the rocks undergoing deformation through intra crystalline plasticity. So generally what happens if you generate new smaller grains from the original grain we will call it parent grain so the new smaller grains the nucleus and the boundaries of the parent grains through the process of dynamic reconciliation.

And therefore it gives rise a very strong Crystallographic preferred orientation or CPO and otherwise the micro structures you can think of it these are characterized by twinning and undulose extinctions sub grains and the different signatures of dynamic re-crystallization. We will see all these things at the end of this lecture different type or different kinds of micro structures produced by intra crystalline plasticity and will see that this flow is not non-Newtonian.

So it is a strain rate dependent essentially but strain rate is not linearly dependent on the stress. We will see the equations somewhere in this lecture. So the very basic idea of intra crystalline plasticity as we have learned that it is the movement of the dislocations through the crystal.

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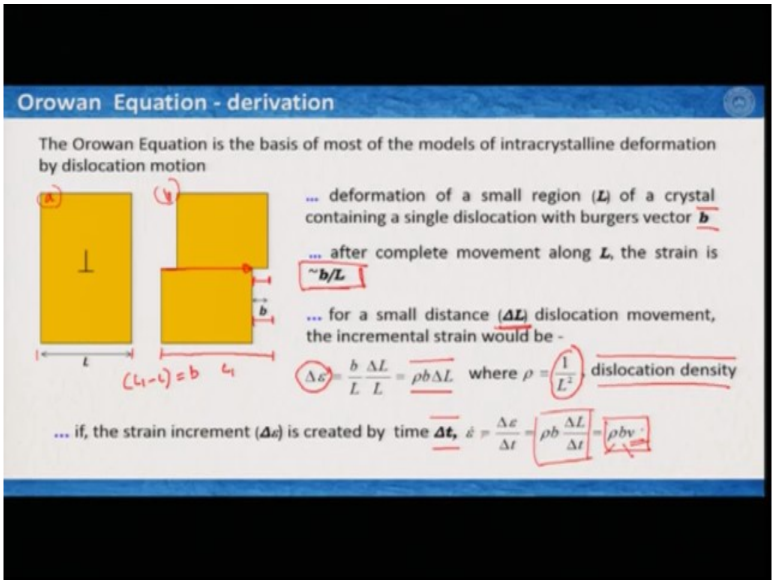

Orowan Equation - derivation

The Orowan Equation is the basis of most of the models of intracrystalline deformation by dislocation motion

... deformation of a small region (*L*) of a crystal containing a single dislocation with burgers vector ***b***

... after complete movement along *L*, the strain is $\boxed{\sim b/L}$

... for a small distance (*ΔL*) dislocation movement, the incremental strain would be -

$\Delta\varepsilon = \frac{b}{L}\frac{\Delta L}{L} = \rho b \Delta L$ where $\rho = \frac{1}{L^2}$, dislocation density

... if, the strain increment (*Δε*) is created by time **Δt**, $\dot{\varepsilon} = \frac{\Delta\varepsilon}{\Delta t} = \boxed{\rho b \frac{\Delta L}{\Delta t}} = \boxed{\rho b v}$

At the present the simplest way to do that is the Orowans equation. So Orowans equation is nothing but the basic of most of the intra crystalline models from which the other complex equations or formulations are derived. So what do we see in this slide we have this yellow grain where this inverted t is a dislocation and the length of this crystal is L now when the dislocation moves from one end to other end of this grain at the initial stage let us say this A at the final stage at B we see that the grain has deformed so the single dislocation move from here to here giving rise a strain in the crystal.

Now if this is L and then I consider this one is L1 then certainly L1 minus L is the burger's vector which is this unit vector of the dislocation movement so if we consider this if we try to theorize it so deformation of a small region L in a crystal containing a single dislocation with Burger's vector b and this is what exactly we just talked about. Now when the movement is complete along this length L then the strain is Burger’s vector divided by the initial length of the crystal. So therefore here the strain is essentially this B. So this is L1 minus L divided by L. So therefore this is the strain that we have generated by moving the dislocation from one point to the other end of this crystal.

Now if you consider that the distance is very small for example Del L of the dislocation movement then the incremental strain we can consider or which we can call Del Epsilon should be b divided by L Del L by L. Now we can clearly see that if we replace this 1 by L square or these two else by a term called rho which will define as this location density then the equation takes the shape of this where Delta Epsilon is equal to rho which is your dislocation density Burger's vector and Delta L these three are multiplied to each other.

Now if we have achieved this little strain through a time of very small Delta T a very small time then this Epsilon dot or strain rate is Delta Epsilon by Delta T. That would give you this form rho B delta L by Delta T. Now delta L by Delta T you can consider this as a velocity. So finally we arrive to this equation strain rate is equal to products of this location density Burger's vector and this V is the velocity of the dislocations or dislocation velocity. Now this is a very important equation and we will see what are the implications of these terms or how this dislocation density Burger's vector and dislocation velocity could influence the strain wreck.

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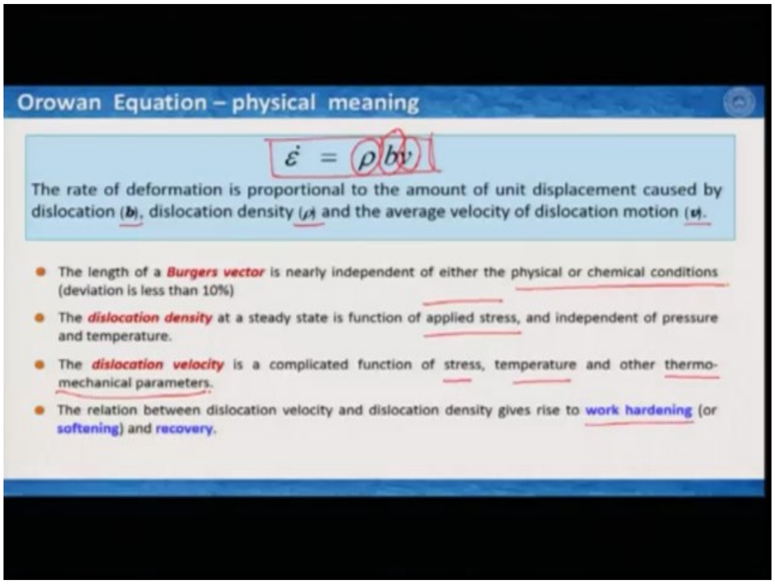

Orowan Equation – physical meaning

$$\boxed{\dot{\varepsilon} = \rho b v}$$

The rate of deformation is proportional to the amount of unit displacement caused by dislocation (**b**), dislocation density (**ρ**) and the average velocity of dislocation motion (**v**).

- The length of a ***Burgers vector*** is nearly independent of either the physical or chemical conditions (deviation is less than 10%)
- The ***dislocation density*** at a steady state is function of applied stress, and independent of pressure and temperature.
- The ***dislocation velocity*** is a complicated function of stress, temperature and other thermo-mechanical parameters.
- The relation between dislocation velocity and dislocation density gives rise to **work hardening** (or **softening**) and **recovery**.

So this equation epsilon dot equal to rho b v is the fundamental equation and it is the rate of deformation is proportional to the amount of unit displacement caused by the dislocation which is Burger's vector dislocation density rho and the average velocity of the dislocation motion which is V.

Now in this equation if we consider these three parameters Burger's vector dislocation density and dislocation velocity we can see that the length of a Burger's vector is nearly independent because this is an intrinsic property of the crystal. So it is very much independent. It does not depend on anything of either any physical or chemical conditions. So deviations are generally observed experimentally less than 10 percent.

The dislocation density at a steady state is a function of the applied stress and it is independent of pressure and temperature, so dislocation density is a function of the stress which are being applied. Dislocation velocity on the other hand is a very complicated function of stress temperature and several other thermal mechanical parameters will not go into the details of this but in summary Burger's vector in this equation is sound sort of constant. It is a function of the material of the crystal we are using dislocation density Rho is a function of the applied stress dislocation velocity is a function of the Applied stress temperature and several other parameters.

Now if we consider all these three and if we have to achieve a strain in the system then there is a computation between two processes that how does a crystal or an aggregate of poly crystals accommodate strain within themselves. Now this gives rise to two distinct mechanisms. One is work hardening or softening and another is recovery. We will see these in the next slide.

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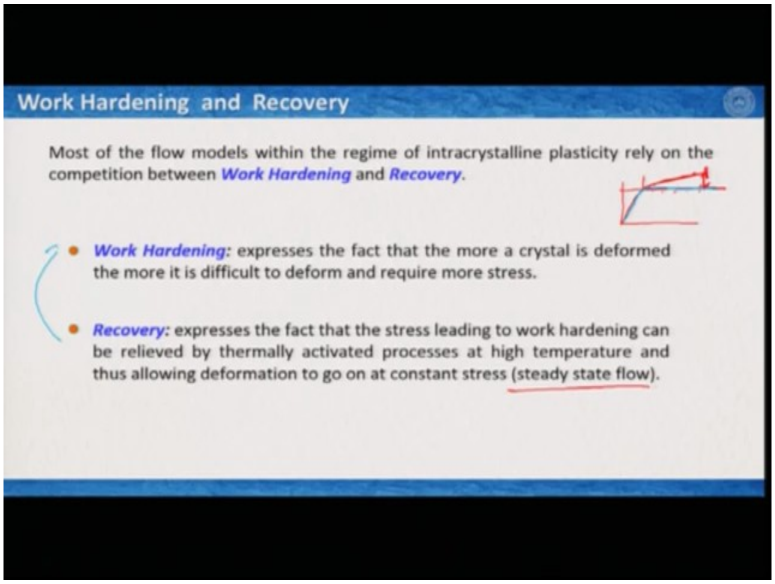

Work Hardening and Recovery

Most of the flow models within the regime of intracrystalline plasticity rely on the competition between ***Work Hardening*** and ***Recovery***.

- ***Work Hardening:*** expresses the fact that the more a crystal is deformed the more it is difficult to deform and require more stress.
- ***Recovery:*** expresses the fact that the stress leading to work hardening can be relieved by thermally activated processes at high temperature and thus allowing deformation to go on at constant stress (steady state flow).

So the flow models if we talk about are within the regime of the crystalline plasticity where the crystals are deforming following Quinto crystalline plasticity. This is a computation as I talked about between work hardening and recovery. Now what is work hardening? Work hardening expresses the fact that more a crystal is deformed the more it is difficult to deform and require more stress. That means the system that I am deforming through the mechanism of into crystalline plasticity it requires more and more stress to deform it.

Now if I start deforming it then it requires more and more stress to continue the deformation. If I look at in the form of a stressed strain curve, so it is simply after the yield it does not flow this way you need more and more stress to deform it and this phenomena we learned is known as hardening or strain hardening. However recovery is essentially the opposite process of work hardening which expresses the fact that the stress leading to work hardening can be relieved by thermally activated processes at high temperature and thus allowing the deformation to go on at constant stress which is also known as Steady State flow.

So, that means the stress I need here this extra stress after the yield can be compromised if I add some temperature to the system so if I add temperature then instead of following the red curve after the yield it can flow along a steady state manner that means you do not need more stress to deform the rocks at a constant stress you can continue the deformation. So the intra crystalline plasticity mechanism from this slide we can summarize that it's a competition between work hardening and recovery whoever wins the deformation continues or deformation stops or the crystal or the poly crystals produce fractures.

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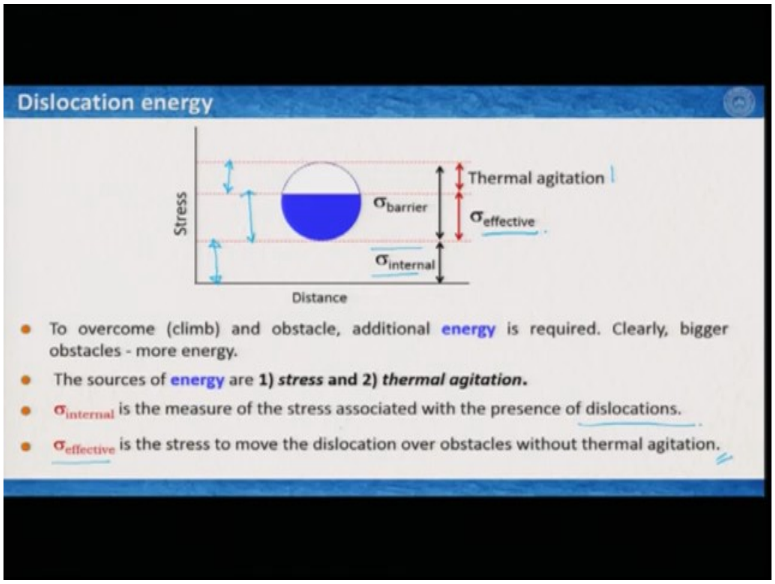

Dislocation energy

- To overcome (climb) and obstacle, additional **energy** is required. Clearly, bigger obstacles - more energy.
- The sources of **energy** are **1) *stress* and 2) *thermal agitation.***
- $\sigma_{internal}$ is the measure of the stress associated with the presence of dislocations.
- $\sigma_{effective}$ is the stress to move the dislocation over obstacles without thermal agitation.

Now the question is how does it work? How what is the control or what are the controls of different types of energies that how temperature can come and lower the stress level required to deform the crystal. Here is a cartoon diagram where I tried to explain the process. We know that inside a Crystal if we have a dislocation or multiple dislocations that means dislocation. Density is there with some values so the individual dislocations if you remember the nearby bonds are either stretched or compressed so therefore we have some sort of internal energy within the crystal.

It is known as Sigma internal so it can give you a certain amount of stress to deform the crystal however if I have this circle here this blue circle here. If this is an obstacle and the dislocation is moving this way then it suddenly cannot overcome this obstacle and come here to move further to continue its movement. We already know that from here to here this jump is known as dislocation climb but work to get this energy now a part of this energy suddenly comes from the stress you are applying.

Accordingly clearly you need this amount of stress to climb this obstacle. It is known as Sigma barrier a part of this stress or energy comes from the deformation or differential stress that is being applied to the system. So let us assume that it is this much which we call Sigma effective but we still are left with this much of energy which can come from the temperature or thermal agitation of the system.

Then we can see that primarily the crystal has energy within this in the form of dislocations which we call Sigma internal and then rest of the energy required to climb the obstacles is Sigma barrier and the Sigma barrier is achieved by combination of the effective stress and some thermal agitations. So this is what is written here to overcome climb and obstacle additional energy is required.

Clearly bigger the obstacles, you need larger energy so the sources of energy to achieve the level of Sigma barrier are stress and thermal agitation and here there are some definitions. Sigma internal is the measured of the stress associated with the presence of dislocations as I have explained and Sigma effective is the stress to move the dislocations over obstacles without any thermal agitation at least in this cartoon diagram.

We see that Sigma effective is not sufficient enough to overcome or to climb the obstacle and continue the motion of the dislocation now in the next slide we will see some different possibilities where this Sigma internal Sigma effective and thermal agitations are competing each other to continue the movement of the dislocation.

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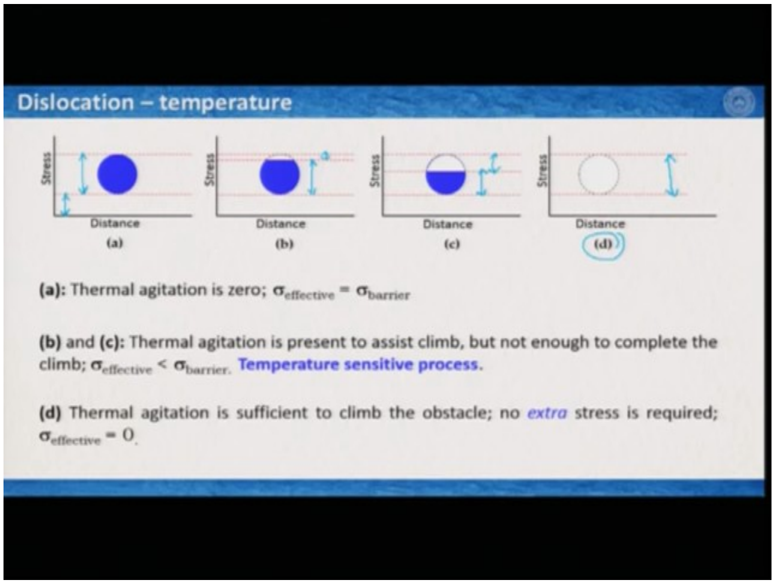

Dislocation – temperature

(a): Thermal agitation is zero; $\sigma_{effective} = \sigma_{barrier}$

(b) and **(c):** Thermal agitation is present to assist climb, but not enough to complete the climb; $\sigma_{effective} < \sigma_{barrier}$. **Temperature sensitive process.**

(d) Thermal agitation is sufficient to climb the obstacle; no *extra* stress is required; $\sigma_{effective} = 0$.

So the first one number a partial agitation is 0. So therefore this is your internal energy or Sigma internal and this one is your Sigma barrier so you have to have your effective stress equal to the Sigma barrier so that individual dislocation can climb this blue obstacle now in B and C thermal agitation is there, here this is this much and here this is a little higher but in both cases the thermal agitation is not high enough or large enough to overcome or to climb the obstacle. So in this case it needs this much of effective stress and in this case it also need this much of effective stress.

However, in the case of d this thermal agitation is absolutely fine to climb this obstacle so you do not need any stress, you do not need any extra stress required to climb this obstacle. So what do you see here clearly that if I have higher temperature then movement of this location is much easier and that can happen at high temperature. So at higher temperature the strength of the stress is not required or you do not need much stress to deform the crystals and if you remember in geology lecture we learned about it that at high temperature the strength of the material decreases drastically.

And now you know the micro mechanics why if you have temperature then the system gets the crystals get do you get enough energy to move the dislocations and deform the crystal through the process of into crystalline plasticity.

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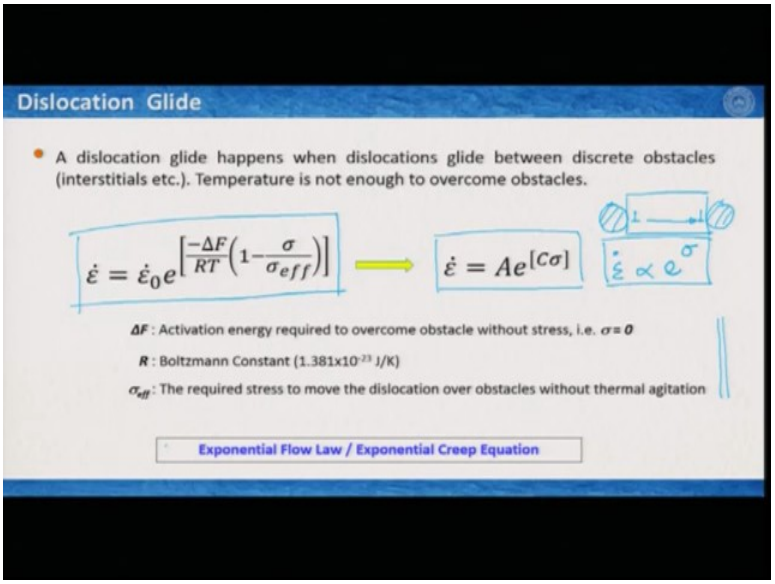

Dislocation Glide

- A dislocation glide happens when dislocations glide between discrete obstacles (interstitials etc.). Temperature is not enough to overcome obstacles.

$$\boxed{\dot{\varepsilon} = \dot{\varepsilon}_0 e^{\left[\frac{-\Delta F}{RT}\left(1-\frac{\sigma}{\sigma_{eff}}\right)\right]}} \Longrightarrow \boxed{\dot{\varepsilon} = Ae^{[C\sigma]}} \quad \boxed{\dot{\varepsilon} \propto e^{\sigma}}$$

ΔF : Activation energy required to overcome obstacle without stress, i.e. $\sigma = 0$

R : Boltzmann Constant ($1.381\text{x}10^{-23}$ J/K)

σ_{eff} : The required stress to move the dislocation over obstacles without thermal agitation

Exponential Flow Law / Exponential Creep Equation

Now we will see very briefly the fundamental equations for this location glide and dislocation climb. I am not going to show you the derivations or I also do not ask you to perform the derivations but if you want then you certainly can do that, there are some books also online materials. I personally prefer the book of Poirier. So you can check that book and get see how the equations are derived. But my aim here is to show by showing the equations mostly to explain or to narrate that. What are the relations between the strain rate and stress in these equations?

So first the dislocation glider dislocation glide happens when dislocations do glide between discrete obstacles. So that means if I have an obstacle here then a dislocation can move from here to here. That means that it does not have enough energy in the system to climb and continue the motion. So it is restricted between two obstacles and in that case the larger form of the equation is like this. You do not have to pay too much attention here. But if we shrink the equation or simplify the equation it takes the form like this.

What is important here that we can see if we simplify it strain rate is proportional to Sigma with an exponential term to stress with an exponential term. So that is known as exponential flow law. So what are the different parameters here for example, delta, if here is activation energy R is the Boltzmann constant Sigma effective the required stress to move the dislocations over obstacles without any thermal agitations and so on.

But I repeat you do not have to pay too much attention in this form but it is important that you understand this fact that in this location glide the strain rate is exponentially related to the stress and therefore this is known as exponential flow law.

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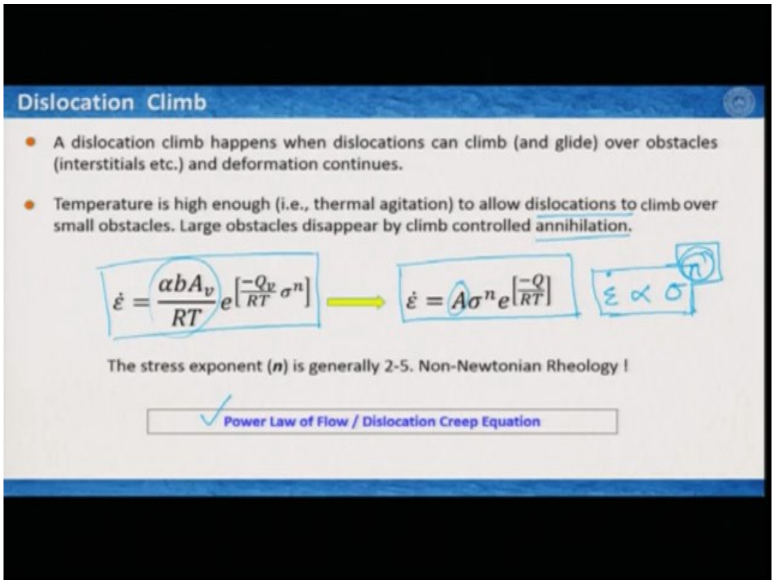

Dislocation Climb

- A dislocation climb happens when dislocations can climb (and glide) over obstacles (interstitials etc.) and deformation continues.
- Temperature is high enough (i.e., thermal agitation) to allow dislocations to climb over small obstacles. Large obstacles disappear by climb controlled annihilation.

$$\boxed{\dot{\varepsilon} = \frac{\alpha b A_v}{RT} e^{\left[\frac{-Q_v}{RT}\sigma^n\right]}} \longrightarrow \boxed{\dot{\varepsilon} = A\sigma^n e^{\left[\frac{-Q}{RT}\right]}} \quad \boxed{\dot{\varepsilon} \propto \sigma^{\boxed{n}}}$$

The stress exponent (n) is generally 2-5. Non-Newtonian Rheology !

✓ Power Law of Flow / Dislocation Creep Equation

In contrary dislocation climb happens when the dislocations can climb and at the same time of course glide over obstacles. And these are industry shills and so on. So what I mean by that I have one obstacle here. I have one obstacle here and other obstacle here. So dislocations can actually climb and move and move and move and so on and then it again can jump and move on.

So it has enough energy to continue the movement of the dislocations so it requires as we have understood a good amount of temperature so it is high enough or thermal agitation to allow the dislocations to climb over small obstacles and of course the large obstacles can disappear by climb controlled annihilation.

We are not going to explain this term right now but annihilation is nothing but if we have two differently oriented dislocations two supposedly oriented dislocations they can come together and the dislocation can vanish. So this is known as annihilation but let us have a look at the equation. Again you do not have to look at this general form but what we can see here this here we have all these burgers vector this some constants and so on.

So therefore one can club all these things to a constant and this recall material constant and the final equation takes the shape of this strain rate is equal to a material constant multiplied by sigma with the stress exponent n e to the power minus Q by R T. But again if we try to see the relationship between strain rate and stress it comes in this form and here strain rate is not related to the stress linearly but it requires an exponent which we call stress exponent.

Now this stress exponent experimentally people found it at this range of dislocation climates generally varies from 2 to 5. It can be much higher but then we assign it to it to a different mechanism. So what we see here strain rate and stress they are not linearly related but it requires an exponent which is n in this case. So therefore it is non-Newtonian Rheology as we have learned at the very beginning and because it has a power sigma as a power of n is known as power or flow or dislocation equation.

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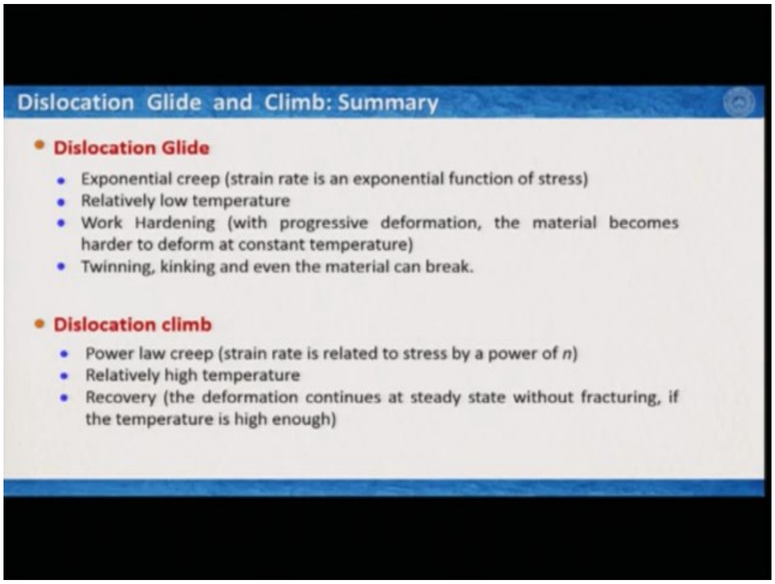

Dislocation Glide and Climb: Summary

- **Dislocation Glide**
  - Exponential creep (strain rate is an exponential function of stress)
  - Relatively low temperature
  - Work Hardening (with progressive deformation, the material becomes harder to deform at constant temperature)
  - Twinning, kinking and even the material can break.

- **Dislocation climb**
  - Power law creep (strain rate is related to stress by a power of *n*)
  - Relatively high temperature
  - Recovery (the deformation continues at steady state without fracturing, if the temperature is high enough)

Now we see that if we try to compare a dislocation glide and dislocation climb then dislocation glide is an exponential creep where strain it is an exponential function of stress. It happens at relatively low temperature because if it is high temperature then it would change to the dislocation climb work hardening with progressive deformation. The material becomes harder to deform at constant temperature is the characteristics because again you do not have enough temperature so to do the climb. It requires more stress therefore work hardening is a characteristics of dislocation glide and it is micro structurally it is characterized by twinning thinking and if you force it because you are applying work hardening so you can even produce a fracture.

On the other hand, if we look at dislocation climb it is a power law creep. So strain rate is related to strain to a power of n. It happens relatively at high temperature and therefore recovery is one of the fundamental processes in dislocation climb where the deformation continues at steady state without fracturing if the temperature is high enough.

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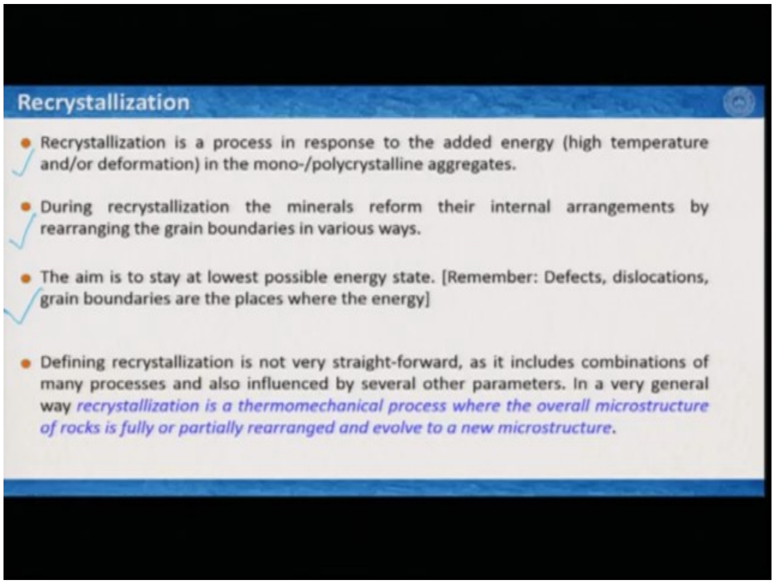

Recrystallization

- Recrystallization is a process in response to the added energy (high temperature and/or deformation) in the mono-/polycrystalline aggregates.
- During recrystallization the minerals reform their internal arrangements by rearranging the grain boundaries in various ways.
- The aim is to stay at lowest possible energy state. [Remember: Defects, dislocations, grain boundaries are the places where the energy]
- Defining recrystallization is not very straight-forward, as it includes combinations of many processes and also influenced by several other parameters. In a very general way *recrystallization is a thermomechanical process where the overall microstructure of rocks is fully or partially rearranged and evolve to a new microstructure.*

Now you're going to learn what are the manifestations of this dislocation glide and climb. What happens to the actual crystal? We learned that at the very beginning when we were talking about the basics of internal crystalline plasticity that new grains appear and the grain boundaries of the older grains. So these are the studies or and so on the crystals itself modifies and takes a new shape unlike the cataclastic deformation. They are not allowed to produce so-called fractures within the domain of intra crystalline plasticity. So we will learn how does it happen and the process that takes care of the entire grain rearrangement within the domain of intra crystalline plasticity is known as re-crystallization.

So recrystallization is the process in response to the added energy. And these are high temperature and are deformation to the mono or poly crystalline aggregates so again it has to happen at high temperature and you have to have some sort of deformation or not. If you have a deformation it is something else. If you do not have deformation it is again something else.

So during re-crystallization the minerals reform their internal arrangements by rearranging the grain boundaries in various ways. We will see those very soon and why the crystals rearrange their grain boundaries the essential aim is to stay at the lowest possible energy state. So if you remember the defects dislocations grain boundaries etc. are the places where the energy stays.

So Now if we have to define re-crystallization. So what I talked about in these three points these are just some sort of characteristics but if we have to define re-crystallization it is not very straightforward because it includes a combination of many processes and also influenced by several other will see them. So in a very general way if we have to define we can say that the crystallization is a thermal mechanical process where the overall micro structure of rocks is fully or partially rearranged and evolve to a new micro structure. So I had one type of micro structures and then I generate to another type of micro structure without producing fracture. If that happens then I certainly have recrystallized my crystalline system.

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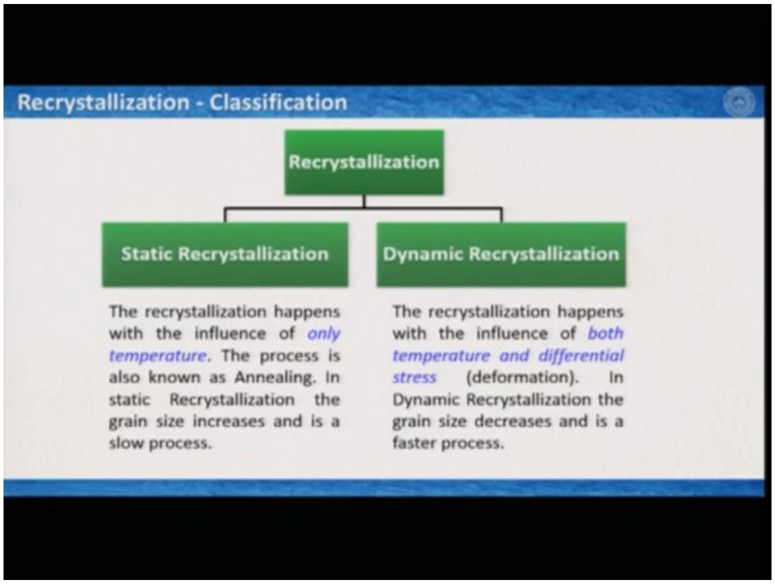

Recrystallization - Classification

Recrystallization

Static Recrystallization

The recrystallization happens with the influence of *only temperature*. The process is also known as Annealing. In static Recrystallization the grain size increases and is a slow process.

Dynamic Recrystallization

The recrystallization happens with the influence of *both temperature and differential stress* (deformation). In Dynamic Recrystallization the grain size decreases and is a faster process.

So we can classify crystallization in two basic ways. One is static recrystallization and another is dynamic recrystallization static recrystallization if you have to understand it is very simple It happens with the only influence of temperature the process is also known Annealing that means it makes your grains strain free.

Anneal means making something strain free in static recrystallization the grain size generally increases and it is a relatively slow process the dynamically recrystallization on the other hand when you have influences of both temperature and differential stress that means deformation in dynamic the crystallization the grain size generally decreases but there are some evidences where grain size have increased and it is a faster process there is also another subcategory of recrystallization other than static and dynamic re crystallization and this is known as meta dynamic recrystallization so after the dynamic recrystallization if you have static crystallization then and then again if the cycle continues. So the what happens in between is known as Meta dynamic crystallization we are not going to that part right now.

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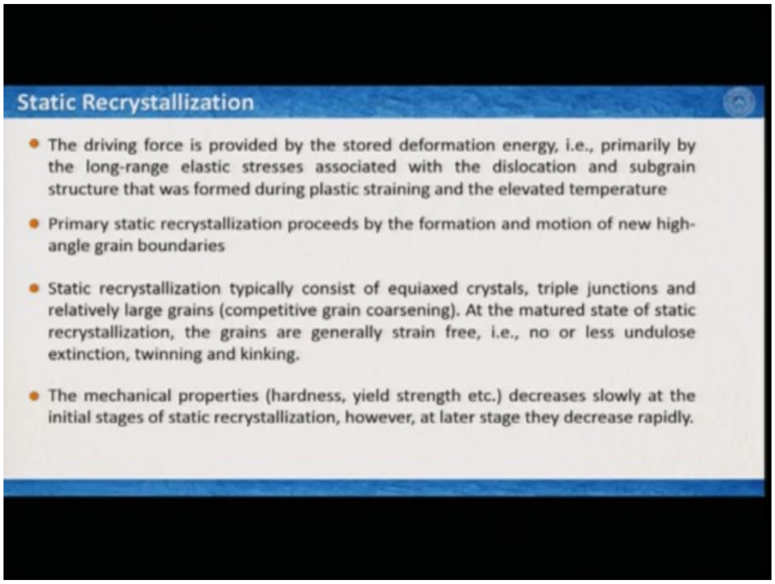

Static Recrystallization

- The driving force is provided by the stored deformation energy, i.e., primarily by the long-range elastic stresses associated with the dislocation and subgrain structure that was formed during plastic straining and the elevated temperature
- Primary static recrystallization proceeds by the formation and motion of new high-angle grain boundaries
- Static recrystallization typically consist of equiaxed crystals, triple junctions and relatively large grains (competitive grain coarsening). At the matured state of static recrystallization, the grains are generally strain free, i.e., no or less undulose extinction, twinning and kinking.
- The mechanical properties (hardness, yield strength etc.) decreases slowly at the initial stages of static recrystallization, however, at later stage they decrease rapidly.

These are the characteristics of static crystallization as you can see it is written here. The driving force is provided by the stored deformation energy. So your Sigma internal that is primarily the large or long range elastic stresses associated dislocation and subject structures that was formed during plastics straining and certainly number two is that elevated temperature.

These are your internal energy and elevated temperature. Primary static liquid is in process some sort of happens by the formation and motion of new high angle grain boundaries. Static re-crystallization typically consists of equiaxed crystals. That means the crystals are mostly of similar size. The micro structure is also characterized by triple junctions and the grain size is relatively larger and this is the green growth is known as competitive grain coarsening that the match your state of statically crystallization the grains are generally strain free as I talked about it is annealing.

The process is called annealing that is you do not have any internal energy within the grain so you know you should not see or very less unduglose extinction twinning and kinking and so on. Interestingly the mechanical properties the hardness instant etc. decreases slowly at the initial stages of statically recrystallization but when the crystals grow in a very large way then these properties the mechanical properties the decrease very rapidly.

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Static Recrystallization

http://maps.unomaha.edu

Photomicrograph mosaic of dunite from North Carolina showing the fairly well developed polygonal texture due to static recrystallization with strain free grain interiors.

So here are some examples show you in couple of slides that the statically recrystallized minerals what we see here in this image is a photo micro graph of the Unite from North Carolina and what we see here as we talked about you can see that this is a crust polarized image that internally the grains do not show any unduglose extinction.

The grains are more or less equal and you can see also very nice triple junctions. If you go wherever you want, you see excellent triple junctions just come so these type of micro structures are classically known or classical characteristics of static re-crystallization. However, in this image you may see that the grains are slightly oriented and this could be the initial deformation that the grains might have at the earlier stage.

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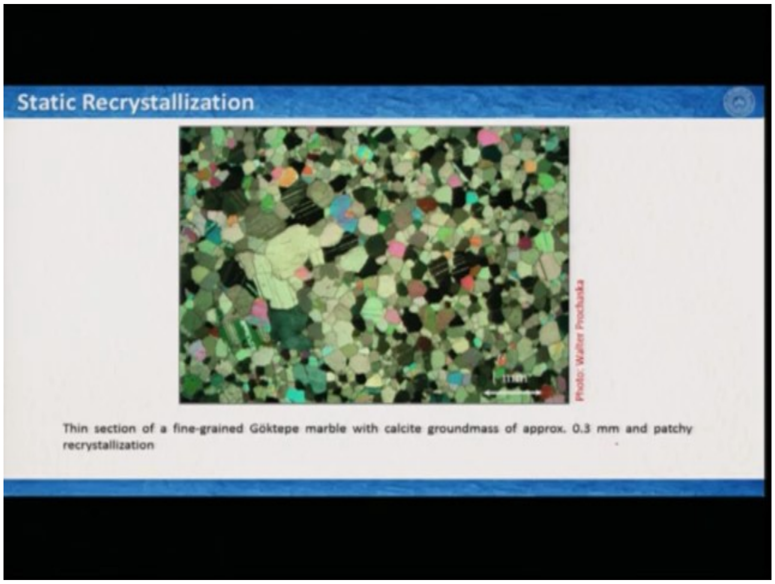

Static Recrystallization

Thin section of a fine-grained Göktepe marble with calcite groundmass of approx. 0.3 mm and patchy recrystallization

Photo: Walter Prochaska

Then the next slide we have a fine grained marble where the mineralogy is calcite brown mass of approximately 0.3 mm and it has a patchy re-crystallization. So you see here, that most of the grains are absolutely strain free. There are few grains like here or here so these three grains somewhere here these grains are characterized and this one these grains are characterized by twinning but most of the grains as you can see again if I look at this Domain most of the grains are again equiaxed more or less of equal size.

You can also see nice triple junctions and the grains are strain free relatively strain free. So these are the signatures of static crystallization. However, as we are studying structural geology we will not pay too much attention on something that did not develop without deformation.

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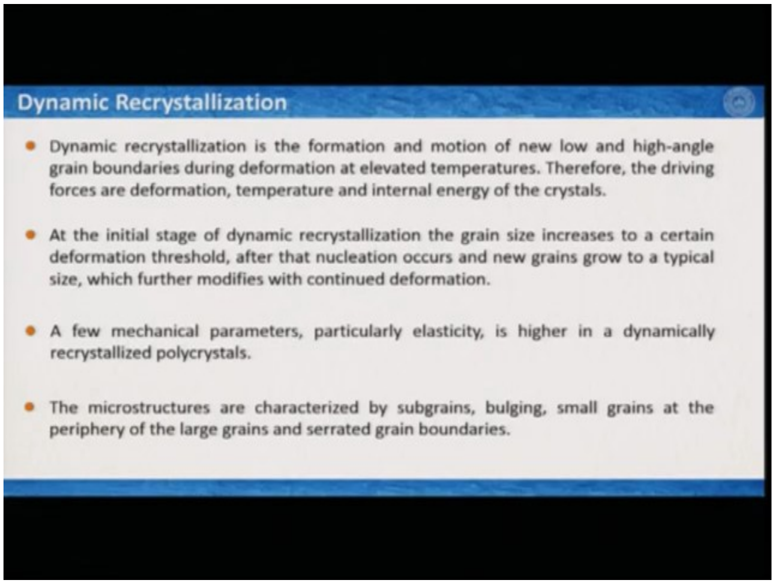

Dynamic Recrystallization

- Dynamic recrystallization is the formation and motion of new low and high-angle grain boundaries during deformation at elevated temperatures. Therefore, the driving forces are deformation, temperature and internal energy of the crystals.
- At the initial stage of dynamic recrystallization the grain size increases to a certain deformation threshold, after that nucleation occurs and new grains grow to a typical size, which further modifies with continued deformation.
- A few mechanical parameters, particularly elasticity, is higher in a dynamically recrystallized polycrystals.
- The microstructures are characterized by subgrains, bulging, small grains at the periphery of the large grains and serrated grain boundaries.

Now let us focus on something that could happen with deformation and this is we learned dynamic re crystallization. So here again there are some basics. It is the text is written here dynamical recrystallization is the formation and motion of new low and high angle grain boundaries during the formation at elevated temperature. So you can now guess as we have discussed that it requires deformation temperature and essentially internal energy of the crystals.

So unlike static crystallization you have added deformation to the dynamically crystallization at the initial stage of dynamic re-crystallization the grain size slightly increases to a certain deformation threshold but after that the nucleation occurs and the new grains grow to a typical size which further modifies with continued deformation.

And this is something very interesting for dynamic re-crystallization. We will see this with some images the mechanical parameters if we talk or if we think of the particular elasticity is higher in a dynamically re-crystallized poly crystals and the micro structures are characterized by sub grains bulging small grains at the periphery of the larger grains and of course serrated grain boundaries. Now we learn about all these things these sub grain bulging small grains at the periphery of the large grains and serrated grain boundaries in the following slides.

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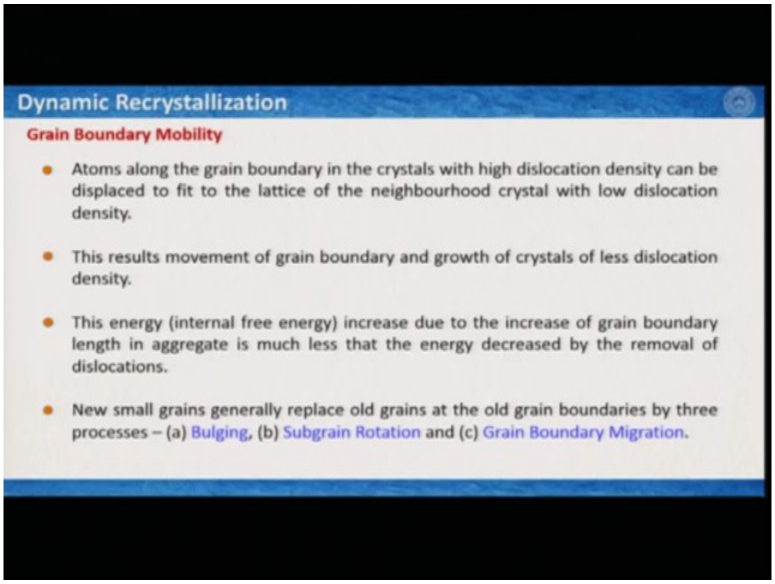

Dynamic Recrystallization

Grain Boundary Mobility

- Atoms along the grain boundary in the crystals with high dislocation density can be displaced to fit to the lattice of the neighbourhood crystal with low dislocation density.
- This results movement of grain boundary and growth of crystals of less dislocation density.
- This energy (internal free energy) increase due to the increase of grain boundary length in aggregate is much less that the energy decreased by the removal of dislocations.
- New small grains generally replace old grains at the old grain boundaries by three processes – (a) Bulging, (b) Subgrain Rotation and (c) Grain Boundary Migration.

We have learned that grain boundaries do move from one place to another place to accommodate the deformation in dynamic re-crystallization. So what drives or what happens during this grain boundary mobility. Here are some points atoms along the grain boundary in the crystals with high dislocation density can be displaced two feet to the lattice of the neighborhood crystal with low dislocation density. So this results movement of grain boundary and growth of crystals of less dislocation density.

So if I have an area of less dislocation density than this boundary of this area tries to invade into the grains where the dislocation density is higher the energy required for this which is internal free energy increases due to the increase of grain boundary length you can you can imagine the fact that I have a fixed area or fixed volume with 10 grams and I have the same area with 50 grams. Certainly the grain boundary areas increases and if the grain boundary areas increases then the grain body energy also do increase.

So you can ask the question am I reducing the energy or I am increasing the energy? But the point is that yes it does. But this is much less that the energy decreased by the removal of the dislocations. So essentially you bring your energy to a lower level. Now dynamic recrystallization happens in three mechanisms so old grains are replaced by new grains.

And as I said it happens by three mechanisms. These are bulging sub grains rotation and grain boundary migration. I must remind you at this stage these are some basic processes bulging sub grain rotation and grain boundary migration. So these you can consider some sort of the stages of the evolution three basic stages of the evolution but many things can happen in between one can influence other greatly.

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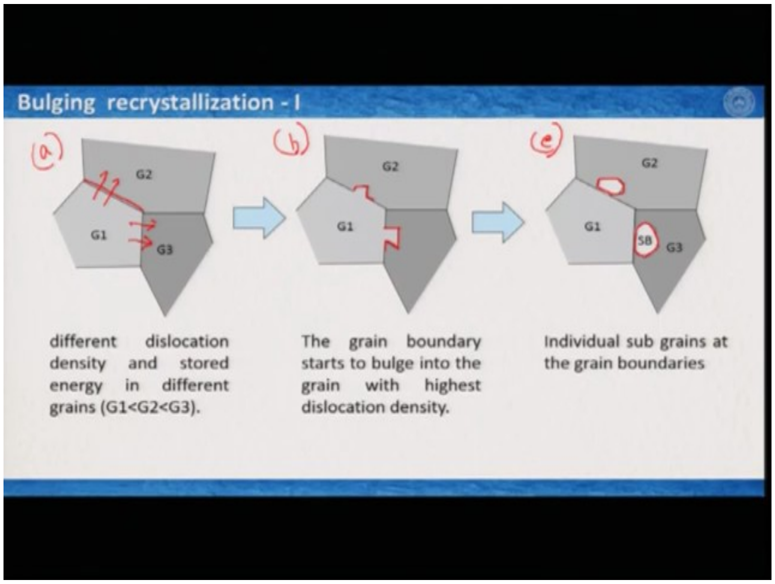

Bulging recrystallization - I

different dislocation density and stored energy in different grains (G1<G2<G3).

The grain boundary starts to bulge into the grain with highest dislocation density.

Individual sub grains at the grain boundaries

So let us start with the bulging re-crystallization. What do we see here in these three illustrations? This is the initial stage say A. This is the second stage B and this is the third stage C these three grains G1, G2 and G3 have three different shades of grey. The lower to the shade has the lower dislocation density. So this one has less than this and this one has less than this dislocation density. Now as I said that because this has less density of this grain boundary here would try to move to the places where the dislocation density is higher and this is exactly what is happening in your figure no B where we see that a little bulge is happening.

So the grain boundary starts to bulge into the grain with higher dislocation density. And if that continues then at the grain boundary you end up with some small little grains these grains are generally strain free.

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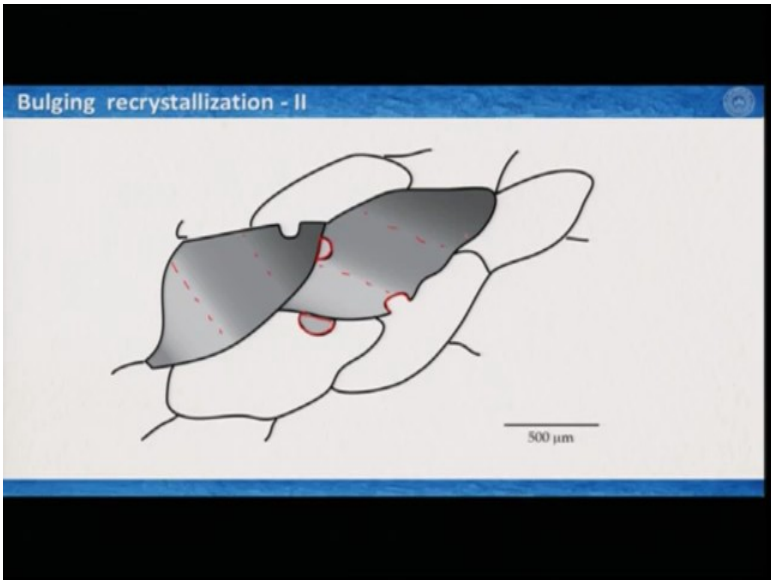

Bulging recrystallization - II

So if I tried to see in a different way a cartoon diagram. So here I have just made two grains so you can see that these grains are showing some sort of unduglose extinction. These two grains are you can say these are sub grain boundaries have already formed but we clearly see that at the grain boundary it is in this cartoon diagram. There are few grains few where the bulging has happened, that means these grain boundaries are not smooth anymore.

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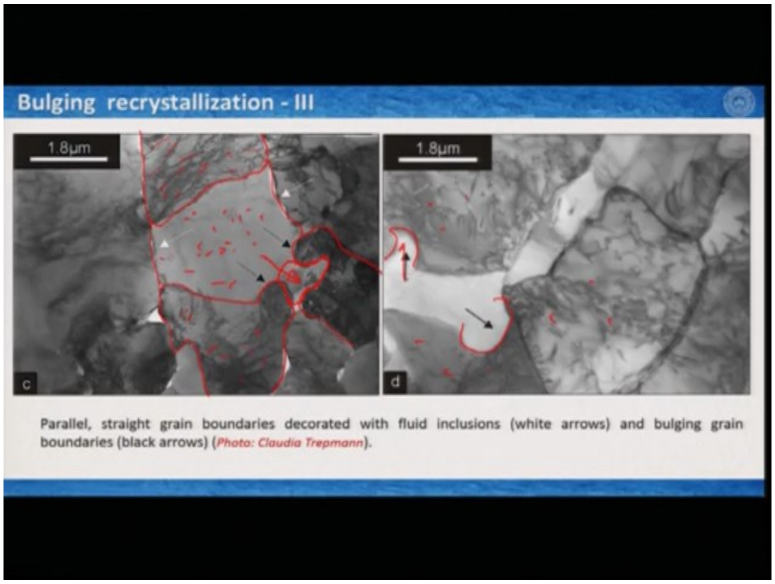

Bulging recrystallization - III

Parallel, straight grain boundaries decorated with fluid inclusions (white arrows) and bulging grain boundaries (black arrows) (*Photo: Claudia Trepmann*).

How does it look like when you see a real thin section let us have a look here? So these things generally you see in optical microscopes but it is better visible if you see them in TEM. So here are two fantastic images that we can see here. And I think this is the first time in this lecture you're also seeing TEM mages with some dislocations. So what do you see if I consider this I will wipe out this later you see all these thin hair like features within the grains these are dislocations here as well these are dislocations all these tiny little things and here all these are also dislocations but this grain which is in the middle it has much less dislocation.

So, now you can see that a grain with less dislocation density is surrounded by three grains with higher dislocation density and interestingly you see that some sort of bulging has happened here where this grain with low dislocation density tried to bulge or invade within the grain where dislocation density much higher the same thing you can see here this whitish area. It has less dislocation density compared to this area here and you can see these are trying to engulf or bulge inside the crystals or grains where they have much higher dislocation density.

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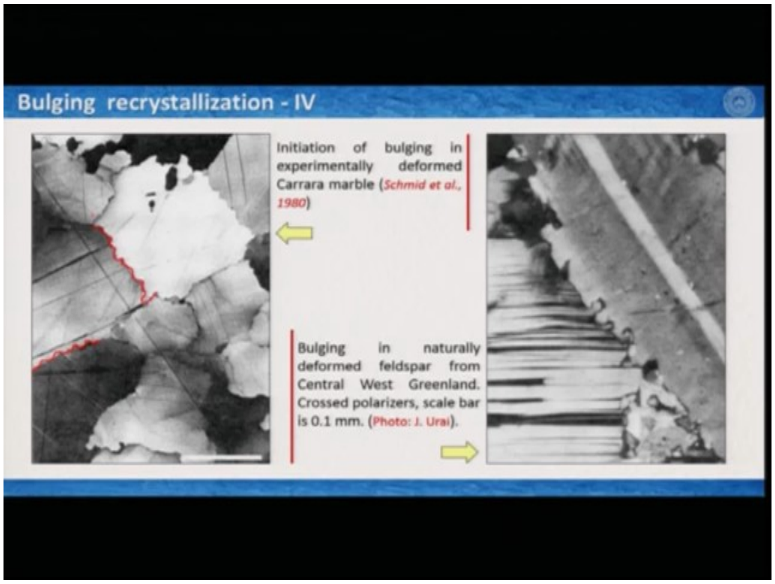

Bulging recrystallization - IV

Initiation of bulging in experimentally deformed Carrara marble (Schmid et al., 1980)

Bulging in naturally deformed feldspar from Central West Greenland. Crossed polarizers, scale bar is 0.1 mm. (Photo: J. Urai).

In optical micro structures that look like this. These are some very old but classic optical photographs on this side you see this is where bulging has just started the grain boundaries you see. These are not straight anymore. These are some sort of (())(41:36) and the bulging here just has started.

This is a cutout of marble so calcite and this is naturally deformed Feldspar. What do you see here? All these things, this is where the bulging has started in this interface of the two crystals so if you see a thin section or micro structure now you will see them in a different way I believe and you tried to figure out that what kind of re-crystallization has happened and if you see some sort of little not a little bulge from one grain mounted to another grain boundary. First you must conclude that this is a deformed micro structure and then you see then you can also conclude that which grain higher density higher dislocation density had compared to the other one.

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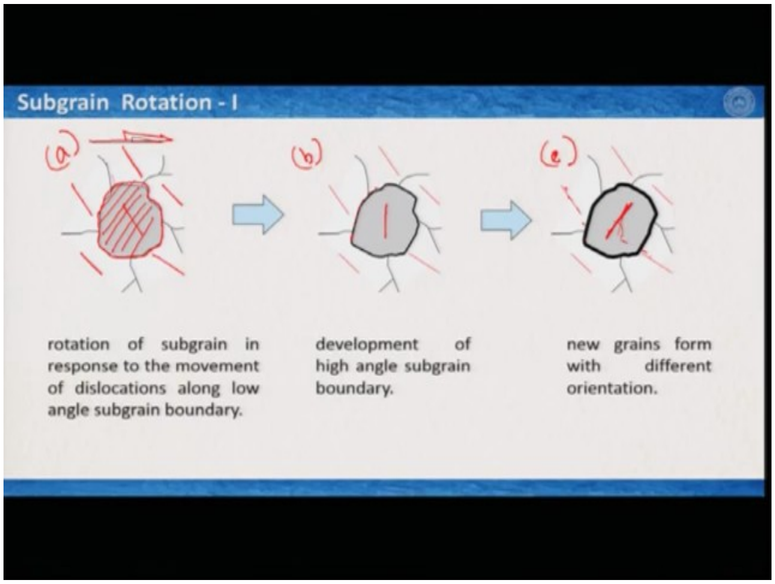

Subgrain Rotation - I

rotation of subgrain in response to the movement of dislocations along low angle subgrain boundary.

development of high angle subgrain boundary.

new grains form with different orientation.

The sub grain rotation is the next stage. So rotation of sub grains in response to the movement of dislocations along low angle sub grain boundary. So in these three illustrations what we tried to see let me mark again here A B and C what we have seen in A that these are certainly grain boundaries. These black lines but these red lines that we see here these are the orientation of the grains. For example, you can consider that these are the C axis oriented this way. So as you can see that they are oriented more or less in a very similar way.

So therefore the grain boundaries are very low angle grain boundaries here. Therefore, these are sub grain boundaries. Now if the deformation continues then this sub grain can rotate and when these grains is rotating then of course the crystallographic orientation of this grain also rotated compared to the neighboring grains.

So therefore you generate some sort of high angle grain boundary with this grain. We are concerned with compared to the other grains at this neighborhood. And other if the rotation continues further then you have this grain boundary at much higher rotation high angle with the neighboring grains. So this is how you form from sub Grain to new grains through the process of sub grain rotation so these things do happen at grain boundaries

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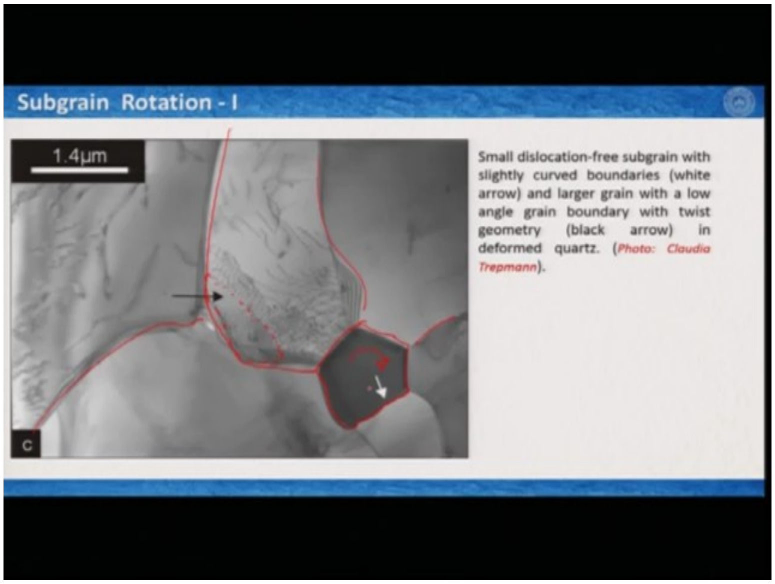

Subgrain Rotation - I

Small dislocation-free subgrain with slightly curved boundaries (white arrow) and larger grain with a low angle grain boundary with twist geometry (black arrow) in deformed quartz. (*Photo: Claudia Trepmann*).

And if we try to look at that this is how it has happened in this TEM image. So for example this one is small dislocation free sub grain with slightly curved boundaries white arrow here and the larger grain with the low angle grain boundary with twist geometry. So this one is another we are not going discuss in the details of this twist Geometry and so on but this is certainly a small grain compared to this large grain. As you can see here this one this one this one and this one. So this grain initially formed probably by bulging and then it got rotated and you have a new grain and it is of much smaller size.

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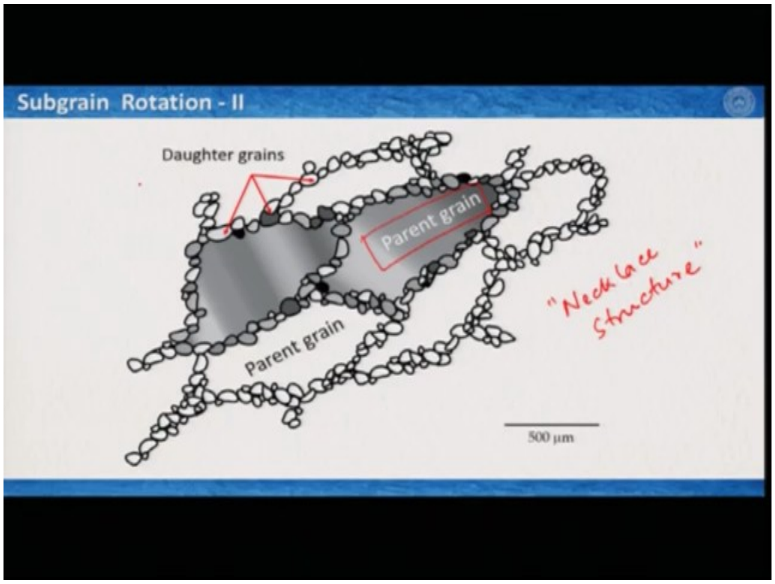
Subgrain Rotation - II

So if we tried to again look at these in a cartoon diagram. So you have this large grains which are now deformed and then you have small grains all over along. This is a sub grains and this got rotated and started forming new grain. The overall this micro structure when you have a large grain which is surrounded by very small dynamically recrystallized small sub grains. This is known as Necklace structural. So this is the name of this type of micro structure and also the ordinal grain is known as parent grain and the new grains are known as daughter grains.

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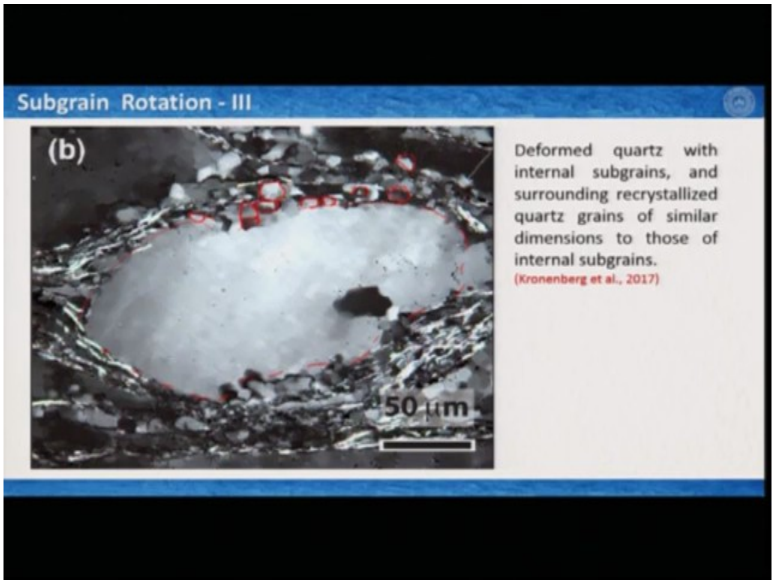

Subgrain Rotation - III

Deformed quartz with internal subgrains, and surrounding recrystallized quartz grains of similar dimensions to those of internal subgrains.

(Kronenberg et al., 2017)

Now this is a fantastic micro structure of sub grain rotation so this is a deformed chord it and you can see this internal entire quartz grain it is also not very flat in terms of color it has also some sort of color variation there for some sort of internal energy but interestingly you see that the outer rim of this large quartz grain is characterized by many small grains and these are sub grains they will continue rotating and then they will form new grains

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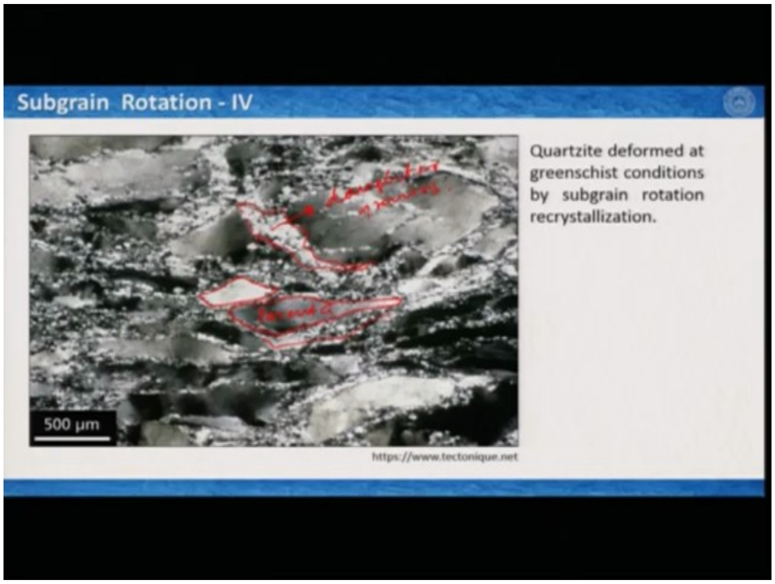

Subgrain Rotation - IV

Quartzite deformed at greenschist conditions by subgrain rotation recrystallization.

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And if we look at in a different scale this is a fantastic necklace micro structure. So these are the large deformed straight quartz grains these are parent grains and all these tiny things decorated at the boundary of the parent grains here and so on. These are daughter grains so if you see this kind of micro structures then you clearly can say that this is suddenly a deformed rock and the deformation mechanism going on here is some sort of sub grain rotation.

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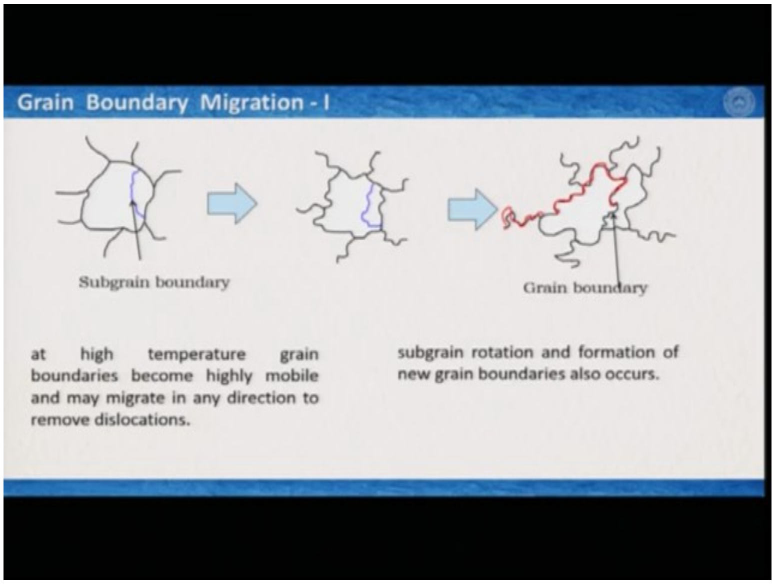

Grain Boundary Migration - I

at high temperature grain boundaries become highly mobile and may migrate in any direction to remove dislocations.

subgrain rotation and formation of new grain boundaries also occurs.

The final one is grain boundary migration in grain boundary migration the temperature is very high. So this is one of the essential parameters. So the temperature is so high that the grain boundaries become very much mobile. So you have a sub grain boundary. It can flow in any direction and therefore you produce grain boundaries like this Amoebidal shape or the grain boundary is known as serrated grain boundary and at the same time you have the sub grain rotation and formation of new grains and so on these things to occur.

I am not explaining all these things in detail but trying to give you an idea that how to identify this type of micro structures when you look at your rock under microscope and particularly if you see these kind of features at least you can classify or separate out that yes this is a deformed grain. The grains are deformed by into crystalline plasticity of the rock as a whole. And these are the stages of the dynamic re-crystallization.

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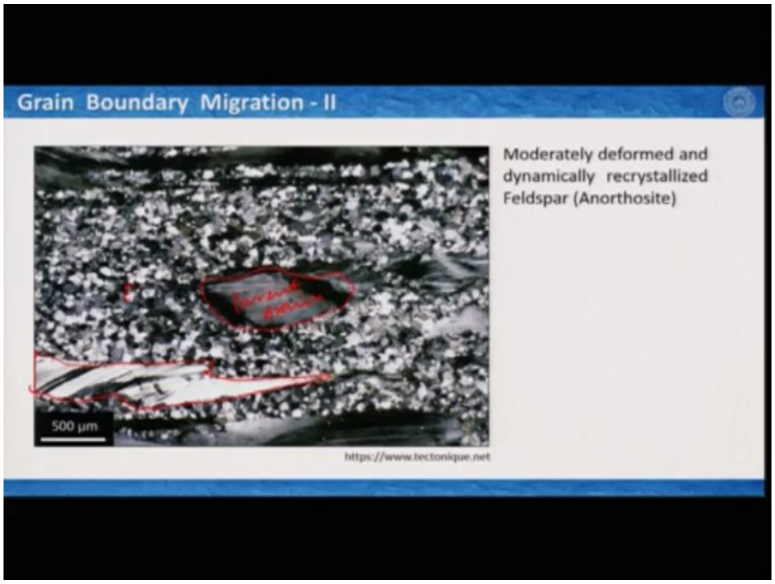

Grain Boundary Migration - II

Moderately deformed and dynamically recrystallized Feldspar (Anorthosite)

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So here there is an example, so you can see this is a feldspar grain. These are again the parent grain this large grain of this entire Rock is some sort of to. This is again a large but the ground mass entire ground mass is characterized by number of small dynamically re-crystallized crystals. And if we can look at their grain boundaries are highly serrated mobile and that must have happened at high temperature.

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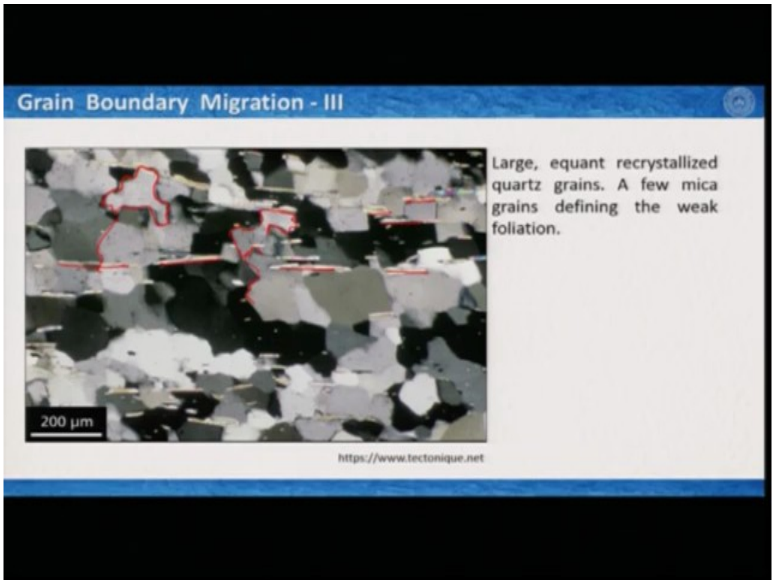

Grain Boundary Migration - III

Large, equant recrystallized quartz grains. A few mica grains defining the weak foliation.

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And here is also an example of large equant re-crystallized quartz. And what you can see that in few places these grain boundaries are also a little random and so on. So these are the signatures of grain boundary migration here and other places and you can also see some micro grains which are defining a very weak foliation.

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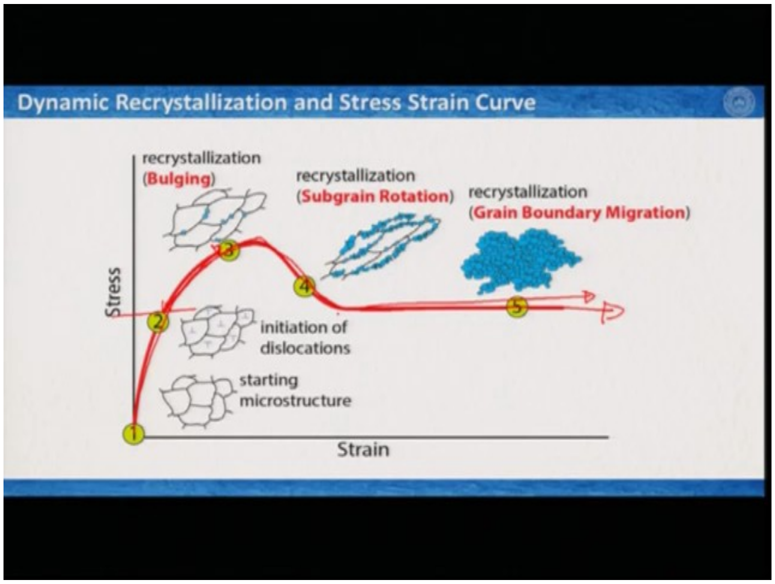

Dynamic Recrystallization and Stress Strain Curve

So with respect to this stress strain curve we have seen this illustration before. If we tried to see this that you have your starting micro structure you start deforming it if you achieve your illustrates somewhere here. So here you start moving your dislocations inside the crystal. Now then it requires a significant number of stress hardening right.

So this is where is your inner strength and then the hardening is required during the bulging process but when you start forming sub grain rotation the new small grains come the strain softening is the process and after that it achieves a steady strict manner of flow. So this is how in general you can idealize also that where this is a very general illustration the actual curve may be a little complicated or different but this curve is very simple and standard where at different segments of this curve different kind of dynamically crystallization do happen within the domain of intra crystalline plasticity.

We focused in this lecture on the intra crystalline plasticity and in the next lecture we will learn about our will we learn in detail or talk about the mechanisms of diffusion creep and diffusive mass transfer. Thank you.