

Creep Deformation of Materials
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Mechanisms of Creep Part I

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Mechanisms of creep



Ok, so till the last lecture, we, we were talking about creep deformation, the factors controlling creep and how the nature of creep curve is influenced by these different factors and also how depending upon the mechanism of creep, the creep curve may look different for different mechanisms.

So now since we talked about mechanisms, so in this lecture we are going to talk about the different mechanisms of creep.

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Mechanisms of creep

- Broadly the two categories are
 - Diffusion of vacancies based creep mechanisms
 - E.g. Coble creep, Nabarro-Herring creep
 - Dislocation based creep mechanisms
 - Viscous creep, Weertman's creep, Jogged screw creep mechanism

The rate controlling mechanism of deformation can be identified from the values of p , n and Q primarily

$$\dot{\epsilon} \propto A d^{-p} \sigma^n \exp\left(\frac{-Q}{RT}\right)$$



Broadly there are two categories of creep. So creep deformation which is controlled by diffusion of vacancies or creep diffusion which is controlled by dislocation.

So

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these are broadly the

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two categories of creep which are, people have identified till date. So when we say diffusion of vacancies, so the plastic deformation is controlled by the motion of the vacancies in this particular case, and the well-known mechanisms under this category are Coble creep and Nabarro-Herring creep.

On the other hand when we say dislocation-based creep mechanisms, the known mechanisms are viscous creep mechanism, then we have also Weertman's creep, which is also known as Power law creep, and we also have a variant of this called the Jogged screw creep mechanism. So these are some common creep mechanisms which are used to explain plastic deformation through dislocations.

Now in the last lecture we were also talking about how the strain rate of deformation can be described by the following equation. So we said

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the strain rate of deformation is a function of the grain size. It is a function of stress and it is a function of temperature. And then

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we introduced all these different parameters such as p,

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n and



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Q.



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The rate controlling mechanism of deformation can be identified from the values of p, n and Q primarily

$$\dot{\epsilon} \propto A d^{-p} \sigma^n \exp\left(\frac{-Q}{RT}\right)$$



So what we said was p was grain size exponent, n is the stress exponent and Q is the activation energy of deformation. Now what can be done is if you know the values of p, n and Q you will be able to tell which mechanism of creep is actually controlling the deformation process.

So for different values of p, n and Q, so what I mean to say is for diffusion of vacancies as an example, so if creep is controlled by the diffusion of vacancies then you will have a certain set of p, n and Q values and whereas if it is controlled by different dislocation-based mechanisms then you will have another set of p, n and Q values.

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Mechanisms of creep

- The values of n, p and q for the different mechanisms are described herea

Creep Mechanism	n	p	Q _c
Nabarro-Herring (N-H)	1	2	Q _c
Coble	1	3	Q _{gb}
Harper-Dorn (H-D)	1	0	Q _c
Grain Boundary Sliding (GBS)	2	2	Q _{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q _c
Power Law Breakdown	>7	-	Q _c

The n = 1 mechanisms are also known as **Newtonian creep mechanisms**



So let me tell you what are the different values of p , n and Q which have been known for these different mechanisms.

So the mechanisms of creep which have been identified so far are listed here. So you have Nabarro-Herring creep, you have Coble creep, Harper-Dorn creep, Grain Boundary Sliding and you have a Viscous Glide, Dislocation Climb controlled creep, and then you have Power Law breakdown.

So these are broadly the different ways in which creep deformation is controlled or basically you can say these are the different rate controlling mechanisms of deformation. Now very clearly the values of n , p and Q are different

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Mechanisms of creep

- The values of n , p and q for the different mechanisms are described herea

Creep Mechanism	n	p	Q_c
Nabarro-Herring (N-H)	1	2	Q_L
Coble	1	3	Q_{gb}
Harper-Dorn (H-D)	1	0	Q_L
Grain Boundary Sliding (GBS)	2	2	Q_{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q_L
Power Law Breakdown	>7	-	Q_L

The $n = 1$ mechanisms are also known as
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for the different mechanisms.

For example for Nabarro-Herring, n that is the stress exponent

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Mechanisms of creep

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Creep Mechanism	n	p	Q_c
Nabarro-Herring (N-H)	1	2	Q_L
Coble	1	3	Q_{gb}
Harper-Dorn (H-D)	1	0	Q_L
Grain Boundary Sliding (GBS)	2	2	Q_{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q_L
Power Law Breakdown	>7	-	Q_L

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has a value of 1, and p which is the grain size exponent

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Mechanisms of creep

- The values of n , p and q for the different mechanisms are described here

Creep Mechanism	n	p	Q_c
Nabarro-Herring (N-H)	1	2	Q_L
Coble	1	3	Q_{gb}
Harper-Dorn (H-D)	1	0	Q_L
Grain Boundary Sliding (GBS)	2	2	Q_{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q_L
Power Law Breakdown	>7	-	Q_L

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has a value of 2. And Q_c which is the activation energy of creep deformation is known to have the value equal to Q_L

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Mechanisms of creep

- The values of n, p and q for the different mechanisms are described here

Creep Mechanism	n	p	Q _c
Nabarro-Herring (N-H)	1	2	Q _L
Coble	1	3	Q _{gb}
Harper-Dorn (H-D)	1	0	Q _L
Grain Boundary Sliding (GBS)	2	2	Q _{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q _L
Power Law Breakdown	>7	-	Q _L

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where Q_L is lattice diffusion activation energy.

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Mechanisms of creep

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Creep Mechanism	n	p	Q _c
Nabarro-Herring (N-H)	1	2	Q _L
Coble	1	3	Q _{gb}
Harper-Dorn (H-D)	1	0	Q _L
Grain Boundary Sliding (GBS)	2	2	Q _{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q _L
Power Law Breakdown	>7	-	Q _L

The n = 1 mechanisms are also known as
Newtonian creep mechanisms

Q_L = Lattice diffusion activation energy



Similarly when we talk of, similarly when we talk of Coble creep n is again 1 but

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Mechanisms of creep

- The values of n , p and q for the different mechanisms are described here

Q_L = Lattice diffusion activation energy

Creep Mechanism	n	p	Q_c
Nabarro-Herring (N-H)	1	2	Q_L
Coble	1	3	Q_{gb}
Harper-Dorn (H-D)	1	0	Q_L
Grain Boundary Sliding (GBS)	2	2	Q_{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q_L
Power Law Breakdown	>7	-	Q_L

The $n = 1$ mechanisms are also known as
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p has now a different value.

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Mechanisms of creep

- The values of n , p and q for the different mechanisms are described here

Q_L = Lattice diffusion activation energy

Creep Mechanism	n	p	Q_c
Nabarro-Herring (N-H)	1	2	Q_L
Coble	1	3	Q_{gb}
Harper-Dorn (H-D)	1	0	Q_L
Grain Boundary Sliding (GBS)	2	2	Q_{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q_L
Power Law Breakdown	>7	-	Q_L

The $n = 1$ mechanisms are also known as
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So p is equal to 3 and here the activation energy Q_c is equal to Q_{gb} and Q_{gb}

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Mechanisms of creep

- The values of n, p and q for the different mechanisms are described here

Creep Mechanism	n	p	Q_c
Nabarro-Herring (N-H)	1	2	Q_L
Coble	1	3	Q_{gb}
Harper-Dorn (H-D)	1	0	Q_L
Grain Boundary Sliding (GBS)	2	2	Q_{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q_L
Power Law Breakdown	>7	-	Q_L

Q_L = Lattice diffusion activation energy

Q_c = Q_{gb}

The n = 1 mechanisms are also known as **Newtonian creep mechanisms**



is known as the grain boundary diffusion activation energy.

So basically

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Mechanisms of creep

- The values of n, p and q for the different mechanisms are described here

Creep Mechanism	n	p	Q_c
Nabarro-Herring (N-H)	1	2	Q_L
Coble	1	3	Q_{gb}
Harper-Dorn (H-D)	1	0	Q_L
Grain Boundary Sliding (GBS)	2	2	Q_{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q_L
Power Law Breakdown	>7	-	Q_L

Q_L = Lattice diffusion activation energy

Q_c = Q_{gb}
: Grain boundary diffusion activation energy

known as **Newtonian creep mechanisms**



as you go from one type of mechanism to another these values keep changing. Now among these if you see these three mechanisms, Nabarro-Herring, Coble and Harper-Dorn, all three bear a value of n is equal to 1.

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Mechanisms of creep

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Creep Mechanism	n	p	Q _c
Nabarro-Herring (N-H)	1	2	Q _L
Coble	1	3	Q _{gb}
Harper-Dorn (H-D)	1	0	Q _L
Grain Boundary Sliding (GBS)	2	2	Q _{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q _L
Power Law Breakdown	>7	-	Q _L

The n = 1 mechanisms are also known as **Newtonian creep mechanisms**

Q_L = Lattice diffusion activation energy
 $Q_c = Q_{gb}$: Grain boundary diffusion activation energy

And these mechanisms, the n is equal to 1 mechanisms are known as Newtonian creep mechanisms. So Nabarro-Herring, Coble and Harper-Dorn creep are known as the Newtonian

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Mechanisms of creep

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Creep Mechanism	n	p	Q _c
Nabarro-Herring (N-H)	1	2	Q _L
Coble	1	3	Q _{gb}
Harper-Dorn (H-D)	1	0	Q _L
Grain Boundary Sliding (GBS)	2	2	Q _{gb}
Viscous Glide	3	0	Q
Dislocation Climb	5-7	0	Q _L
Power Law Breakdown	>7	-	Q _L

The n = 1 mechanisms are also known as **Newtonian creep mechanisms**

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 $Q_c = Q_{gb}$: Grain boundary diffusion activation energy



creep mechanisms.

So why are they known as the Newtonian creep mechanisms? Well

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Newtonian viscous creep mechanisms

- Newtonian fluids are those where the viscous stresses arising from their flow are linearly proportional to the local strain rate

$$\dot{\gamma} \propto \tau$$

- See the similarity between the above equation and the creep strain rate dependence on applied stress

$$\dot{\epsilon} \propto \sigma^1$$



that is because of the following things. So the Newtonian fluids, so Newtonian fluids are those where the viscous stresses arising from the flow are linearly proportional to the local strain rate. So essentially what this means is the local strain rate of deformation in Newtonian fluids is directly proportional to

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Newtonian viscous creep mechanisms

- Newtonian fluids are those where the viscous stresses arising from their flow are linearly proportional to the local strain rate

$$\dot{\gamma} \propto \tau$$

- See the similarity between the above equation and the creep strain rate dependence on applied stress

$$\dot{\epsilon} \propto \sigma^1$$



the applied stress.

And if you see there is a similarity between this equation and the equation of creep when n is equal to 1.

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Newtonian viscous creep mechanisms

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$$\dot{\gamma} \propto \tau$$

- See the similarity between the above equation and the creep strain rate dependence on applied stress

$$\dot{\epsilon} \propto \sigma^1$$



So when n is equal to 1, you can see that the strain rate of deformation or the creep rate of deformation is going to be directly dependent on the value of sigma.

So that is why all those cases where n is equal to 1 where there is a direct

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Newtonian viscous creep mechanisms

- Newtonian fluids are those where the viscous stresses arising from their flow are linearly proportional to the local strain rate

$$\dot{\gamma} \propto \tau$$

- See the similarity between the above equation and the creep strain rate dependence on applied stress

$$\dot{\epsilon} \propto \sigma^1$$

$n=1$



dependence, linear dependence of epsilon dot on sigma, those are known as the Newtonian creep mechanisms or the Newtonian viscous creep mechanisms.

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Newtonian viscous creep mechanisms

- Newtonian fluids are those where the viscous stresses arising from their flow are linearly proportional to the local strain rate

$$\dot{\gamma} \propto \tau$$

- See the similarity between the above equation and the creep strain rate dependence on applied stress

$$\dot{\epsilon} \propto \sigma^n$$

$n=1$
Newtonian viscous
creep mechanisms



So from here on, for the next few minutes we are going to talk more about the Newtonian viscous creep mechanisms. So we will go into the details of Harper-Dorn, we are going to go into the details of Nabarro-Herring creep, Coble creep and Harper-Dorn creep.

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Newtonian viscous creep mechanisms

- Nabarro-Herring and Coble creep are the diffusion creep mechanisms whereas Harper-Dorn is considered to be a dislocation based creep mechanism
- Nabarro-Herring, $p = 2$, $Q = Q_L$
- Coble creep, $p = 3$, $Q = Q_{gb}$

F.R.N. Nabarro, *Report of conference on solids* The Physical Society, London, 1948
C. Herring, "Diffusional viscosity of a polycrystalline solid," *J. Appl. Phys.*, **21** (1950) 437-
R.L. Coble, "A model for boundary diffusion controlled creep in polycrystalline material,"
Appl. Phys., **34** (1963) 1679-1682



So first let us talk about Nabarro-Herring and Coble creep. So the reason I am, so between Nabarro-Herring, Coble and Harper-Dorn there are some subtle differences, but the main difference between Nabarro-Herring, Coble and Harper-Dorn is that Nabarro-Herring and Coble creep are known as diffusion creep mechanisms that means the creep deformation is controlled by the diffusion vacancies.

Whereas Harper-Dorn, although there are lot of points of view about Harper-Dorn but by and large I think one thing that has been agreed upon is that Harper-Dorn is considered to be a dislocation-based creep mechanism. So we are going to talk more about Harper-Dorn creep in the coming slides but right now I am going to focus about Nabarro-Herring and Coble creep.

So now Nabarro-Herring and Coble creep diffusion creep based mechanisms and the main difference between these two is that the grain size exponent

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Newtonian viscous creep mechanisms

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p is equal to 2

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C. Herring, "Diffusional viscosity of a polycrystalline solid," *J. Appl. Phys.*, **21** (1950) 437-445
R.L. Coble, "A model for boundary diffusion controlled creep in polycrystalline materials," *J. Appl. Phys.*, **34** (1963) 1679-1682



for Nabarro-Herring and it is 3 for Coble creep.

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Newtonian viscous creep mechanisms

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- Coble creep, $p = 3$, $Q = Q_{gb}$ }

F.R.N. Nabarro, *Report of conference on solids* The Physical Society, London, 1948
C. Herring, "Diffusional viscosity of a polycrystalline solid," *J. Appl. Phys.*, **21** (1950) 437-445
R.L. Coble, "A model for boundary diffusion controlled creep in polycrystalline materials," *J. Appl. Phys.*, **34** (1963) 1679-1682



And for Nabarro-Herring the activation energy

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Newtonian viscous creep mechanisms

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- Coble creep, $p = 3$, $Q = Q_{gb}$ }

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of deformation, creep deformation Q is equal to Q_L whereas it is Q is equal to

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Newtonian viscous creep mechanisms

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- Coble creep, $p = 3$, $Q = Q_{gb}$

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Q_{gb} for Coble creep.

So Nabarro-Herring creep was identified by Nabarro in the year 1948 and independently by Herring in the year 1950 that is why this mechanism of deformation has been named against these two gentlemen. So it is known as Nabarro-Herring whereas Coble was identified by R. L. Coble in the year 1963. So the references are mentioned here.

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Newtonian viscous creep mechanisms

- When a stress is applied, in Nabarro-Herring creep, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the lattice
- During Coble creep, when a stress is applied, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the grain boundaries



So what happens in Nabarro-Herring creep and what happens in Coble creep? So we are talking about diffusion of vacancies, so what, how exactly or what exactly happens during diffusion?

So what has been observed is when a stress is applied, so creep, for creep you need stress, you need temperature, so when you apply a stress under certain conditions, combinations of stress and temperature, what has been observed is there is diffusion of vacancies from grain boundaries perpendicular to the applied stress to the grain boundaries parallel to the applied stress throughout the lattice.

So in Nabarro-Herring creep what is happening is there is some form of diffusion of vacancies and

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Newtonian viscous creep mechanisms

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- During Coble creep, when a stress is applied, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the grain boundaries



this diffusion of vacancies is happening from grain boundaries which are perpendicular to the applied stress

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Newtonian viscous creep mechanisms

- When a stress is applied, in Nabarro-Herring creep, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the lattice
- During Coble creep, when a stress is applied, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the grain boundaries



to grain boundaries which are parallel to the applied



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Newtonian viscous creep mechanisms

- When a stress is applied, in Nabarro-Herring creep, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the lattice
- During Coble creep, when a stress is applied, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the grain boundaries



stress and the diffusion takes place through the lattice, through the bulk of the crystal.



Whereas in Coble creep, so what happens in Coble creep is when a stress is applied again for certain combinations of stress and temperatures, there the diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to the applied stress actually happens through the grain boundaries.

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Newtonian viscous creep mechanisms

- When a stress is applied, in Nabarro-Herring creep, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the lattice
- During Coble creep, when a stress is applied, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the grain boundaries



Instead of diffusion happening through the lattice,

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Newtonian viscous creep mechanisms

- When a stress is applied, in Nabarro-Herring creep, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the lattice
- During Coble creep, when a stress is applied, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the grain boundaries



in the case of Coble creep the diffusion of vacancies happens



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Newtonian viscous creep mechanisms

- When a stress is applied, in Nabarro-Herring creep, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the lattice
- During Coble creep, when a stress is applied, there is diffusion of vacancies from grain boundaries perpendicular to applied stress to grain boundaries parallel to applied stress through the grain boundaries

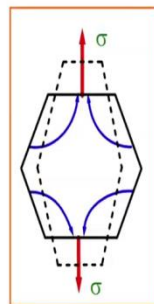


through the grain boundaries. So that is how Nabarro-Herring and Coble creep are different from each other.

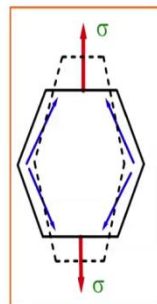
So

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



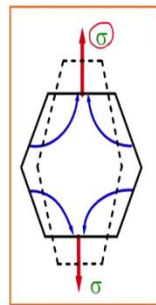
Coble
Creep Mechanism



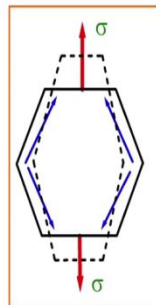
in this picture I am giving you an illustration of the mechanism, so Nabarro-Herring, so you have a stress, sigma and this is grain

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



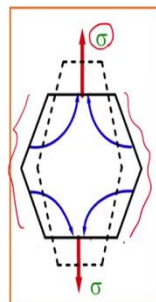
Coble
Creep Mechanism



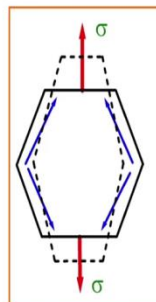
boundary which is perpendicular to the applied stress, another grain boundary which is perpendicular to the applied stress and these two, these grain boundaries can be assumed to be more or less parallel

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism



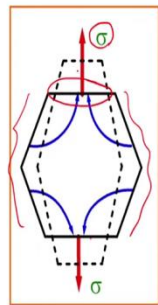
to the applied stress.

So what happens is when you are applying a stress so there is excess of vacancies which is generated at the grain boundaries

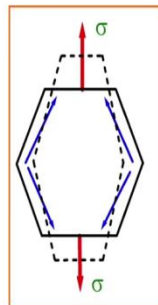


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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism

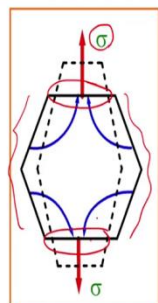


perpendicular to the applied stress.

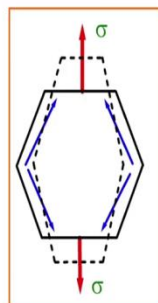
So there is more amount of

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism

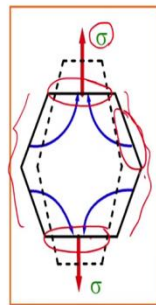


vacancies here and less amount of vacancies on

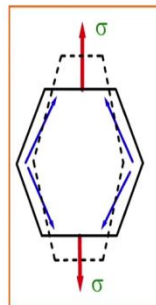


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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



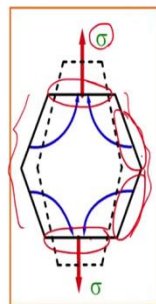
Coble
Creep Mechanism



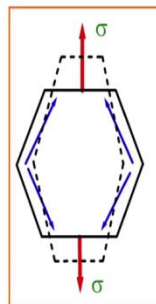
the grain boundaries which are

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism



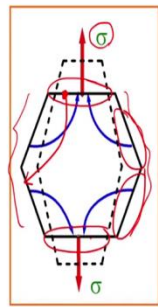
parallel to the applied stress so vacancies are going to move from the grain boundaries perpendicular to the applied stress to the grain boundaries parallel to the applied stress.

So you have

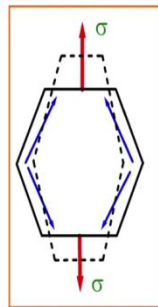


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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



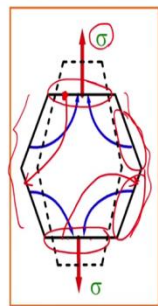
Coble
Creep Mechanism



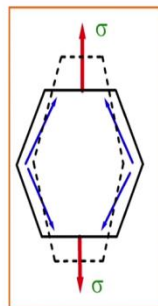
diffusion of vacancies like that. So

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism



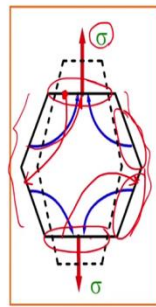
vacancies are going from grain boundaries perpendicular to grain boundaries parallel.

If you see in this picture the blue arrows actually show motion from here to here and that is

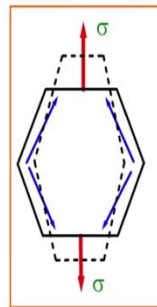


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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism

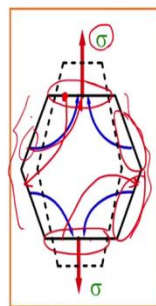


because that is the direction in which atoms are going to move. So when you say vacancies are moving, the opposite of it is atoms are moving in the opposite direction. So the atoms move in a direction opposite to the motion of vacancies.

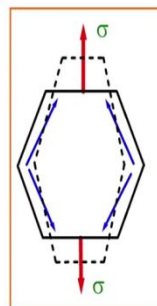
So because there is atoms moving from the grain boundaries parallel to

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



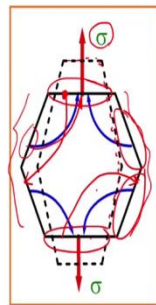
Coble
Creep Mechanism



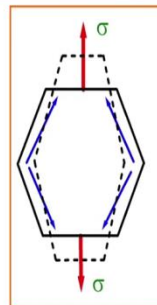
the applied stress to the grain boundaries perpendicular to the applied stress, so what eventually happens is that you have an extension of the grain. So if

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism



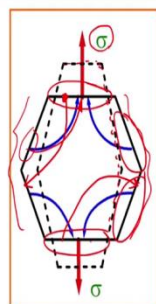
you see the dotted line actually indicates the change in the grain length. So the grains tend to elongate along the direction of the applied stress.

Now let us look at the case of Coble creep. So in Coble creep again you have a stress which is applied perpendicular to the grain boundaries.

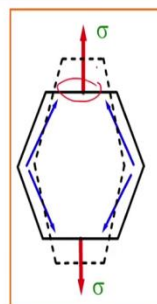
So all those grain boundaries which are perpendicular to the applied stress are going to have an excess of vacancies

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



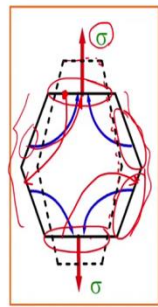
Coble
Creep Mechanism



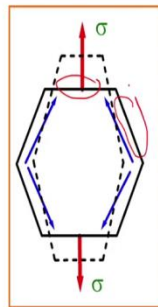
and the grain boundaries which are parallel to the applied stress

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism

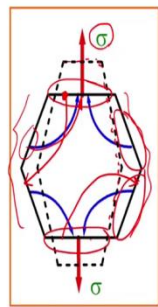


are going to have a lower concentration of vacancies. So again there is a vacancy concentration gradient.

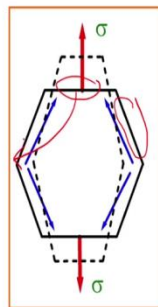
So vacancies are going to move in this direction

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



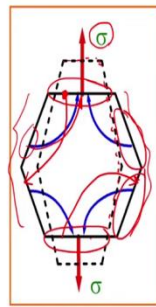
Coble
Creep Mechanism



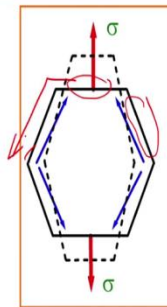
and in this case the vacancies prefer to move along the grain boundaries.

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism

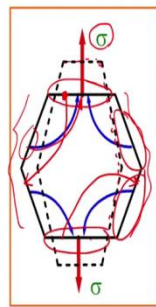


So in comparison to Nabarro-Herring where the vacancy diffusion is through the bulk of the grain, in Coble, Coble creep the idea is that vacancies tend to go along the grain boundaries.

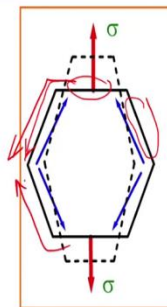
So these are the grain boundaries.

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



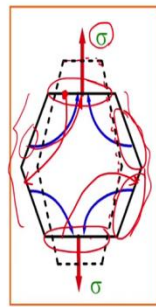
Coble
Creep Mechanism



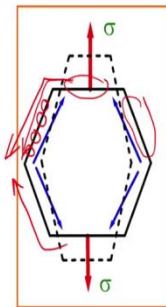
So the vacancies consider the grain boundaries as a easier path to, by which they can travel. So again the same thing, the blue arrows indicate the direction of motion of the atoms. So the atoms move from parallel grain boundaries

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



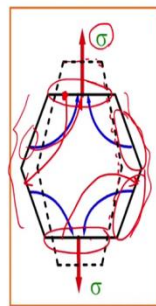
Coble
Creep Mechanism



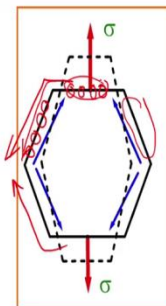
to the perpendicular grain boundaries.

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism



So again just in like Nabarro-Herring creep there is going to be shape change in the shape of the grains. The grains are going to get deformed because of the process and so they are going to get elongated. So this is basically an overview of what is exactly happening in Nabarro-Herring creep and what is happening in Coble creep mechanism.

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Newtonian viscous creep mechanisms

Derivation of Nabarro-Herring creep

- The creep happens by stress assisted diffusional mass transport
- The diffusion of vacancies or the motion of atoms from one grain boundary to another leads to a crystal strain which in turn contributes to the deformation of the grains and consequently the material
- Assumptions
 - The grain boundaries are perfect sources and sinks of vacancies, and
 - The initial dislocation density of the crystal is low.



So the strain rate of deformation, so Nabarro-Herring have developed equations to explain how creep happens by the mechanism they identified. So that is what we are going to talk from here on. So we are going to talk about the derivation of the Nabarro-Herring creep equation.

So since there is a stress present and there is also diffusion happening, so the creep basically happens here in the case of Nabarro-Herring creep, the creep happens by the stress assisted diffusional mass transfer.

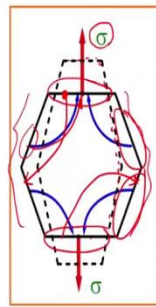
So mass in the sense atoms are moving from one grain boundary to another. So there is diffusion, so it is basically assisted by stress, so it is called stress assisted diffusional mass transfer.

Now like I showed in the diagram the diffusion of vacancies or the motion of atoms from one grain boundary to another is leading to a crystal strain which in turn contributes to the deformation of the grains and consequently the material.

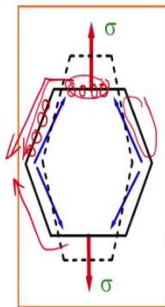
So in the previous diagram, so here

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Newtonian viscous creep mechanisms



Nabarro-Herring
Creep Mechanism



Coble
Creep Mechanism



I showed how grains are getting elongated. So

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Newtonian viscous creep mechanisms

Derivation of Nabarro-Herring creep

- The creep happens by stress assisted diffusional mass transport
- The diffusion of vacancies or the motion of atoms from one grain boundary to another leads to a crystal strain which in turn contributes to the deformation of the grains and consequently the material
- Assumptions
 - The grain boundaries are perfect sources and sinks of vacancies, and
 - The initial dislocation density of the crystal is low.



basically the diffusion of vacancies or the motion of atoms from one grain boundary to another leads to a crystal strain.

So there is a deform plastic strain that is getting introduced in the process and this crystal strain in turn contributes to deformation of the grains and consequently, globally, at local level you can think of deformation of crystal but when several such crystals are getting deformed at a globally it is also deforming your material.

So Nabarro-Herring developed equations to determine the strain rate of deformation happening by this mechanism. So when they developed these equations the assumptions they made were as follows. The first assumption is that the grain boundaries are perfect sources and sinks of vacancies.

So the reason is, if the grain boundaries, they have considered the grain boundaries are perfect sources and sinks of vacancies. If the grain boundaries are not perfect sources and sinks of vacancies then it will be difficult for deformation to happen by grain boundaries releasing the vacancies.

So basically what I am trying to say here is if the grain boundaries are not perfect sources, then you may have to apply a stress higher than a certain level for, to create an excess of vacancies at the grain boundaries.

But on the other hand, if you look at them as perfect sources and sinks of vacancies so you are saying, just by the application of even a tiny load you are able to initiate excess vacancies or create excess vacancies and so it is easier, just in the presence of a small stress for the diffusion process to start at a high temperature. So that is the first thing.

So the grain boundaries can release vacancies easily as well as absorb vacancies easily. If that does not happen then there is going to be either a threshold stress that need to be overcome to, for the process to start and again if they do not absorb vacancies easily then also the mechanism of creep is not going to operate. So that is the first assumption.

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Newtonian viscous creep mechanisms

Derivation of Nabarro-Herring creep

- The creep happens by stress assisted diffusional mass transport
- The diffusion of vacancies or the motion of atoms from one grain boundary to another leads to a crystal strain which in turn contributes to the deformation of the grains and consequently the material
- Assumptions
 - The grain boundaries are perfect sources and sinks of vacancies, and ✓
 - The initial dislocation density of the crystal is low.



Now the second assumption is that the initial dislocation density of the crystal is very low. So Nabarro-Herring also assumed that the dislocation density of the crystal has to be low, the reason is we want the plastic deformation to happen only by diffusion of vacancies.

But if the material has a surplus of dislocations, if the dislocation density is high then what would happen is the dislocations will invariably start contributing to the plastic deformation process and hence then the deformation is not entirely by diffusion of vacancies.

It will also have a component of deformation coming from the dislocations motion and thus the derivation of Nabarro-Herring creep will then become complicated.

That is why they assumed, Nabarro and Herring assumed that the initial dislocation density of the crystal should be low, Ok so with these two assumptions

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Newtonian viscous creep mechanisms

Derivation of Nabarro-Herring creep

- The creep happens by stress assisted diffusional mass transport
- The diffusion of vacancies or the motion of atoms from one grain boundary to another leads to a crystal strain which in turn contributes to the deformation of the grains and consequently the material
- Assumptions
 - The grain boundaries are perfect sources and sinks of vacancies, and ✓
 - The initial dislocation density of the crystal is low. ✓



they started deriving the equation. So now I am going to derive the equation.

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



So we said you have a grain boundary; you have a grain and you are going to apply a stress σ ,

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



so the grain boundaries which are perpendicular to the applied stress are going to develop more vacancies. So the concentration of the vacancies in these grain boundaries which are perpendicular to the applied stress is going to be higher than the grain boundaries which are parallel to the applied stress.

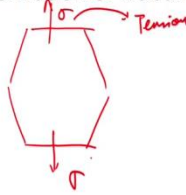
That is because as you apply a stress, you are basically forcing, you are stretching the bond so you are going to create more space so that is a very simplistic way of looking at it but you are applying the stress and you are stretching you are basically creating more gap. So that is why the grain boundaries which are perpendicular to the applied stress will have an excess of vacancies.

Whereas the grain boundaries which are under compression, so this is basically, these grain boundaries can be called under tension

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

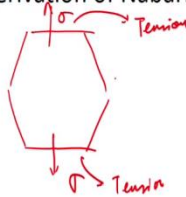


and say, let us say

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



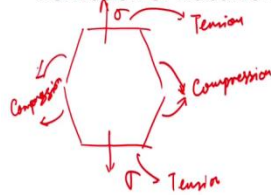
these grain boundaries are going to be under compression because when you are trying to stretch something, then automatically on the other, the other spaces will try to compress.

So naturally you are going to have compression on these, a compressive stress state on these grain boundaries.

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



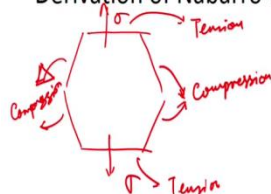
So what happens is now because of this, the grain boundaries which are perpendicular to the stress or which are under tension are going to have an excess of vacancies or surplus vacancies compared to the grain boundaries which are under compression.

So this creates a concentration of, gradient of vacancies. Now as a function of stress, so here for a creep to happen, you need both stress and temperature. And what we know is generally the concentration of vacancies at a given temperature is equal to e to the power minus Q over kT . So

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$$\frac{N}{N_0} = e^{-Q/kT}$$

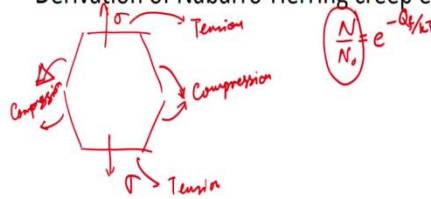


that is the concentration of vacancies

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



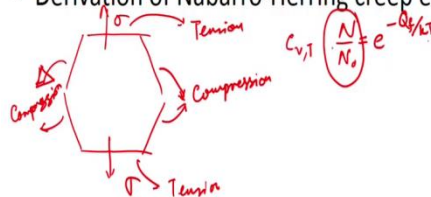
as a function of temperature and so this is the role of temperature.

So at every temperature you will have an equilibrium concentration of vacancies. Now when you have an applied stress combining, so if you, if you define this as C_v due to only temperature,

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



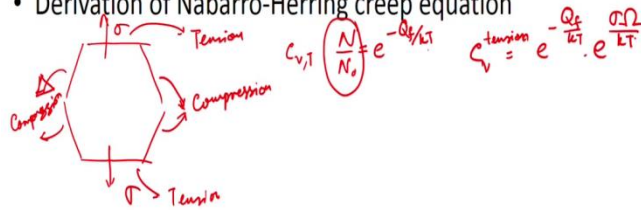
this is what you will get.

Now when you have stress superimposed on this, so you are contributing vacancies also because of the application of a stress then the grain boundaries which were in tension will have vacancy concentration given by the following equation.

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

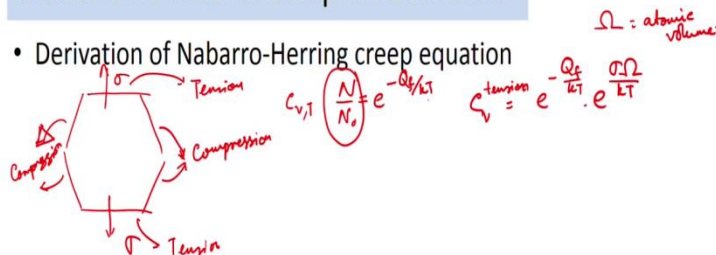


So Q_f is the activation energy for formation of vacancies and $\sigma\Omega$ is, σ is the applied stress and Ω is the atomic volume.

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



So $\sigma\Omega$ basically gives you an energy term.

So what basically this equation says is when you have applied, when you have applied a stress you are basically providing energy for the creation of vacancies especially because of the tension, because under, because these grain boundaries are under tension.

Now let us look at the other case when the grain boundaries are in compression. So your concentration of vacancies is going down, going to come down.

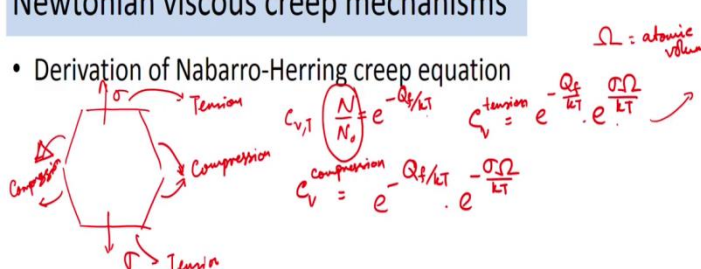
So here you are creating more vacancies, vacancies greater than what you have because of the temperature effect and when the grain boundaries are in compression, C_v compression, you have, you are going to have a reduction in the vacancy concentration.

So you have $e^{-\frac{\sigma\Omega}{kT}}$ in the compression grain boundaries. So clearly you have higher concentration

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



The diagram shows a grain with tension σ and compression σ forces. Handwritten equations show the derivation of the Nabarro-Herring creep equation:

$$c_{v,T} = \frac{N}{N_0} = e^{-\frac{Q_f}{kT}}$$

$$c_{v,C} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

where Ω = atomic volume.



of vacancies in tensile grain boundaries and lower concentration of vacancies in compression grain boundaries, so you have a concentration gradient. So you have ΔC_v and because the vacancies are moving from tension to compression so the diffusion path is from the, from tension to compression.

So you can say the vacancy concentration is C_v , gradient is C_v compression minus C_v tension.

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

The diagram shows a hexagonal grain with arrows indicating tension (pulling) and compression (pushing) forces. To the right, handwritten equations define the equilibrium concentration of vacancies:

- $c_{v,T} = \frac{N}{N_0} = e^{-Q_f/kT}$
- $c_v^{tension} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$
- $c_v^{compression} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$
- $\Delta c_v = c_v^{comp} - c_v^{tension}$

A note indicates $\Omega = \text{atomic volume}$.



So that will be, so Δc_v will be $e^{-Q_f/kT}$ times $e^{\frac{\sigma\Omega}{kT}}$. If you take it out common, then it will have $e^{-\frac{Q_f - \sigma\Omega}{kT}}$ minus $e^{-\frac{Q_f + \sigma\Omega}{kT}}$.

So that is what you will end up

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

The diagram is identical to the previous slide. The equations are repeated, with an additional equation for the difference in vacancy concentrations:

- $\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$

A note indicates $\Omega = \text{atomic volume}$.



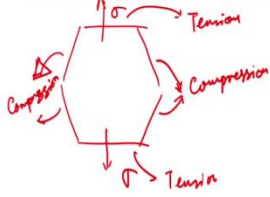
with Δc_v represented by $e^{-\frac{Q_f}{kT}}$ times $\left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$.

Now the flux, that is, now because there is diffusion happening so there is a flux that is created and by Fick's law, Fick's first law we know J is equal to $-D \frac{dc}{dx}$, so that is

(Refer Slide Time: 22:30)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$$

$$c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$\Delta c_v = c_v^{\text{tension}} - c_v^{\text{compression}}$$

$$J = -D \frac{dc}{dx}$$



Fick's first law. And D is the diffusivity.

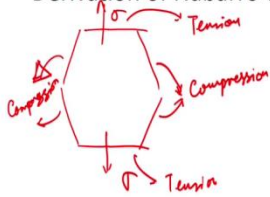
And so if you go by this equation you will have minus D and d c is basically the concentration gradient so that is delta C v, so that becomes e to the power minus Q f over k T e to the power minus sigma omega over k T minus... by d x.

So

(Refer Slide Time: 23:06)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$$

$$c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$\Delta c_v = c_v^{\text{tension}} - c_v^{\text{compression}}$$

$$J = -D \frac{dc}{dx} = -D \frac{e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right)}{dx}$$

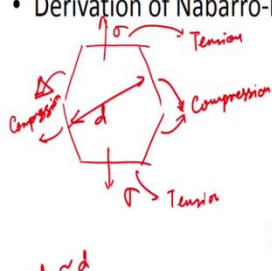


d x is basically the diffusion distance and in the case of this grain, with a grain size d, that d x can be approximated as d. So

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$$

$$c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$\Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$

$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D \frac{dc}{dx} = -b e^{-\frac{Q_f}{kT}} \left(\frac{e^{-\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}}}{d\alpha} \right)$$

$d\alpha \approx d$

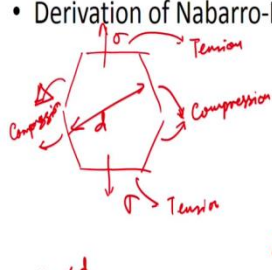


it is going to be some constant of d , constant times d but we can approximate it as, approximately as the grain size, so d is the grain size.

(Refer Slide Time: 23:29)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$$

$$c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$\Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$

$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D \frac{dc}{dx} = -b e^{-\frac{Q_f}{kT}} \left(\frac{e^{-\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}}}{d\alpha} \right)$$

$d\alpha \approx d$
 $d = \text{grain size}$

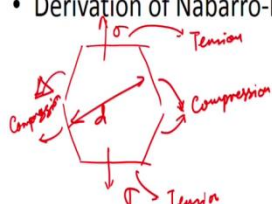


So J then becomes, so because this is diffusion of vacancies so let us call it D_v , and so this basically becomes $D_v e^{-\frac{Q_f}{kT}}$ into $e^{-\frac{\sigma\Omega}{kT}}$ minus $e^{-\frac{\sigma\Omega}{kT}}$ over kT by d .

(Refer Slide Time: 24:03)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$$

$$c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$\Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$

$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D_v \frac{dc}{dx} = -b_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right) \frac{d\sigma}{d}$$

$$J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) d\sigma}{d}$$

$d\sigma \approx d$
 $d = \text{grain size}$

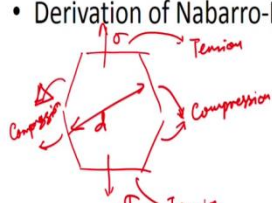


So that is what the flux will be equal to. Now when $\sigma\Omega$ is very small compared to kT , so if you have a condition like that,

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$$

$$c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$\Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$

$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D_v \frac{dc}{dx} = -b_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right) \frac{d\sigma}{d}$$

$$J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) d\sigma}{d}$$

$d\sigma \approx d$
 $d = \text{grain size}$
when $\sigma\Omega \ll kT$



when $\sigma\Omega$ is very small compared to kT then we know e to the power $\sigma\Omega$ over kT will be equal to $\sigma\Omega$ over kT .

So

(Refer Slide Time: 24:31)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$\Omega = \text{atomic volume}$
 $c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$
 $c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$
 $c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$
 $\Delta c_v = c_v^{\text{tension}} - c_v^{\text{compression}}$
 $\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$
 $J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right) \frac{d\sigma}{d\Omega}$
 $J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) d\sigma}{d}$
 When $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$
 $e^{-\frac{\sigma\Omega}{kT}} \approx 1 - \frac{\sigma\Omega}{kT}$

when the exponential term is small then the exponent, the e to the power x is, if x is very small then e to the power x is basically x. So here e to the power sigma omega by k T becomes sigma omega over k T. So what that means is you can expand this saying it is D v e to the power minus Q f over k T into 2 sigma omega by k T over d. So this is what J is

(Refer Slide Time: 25:05)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$\Omega = \text{atomic volume}$
 $c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$
 $c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$
 $c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$
 $\Delta c_v = c_v^{\text{tension}} - c_v^{\text{compression}}$
 $\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$
 $J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right) \frac{d\sigma}{d\Omega}$
 $J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) d\sigma}{d} = \frac{D_v e^{-\frac{Q_f}{kT}} \cdot 2\sigma\Omega}{d \cdot kT}$
 When $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$
 $e^{-\frac{\sigma\Omega}{kT}} \approx 1 - \frac{\sigma\Omega}{kT}$

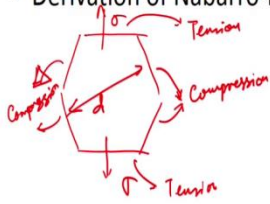
equal to.

Now, so just to give you an example of cases where sigma omega is going to be smaller than k T so if your applied stress sigma is in the range of 1 to 50 M P a,

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$ $c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$

$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$ $\Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$

$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$


$J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$

$J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) dx}{d} = \frac{D_v e^{-\frac{Q_f}{kT}}}{d} \cdot \frac{2\sigma\Omega}{kT}$

$dx \approx d$ $\sigma = 1-50 \text{ MPa}$

$d = \text{grain size}$ $\Omega = 10^{-29} \text{ m}^3$

When $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$

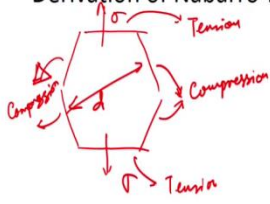


and if your atomic volume is 10 to the power minus 29, then

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$ $c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$

$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$ $\Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$

$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$


$J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$

$J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) dx}{d} = \frac{D_v e^{-\frac{Q_f}{kT}}}{d} \cdot \frac{2\sigma\Omega}{kT}$

$dx \approx d$ $\sigma = 1-50 \text{ MPa}$

$d = \text{grain size}$ $\Omega = 10^{-29} \text{ m}^3$

When $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$



in cases like these you will see kT at high temperatures, kT at high temperatures will be equal to somewhere in the range of 10 to the power minus 20 Joule

So you will see this number is

(Refer Slide Time: 25:45)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT} \quad c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}} \quad \Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$

$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right) \frac{d\sigma}{dx}$$

$$J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) d\sigma}{d} = \frac{D_v e^{-\frac{Q_f}{kT}}}{d} \cdot \frac{2\sigma\Omega}{kT}$$

$$J = D_0 e^{-\frac{Q_m}{kT}} d$$

$\sigma = 1-50 \text{ MPa}$
 $\Omega = 10^{-29} \text{ m}^3$
 $d = \text{grain size}$
 $kT = 10^{-20} \text{ J}$
 when $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$

significantly larger than the product of sigma and omega, and in cases like this your sigma omega is going to be smaller than k T.

So you will have, you end up with this particular form of the equation. So J is equal to, so if we expand D v, so basically the expansion of D v will be some constant D naught and it is going to be e to the power minus Q m over k T.

(Refer Slide Time: 26:09)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT} \quad c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}} \quad \Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$

$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right) \frac{d\sigma}{dx}$$

$$J = \frac{D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) d\sigma}{d} = \frac{D_v e^{-\frac{Q_f}{kT}}}{d} \cdot \frac{2\sigma\Omega}{kT}$$

$$J = D_0 e^{-\frac{Q_m}{kT}} d$$

$\sigma = 1-50 \text{ MPa}$
 $\Omega = 10^{-29} \text{ m}^3$
 $d = \text{grain size}$
 $kT = 10^{-20} \text{ J}$
 when $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$

So D is equal to D naught into e to the power minus Q m over k T, so Q m is the activation energy for migration of the vacancies.

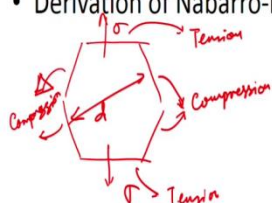
So there are two aspects here. The first aspect was Q_f which is the activation energy for the formation of vacancies. The second thing, activation energy is Q_m which is the activation energy for the migration of the vacancies.

So J is equal to $D_0 e^{-\frac{Q_m}{kT}}$ into $2\sigma\Omega$ over $d k T$. So that is what,

(Refer Slide Time: 26:46)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-\frac{Q_f}{kT}} \quad c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{-\sigma\Omega}{kT}} \quad \Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$


$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{-\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{-\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right)$$

$$J = D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) dx = D_v e^{-\frac{Q_f}{kT}} \cdot \frac{2\sigma\Omega}{d} \cdot \frac{2\sigma\Omega}{kT}$$

$$J = D_0 e^{-\frac{Q_m}{kT}} \cdot \frac{2\sigma\Omega}{d kT}$$

$d \approx d$ $\left\{ \begin{array}{l} \sigma = 1-50 \text{ MPa} \\ \Omega = 10^{-29.3} \text{ m}^3 \\ d = \text{grain size} \\ kT = 10^{-20} \text{ J} \end{array} \right.$
 when $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$

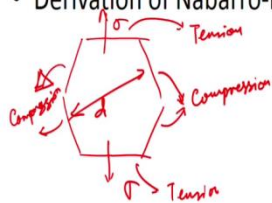


Into, so then there is a term $e^{-\frac{Q_f}{kT}}$ to the power minus Q_f over kT

(Refer Slide Time: 26:54)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-\frac{Q_f}{kT}} \quad c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$$

$$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{-\sigma\Omega}{kT}} \quad \Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$$


$$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{-\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right)$$

$$J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{-\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right)$$

$$J = D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) dx = D_v e^{-\frac{Q_f}{kT}} \cdot \frac{2\sigma\Omega}{d} \cdot \frac{2\sigma\Omega}{kT}$$

$$J = D_0 e^{-\frac{Q_m}{kT}} \cdot \frac{2\sigma\Omega}{d kT} \cdot e^{-\frac{Q_f}{kT}}$$

$d \approx d$ $\left\{ \begin{array}{l} \sigma = 1-50 \text{ MPa} \\ \Omega = 10^{-29.3} \text{ m}^3 \\ d = \text{grain size} \\ kT = 10^{-20} \text{ J} \end{array} \right.$
 when $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$

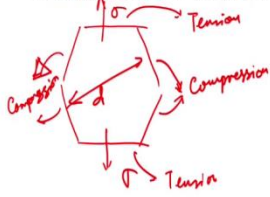


so that becomes equal to $D_0 e^{-\frac{Q_m}{kT}}$ into $2\sigma\Omega$ over d into k times T . So that is what the

(Refer Slide Time: 27:18)

Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation



$\Omega = \text{atomic volume}$

$c_{v,T} \left(\frac{N}{N_0} \right) = e^{-Q_f/kT}$

$c_v^{\text{tension}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$

$c_v^{\text{compression}} = e^{-\frac{Q_f}{kT}} \cdot e^{-\frac{\sigma\Omega}{kT}}$

$\Delta c_v = c_v^{\text{comp}} - c_v^{\text{tension}}$


$\Delta c_v = e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$

$J = -D_v \frac{dc}{dx} = -D_v e^{-\frac{Q_f}{kT}} \left(e^{-\frac{\sigma\Omega}{kT}} - e^{\frac{\sigma\Omega}{kT}} \right)$

$J = D_v e^{-\frac{Q_f}{kT}} \left(e^{\frac{\sigma\Omega}{kT}} - e^{-\frac{\sigma\Omega}{kT}} \right) \frac{d\sigma}{dx}$

$J = D_0 e^{-\frac{Q_m}{kT}} \frac{d}{dT} \left(2\sigma\Omega \right) \cdot e^{-\frac{Q_f}{kT}} = D_0 e^{-\frac{(Q_m+Q_f)}{kT}} \cdot \frac{2\sigma\Omega}{d \cdot kT}$

$\sigma = 1-50 \text{ MPa}$
 $\Omega = 10^{-29} \text{ m}^3$
 $d = \text{grain size}$
 $kT = 10^{-20} \text{ J}$
 when $\sigma\Omega \ll kT$
 $e^{\frac{\sigma\Omega}{kT}} \approx \frac{\sigma\Omega}{kT}$



flux, diffusion flux ends up as.

Now if you want to, so because there is some mass transport happening and accordingly there is change in shape of the crystal so the amount of material that is flowing from one grain boundary to another, to determine that you basically have to, you can talk about it in terms of rate of change of volume and that will be equal to the flux into the area.

So units,

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

Rate of change of volume = $J \cdot d^2$



so J into d square, so if we say it is d V over d t so that becomes D naught into e to the power minus Q m plus Q f over k T into 2 sigma omega by d k T into d square.

So that

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_A + Q_C}{kT}} \cdot \frac{2\sigma\Omega}{d kT} \cdot d^2 \end{aligned}$$



is what will be the rate of change of volume and since it is rate of change of volume then we convert it into rate of change of length. So you can convert rate of change of volume to rate of change of length by doing this. So $1/d^2$ into dV/dt that would be the rate of change of length, let us call this some Δd over Δt .

So that becomes equal to $1/d^2$

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_A + Q_C}{kT}} \cdot \frac{2\sigma\Omega}{d kT} \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{\Delta d}{\Delta t} \end{aligned}$$



into dV/dt and so the rate of change of strain, so the rate of strain is going to be $1/d^2$ into Δd by Δt , so that becomes

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ \downarrow \frac{\delta d}{\delta t} &\rightarrow \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \end{aligned}$$



1 over d into 1 over d square into delta d V by d t which is D naught e to the power minus Q m plus Q f by k T into 2 sigma omega by d k T

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ \downarrow \frac{\delta d}{\delta t} &\rightarrow \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \end{aligned}$$



into d square.

So you have d square, d square cancelling

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ \hookrightarrow \frac{\delta d}{\delta t} &\rightarrow \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \end{aligned}$$



each other and you have a d and d product, so the rate of change of strain which is basically strain rate is, ends up as D naught e to the power minus Q m plus Q v over k T into 2 sigma omega by d square k T.

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ \hookrightarrow \frac{\delta d}{\delta t} &\rightarrow \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \end{aligned}$$



So this is basically the derivation of Nabarro-Herring creep. So the thing to be noted is

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d} \cdot \frac{dV}{dt} = \\ &= \frac{1}{d} \cdot \frac{1}{d} \cdot \frac{d^2}{dt} \cdot D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d} \cdot \frac{d^2}{dt} \cdot D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \rightarrow \text{Nabarro-Herring creep} \end{aligned}$$



when you have Q_m plus Q_v , Q_f , so you have Q_m plus Q_f , this can be taken as equal to Q_L .

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d} \cdot \frac{dV}{dt} = \\ &= \frac{1}{d} \cdot \frac{1}{d} \cdot \frac{d^2}{dt} \cdot D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d} \cdot \frac{d^2}{dt} \cdot D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m + Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \rightarrow \text{Nabarro-Herring creep} \\ & \quad Q_m + Q_f = Q_L \end{aligned}$$



So Q_L is basically the activation energy required for the vacancies to move for the Nabarro-Herring creep to happen.

So Q_L is the lattice diffusivity and it is equivalent to the activation energy required for Nabarro-Herring creep to happen. So Q_m plus Q_L equal to, Q_f is equal to Q_L .

So if we, this equation ϵ_0 equal to D_0 and this equation can eventually

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ &\quad \frac{1}{d^2} \cdot \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{dt} \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{dt} \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \rightarrow \text{Nabarro-Herring creep} \\ &\quad Q_m + Q_f = Q_L \end{aligned}$$



be written as epsilon dot for Nabarro-Herring is equal to A_{NH} approximately equal to A_{NH} and D_L

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d^2} \cdot \frac{dV}{dt} = \\ &\quad \frac{1}{d^2} \cdot \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{dt} \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{dt} \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \rightarrow \text{Nabarro-Herring creep} \\ &\quad Q_m + Q_f = Q_L \\ \dot{\epsilon}_{NH} &\approx A_{NH} \cdot D_L \end{aligned}$$



so D_L is basically D naught lattice into e to the power minus Q_L over kT . So

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d} \cdot \frac{dV}{dt} = \\ &\rightarrow \frac{1}{d} \cdot \frac{dV}{dt} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \rightarrow \text{Nabarro-Herring creep} \\ &\rightarrow Q_m+Q_f = Q_L \quad D_L = D_0 \cdot e^{-\frac{Q_L}{kT}} \\ \dot{\epsilon}_{NH} &\approx A_{NH} \cdot \frac{D_L}{d^2} \end{aligned}$$



it is D L by d square into sigma omega over k T.

So epsilon dot N H is equal to A N H

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d} \cdot \frac{dV}{dt} = \\ &\rightarrow \frac{1}{d} \cdot \frac{dV}{dt} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \rightarrow \text{Nabarro-Herring creep} \\ &\rightarrow Q_m+Q_f = Q_L \quad D_L = D_0 \cdot e^{-\frac{Q_L}{kT}} \\ \dot{\epsilon}_{NH} &\approx A_{NH} \cdot \frac{D_L}{d^2} \cdot \frac{\sigma\Omega}{kT} \end{aligned}$$



into D L by d square into sigma omega by k T. So D L is equal to the lattice diffusivity.

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$$\begin{aligned} \text{Rate of change of volume} &= J \cdot d^2 \\ \frac{dV}{dt} &= D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2 \\ \text{Rate of change of length} &= \frac{1}{d} \cdot \frac{dV}{dt} = \\ &= \frac{1}{d} \cdot \frac{1}{d} \cdot \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{d^2} \\ \text{Rate of change of strain} &= \frac{1}{d} \cdot \frac{dL}{dt} = \frac{1}{d} \cdot \frac{1}{d} \cdot \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{d^2} \\ \dot{\epsilon} &\approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT} \rightarrow \text{Nabarro-Herring creep} \\ & \quad Q_m+Q_f = Q_L \quad D_L = D_0 \cdot e^{-\frac{Q_L}{kT}} \\ \dot{\epsilon}_{NH} &\approx A_{NH} \cdot \frac{D_L}{d^2} \cdot \frac{\sigma\Omega}{kT} \quad D_L = \text{Lattice diffusivity} \end{aligned}$$



So that is the derivation of the equation for Nabarro-Herring creep deformation.

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature



So a similar equation

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

Rate of change of volume = $J \cdot d^2$

$$\frac{dV}{dt} = D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of length = $\frac{1}{d} \cdot \frac{dV}{dt} =$

$$\frac{1}{d} \cdot \frac{dV}{dt} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of strain = $\frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$

$$\dot{\epsilon} \approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT}$$

Nabarro-Herring creep

$$Q_m + Q_f = Q_L \quad D_L = D_0 \cdot e^{-\frac{Q_L}{kT}}$$

$$\dot{\epsilon}_{NH} \approx A_{NH} \cdot \frac{D_L}{d^2} \cdot \frac{\sigma\Omega}{kT} \quad D_L: \text{Lattice diffusivity}$$



has been developed for Coble creep. So the difference between, so the strain rate of deformation by Coble creep is given by $A C$ over π into $D g b$ over d cube into δ grain boundary into $\sigma \omega$ over $k T$. So

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

Rate of change of volume = $J \cdot d^2$

$$\frac{dV}{dt} = D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of length = $\frac{1}{d} \cdot \frac{dV}{dt} =$

$$\frac{1}{d} \cdot \frac{dV}{dt} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of strain = $\frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$

$$\dot{\epsilon} \approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 kT}$$

Nabarro-Herring creep

$$Q_m + Q_f = Q_L \quad D_L = D_0 \cdot e^{-\frac{Q_L}{kT}}$$

$$\dot{\epsilon}_{NH} \approx A_{NH} \cdot \frac{D_L}{d^2} \cdot \frac{\sigma\Omega}{kT} \quad D_L: \text{Lattice diffusivity}$$



this is the equation for Coble creep.

So you have $A C$ over π into $D g b$ by d cube, so $D g b$ is grain boundary diffusivity. $D g b$ is grain boundary diffusivity and

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

Rate of change of volume = $J \cdot d^2$

$$\frac{dV}{dt} = D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of length = $\frac{1}{d} \cdot \frac{dV}{dt} =$

$$\frac{1}{d} \cdot \frac{dV}{dt} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of strain = $\frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$

Nabarro-Herring creep

$$\dot{\epsilon} \approx \frac{A \cdot D_{gb} \cdot \sigma \Omega}{\pi \cdot d^3 \cdot kT} \approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 \cdot kT}$$

$Q_m + Q_f = Q_L$ $D_L = D_0 \cdot e^{-\frac{Q_L}{kT}}$

D_{gb} = Grain boundary diffusivity $\dot{\epsilon}_{NH} \approx A_{NH} \cdot \frac{D_L}{d^2} \cdot \frac{\sigma\Omega}{kT}$ D_L = Lattice diffusivity



δg_b , δg_b is grain boundary thickness.

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Newtonian viscous creep mechanisms

δ_{gb} = Grain boundary thickness

- Derivation of Nabarro-Herring creep equation

Rate of change of volume = $J \cdot d^2$

$$\frac{dV}{dt} = D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of length = $\frac{1}{d} \cdot \frac{dV}{dt} =$

$$\frac{1}{d} \cdot \frac{dV}{dt} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$$

Rate of change of strain = $\frac{1}{d} \cdot \frac{\delta d}{\delta t} = \frac{1}{d} \cdot \frac{1}{d^2} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot \frac{dV}{dt} = \frac{1}{d^3} \cdot D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$

Nabarro-Herring creep

$$\dot{\epsilon} \approx \frac{A \cdot D_{gb} \cdot \sigma \Omega}{\pi \cdot d^3 \cdot kT} \approx \frac{D_0 \cdot e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2 \cdot kT}$$

$Q_m + Q_f = Q_L$ $D_L = D_0 \cdot e^{-\frac{Q_L}{kT}}$

D_{gb} = Grain boundary diffusivity $\dot{\epsilon}_{NH} \approx A_{NH} \cdot \frac{D_L}{d^2} \cdot \frac{\sigma\Omega}{kT}$ D_L = Lattice diffusivity



So D_{gb} , the expansion of D_{gb} is D_{gb} is equal to $D_0 e^{-\frac{Q_{gb}}{kT}}$

So

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Newtonian viscous creep mechanisms

- Derivation of Nabarro-Herring creep equation

$\delta_{gb} = \text{Grain boundary thickness}$
 $D_{gb} = D_0 e^{-Q_{gb}/kT}$

Rate of change of volume $= J \cdot d^2$
 $\frac{dV}{dt} = D_0 e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2$

Rate of change of length $= \frac{1}{d} \cdot \frac{dV}{dt} = \frac{1}{d} \cdot \frac{D_0 e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{d^3} = \frac{D_0 e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2}$

Rate of change of strain $= \frac{1}{d} \cdot \frac{\delta d}{dt} = \frac{1}{d} \cdot \frac{1}{d} \cdot \frac{D_0 e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega \cdot d^2}{d^2} = \frac{D_0 e^{-\frac{Q_m+Q_f}{kT}} \cdot 2\sigma\Omega}{d^2}$

$\dot{\epsilon} \approx \frac{A \cdot D_{gb} \cdot \sigma \Omega}{\pi \cdot d^3 \cdot kT}$

$\dot{\epsilon} \approx D_0 e^{-\frac{Q_m+Q_f}{kT}} \cdot \frac{2\sigma\Omega}{d^2}$

$\dot{\epsilon}_{NH} \approx A_{NH} \cdot \frac{D_L}{d^2} \cdot \frac{\sigma\Omega}{kT}$

$Q_m + Q_f = Q_L$

$D_L = D_0 e^{-\frac{Q_L}{kT}}$

D_L : Lattice diffusivity



the activation energy required for Coble creep is basically equal to the grain boundary diffusion activation energy whereas the activation energy required for Nabarro-Herring is lattice diffusion activation energy. So these are basically the two equations, one for Nabarro-Herring, one for Coble.

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature



Now if you see Coble creep from the previous equation is proportional to 1 over d cube

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Newtonian viscous creep mechanisms

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature



and Nabarro-Herring is proportional to 1 over

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Newtonian viscous creep mechanisms

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$
$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature



d square. So clearly Coble creep is more sensitive to grain size changes than Nabarro-Herring.

So what happens is as the grain size continues to reduce, so if you have a material with a finer grain size, so why is it sensitive to d cube?

That is because when you reduce the grain size, you are introducing more and more grain boundaries into the material. So that is why Coble creep is going to become more and more prominent.

Because Coble creep requires diffusion of vacancies through the grain boundaries so as you refine the grain size you are introducing more grain boundaries into the material so naturally Coble creep tends to become more prominent.

So at a certain grain size, critical grain size, Coble creep will eventually become dominant over the Nabarro-Herring creep. And what we are also seeing is that the strain rate of deformation is more sensitive to grain size in Coble creep than it is in Nabarro-Herring creep.

Now between Coble creep and Nabarro-Herring creep one key difference is if your test is being carried out at lower temperatures then Coble creep will be the favored mechanism of creep.

So low temperatures, between Nabarro-Herring and Coble creep, at lower temperatures Coble creep will be more favored and at higher temperatures Nabarro-Herring creep will be more favored.

So the reason is the activation energy for vacancy diffusion within the lattice that is Q_L is greater than the activation energy required for diffusion along the grain boundaries. So Q_L is

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep.
- The activation energy for vacancy diffusion within lattice is larger than that for diffusion along grain boundaries. Thus lattice diffusion is slower than grain boundary diffusion with decreasing grain size.

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$

$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$

$$Q_L > Q_{gb}$$



greater than Q_{gb} .

So what happens is, as you go down in temperature, lattice diffusion is slowly going to come down. So for the vacancy, as you go down in temperature the vacancies will find it difficult to go through the lattice compared to the more open structure available in the grain boundary.

So you are talking about diffusion of vacancies and the diffusion of vacancies can happen through the lattice or they can happen through the grain boundary. Now the grain boundary has a more open structure compared to the lattice.

So when the temperature is low, that means the energy that you are providing through temperature is not high enough then the vacancies would rather prefer to go through a open structure like the grain boundary than go through a more ordered structure like the lattice. That is why, at lower temperatures Coble creep going to be dominant at low temperatures.

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for diffusion within lattice is larger than that for diffusion along grain boundaries. Thus lattice diffusion slows down more rapidly than grain boundary diffusion with decreasing temperature.

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$

$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$

$$Q_L > Q_{gb}$$

Coble creep is going to be dominant @ low temperature



So another way of also looking at the same point is the strain rate is proportional to $e^{-Q/RT}$.

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$
$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$
$$\dot{\epsilon} \propto e^{-Q/kT}$$

$Q_L > Q_{gb}$
Coble creep is going to be dominant @ low temperature



So when T is low, so when T is low k T is small.

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$
$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$
$$\dot{\epsilon} \propto e^{-Q/kT}$$

T is low, kT is small

$Q_L > Q_{gb}$
Coble creep is going to be dominant @ low temperature



So if you have, when T is small, if T is low and k T is small if you have Q, the activation energy is equal to Q L then the strain rate is going to come down.

If Q is equal to Q L then the strain rate is smaller compared to Q is equal to Q g b.

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$
$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$
$$\dot{\epsilon} \propto e^{-Q/RT}$$

*T is low, RT is small
If $Q = Q_L$
 $\dot{\epsilon}$ is smaller compared to $Q = Q_{gb}$*

$$Q_L > Q_{gb}$$

Coble creep is going to be dominant @ low temperature



So the point is if T is small, k T is small and if Q is larger

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$
$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$
$$\dot{\epsilon} \propto e^{-Q/RT}$$

*T is low, RT is small
If $Q = Q_L$
 $\dot{\epsilon}$ is smaller compared to $Q = Q_{gb}$*

$$Q_L > Q_{gb}$$

Coble creep is going to be dominant @ low temperature



then the overall term in the exponent

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$
$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$
$$\dot{\epsilon} \propto e^{-\frac{Q}{kT}}$$

*T is low, kT is small
If $Q = Q_L$
 $\dot{\epsilon}$ is smaller compared to $Q = Q_{gb}$*

$$Q_L > Q_{gb}$$

Coble creep is going to be dominant @ low temperature



is also going to be larger, so it has a negative point, so it is minus Q over k T.

So if Q is large, then minus Q over k T also being to be large which means the strain rate is going to be low. So in such a case you would rather prefer Q to be equal to Q g b rather than

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Newtonian viscous creep mechanisms

- When the grain size reduces, the fraction of grain boundaries increases and hence at finer grain sizes Coble creep becomes dominant over Nabarro-Herring creep
- The strain rate in Coble creep is more sensitive to grain size than that in Nabarro-Herring creep.
- Low temperatures favor the operation of Coble creep and higher temperatures favor the operation of Nabarro-Herring creep
- The activation energy for vacancy diffusion within lattice is larger than that along grain boundaries. Thus lattice diffusion slows down relative to GB diffusion with decreasing temperature

$$\dot{\epsilon}_c \propto \frac{1}{d^3}$$
$$\dot{\epsilon}_{NH} \propto \frac{1}{d^2}$$
$$\dot{\epsilon} \propto e^{-\frac{Q}{kT}}$$

*T is low, kT is small
If $Q = Q_L$
 $\dot{\epsilon}$ is smaller compared to $Q = Q_{gb}$*

$$Q = Q_{gb}$$
$$Q_L > Q_{gb}$$

Coble creep is going to be dominant @ low temperature



Q is equal to Q L so that is why if Q is equal to Q g b at lower temperatures then you will have a higher strain rate of deformation achieved with Coble than with Nabarro-Herring. So that is the reason behind this.