

Mechanical behavior of materials

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Week-9

Lecture-48

Grain Size Strengthening



Mechanical Behavior of Materials (Hindi)

Grain Size Strengthening



Namaskar swagat karta hoon aapka is course mein mechanical behavior of materials mein jo ki hum hindi mein padhenge last part mein humne precipitation strengthening aur dispersion strengthening yeh jo do strengthening mechanism the iske baare mein padha tha is part mein hum grain size strengthening ke baare mein padhenge yaani grain size jo hota hai material mein woh kis tarah se material ko strengthen kar sakta hai jab main grain size ki baat karunga tab mere vichar mein do cheezein aani chahiye ek hai single crystalline aur polycrystalline material ye hum crystalline material ki baat kar rahe to mere paas single crystalline aur polycrystalline material aane chahiye to difference kya hai single crystalline aur polycrystalline material mein kyunki humne deformation dekha tha ki single crystal mein kis tarah se hota hai polycrystal ke baare mein dekhte hain ki polycrystals hote kya hai aur yeh kyun important hai jab hum dekhte hain koi bhi jo solid hai woh usmein bahut saare grains hote hain jo grains jo hote hain main unko keh sakta hoon small crystals aur collection of single crystals main is tarah se keh sakta hoon aur jo hai yeh number of single crystals collectively mujhe polycrystalline material dete hain abhi ye

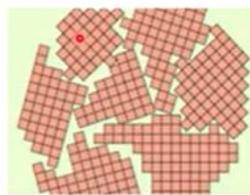
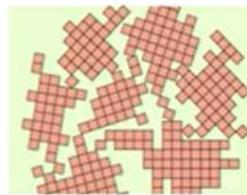
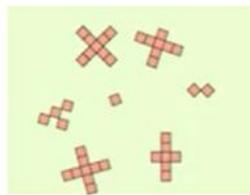
polycrystalline material bante kaise hain to agar hum simple process dekhenge jaise main casting process dekh raha hoon hum dekhte hain ki nucleation aur growth wahan par hoti hai to yahan par aap dekh rahe honge ki yahan par kuch nuclei bane hain metal mein liquid mein aur yeh nuclei ek particular orientation ke saath honge aap dekh rahe honge ki dusri figure mein yeh nuclei abhi grow ho rahe hai yaani inki growth ho rahi hai to ek particular orientation ke saath growth honge ab yeh jo complete solid ban jayega ya inki growth is tarah se hogi to aap dekhe honge ki yeh jo ek particular orientation is part ka hai ek particular orientation is part ka hai ek particular orientation part ka hai jab ye complete solid ho jayega to ek dusre pe taraf ek interface banayenge agar aap dekhenge yahan par ek interface banega yaani yahan par koi orientation hoga yahan par koi orientation hoga aur yeh jo boundary hogi inke beech mein yeh meri grain boundary hogi to yeh jo individual orientation jahan pe orientation same hai inko hum kehte hain a ek grain aur inka jo aggregate hai yaani collectively in sabko hum kahenge polycrystalline material to ek ek hamara crystallite ho gaya aur yeh bahut saare milke ek polycrystalline material humein milega to humein ye solidification ke dauran hi milta hai mostly metals aur alloys solidification process ke through hi banaye jaate hain to aap dekhenge ki humein koi bhi application ke liye jo material milega wo mostly polycrystalline material hota hai to isliye yahan pe grain boundary ka mahatva humein samajhna chahiye.



Crystalline materials: Single Vs Polycrystalline

- What is the difference between polycrystalline metal and single crystal

Most crystalline solids are composed of a collection of many small crystals or **grains**; such materials are termed **polycrystalline**.



Abhi kuch aur cheezein hum padh lete hain grain aur grain boundaries ke baare mein jab main polycrystal material baat karunga to humein jo crystallographic orientation hai ek grain ki wo alag-alag hai yahan par hum dekh paa rahe hain aur yahan pe ek example diya hai nickel aluminate polycrystal ka jahan par hum inverse pole figure humein mila hai inverse pole figure map to ye milta hai humein ebsd studies se electron backscatter diffraction studies se to yahan pe aap dekh paa rahe honge ki ek ye color jo hai woh ek orientation bata raha hai yaani is grain ka kya orientation hai hamare surface ke hisaab se to yahan pe color code map diya hai aur isse aap pehchan sakte hain ki kaun sa grain kis direction mein oriented hai to jab agar blue grain hai to aap dekh paa rahe honge ki uski (111) plane jo hai woh surface se parallel hogi agar red grain hai yahan pe kuch is tarah se ya yahan pe yeh jo grains hai yeh inki (001) planes hai jo parallel hogi

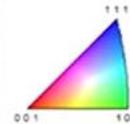
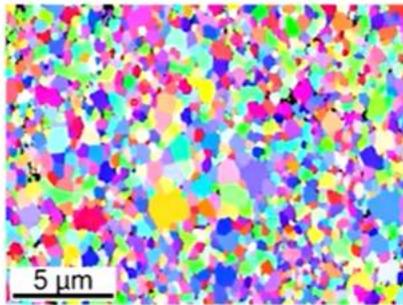
surface ke hisaab se agar green hai to (101) grains to yahan se aap is tarah se padh sakte hain to aap dekh paa rahe honge ki is microstructure mein aapke paas bahut saare grains hai individual grains hai aur humein pata hai ki jo individual grains hote hain wo anisotropic hote hain par ab dekh paa rahe honge ki yahan pe jo orientation hai wo random hai complete random hai yahan pe koi texture nahi hai texture yaani preferred preferred orientation nahi hai yahan pe kisi grains ke surface ke hisaab se to yahan pe koi texture nahi hai aur ye random orientation hai grain ke to humein jo property milegi is polycrystalline material mein wo average out property rehti hai saare direction mein isliye ye jo polycrystalline material hai wo isotropic behave karta hai kyunki yahan par koi ek preferred texture nahi hai.



Grain and grain boundaries

- For many polycrystalline materials, the crystallographic orientations of the individual grains are totally random.

NiAl



- Individual grain is anisotropic, however, a specimen with grain aggregate behaves isotropically.
- The magnitude of a measured property is the average of the directional values.
- "Texture" : preferential crystallographic orientation of grains

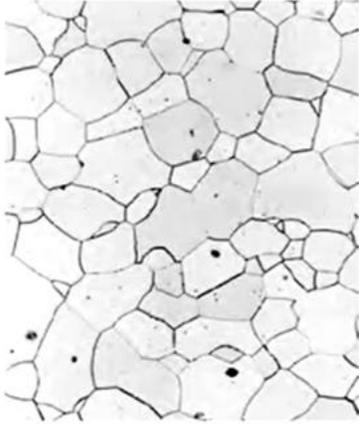
To yeh ho gaya hamara properties single crystal line ya single grain aur polycrystalline material mein to aap abhi aur phir se dekhte hain ki grain aur grain boundaries kya hai to grain boundary jab main baat karunga tab humein grain boundaries yaani dekh sakte jaise maine bola ki grain boundary ek region hai mere do jahan par do grains ke beech ka aur do grain jab main baat karunga to dono grains ka jo orientation hoga woh kuch alag hoga yahan par yaani grain boundary ek mismatch region hoga ek atomic mismatch yahan par taiyaar hoga isi ko hum is boundary ko hum aur is area ko hum grain boundary kehte hain to grain boundary dikhti kaise material mein to yahan par aap dekh paa rahe honge ki grain boundary yahan pe black dikh rahi hai jab main kisi bhi microscope mein mera polished surface mirror polished surface agar rakhunga aur usko etch karunga to aap dekh paa honge kyu grain boundary area jo hota hai wo high energy area hota hai ki kyunki wahan pe ek atomic mismatch hota hai aur wahan pe bonds broken hote hain wahan pe ordered structure nahi hota hai a grains ki tulna mein aur grains ki interior ki tulna mein to aap dekh paa rahe honge ki yahan pe material remove hai yahan pe ek surface groove taiyaar hota hai jab main etch karta hoon material ko to aapne ek physical metallurgy mein padha hoga to yahan par hum dekhenge ki jab koi light ispe takrati hai aur wapas jayegi to yahan se jyada scattering milegi as compared to aapke polished surface to aap dekhenge ki agar main bright field mode mein agar main apni image le raha isko bhi likh lete hain agar main bright field mode mein image lunga

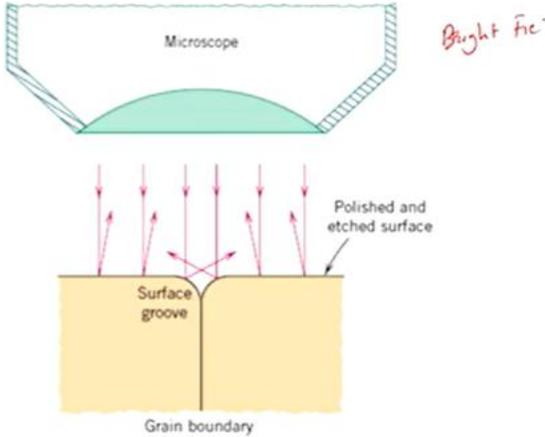
to aapko dikhega ki yeh grain boundary mujhe black dikh rahi hai usi tarah se agar dark field mein lunga to aapko grain boundaries bright nazar aayengi aur grain interior grains aapko dark nazar aayenge to is tarah se hum grain boundaries ko dekhte hain material mein.



What is grain boundary?

There exists some atomic mismatch within the region where two grains meet; this area, called a **grain boundary**





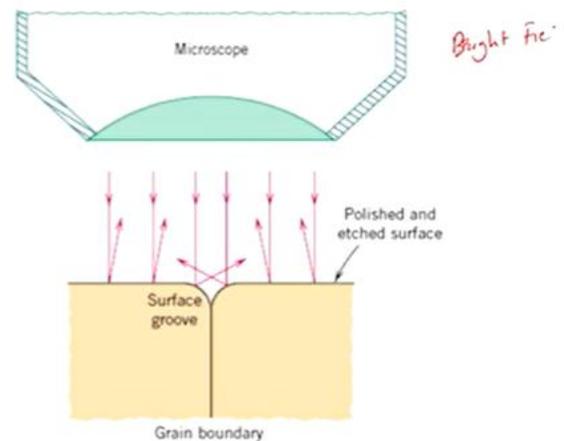
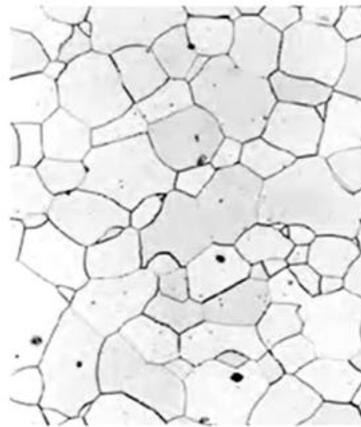
Bright line

Jab main grain boundaries ki baat karta hoon crystalline material mein maine abhi isko kaha tha ki ek mismatch region hai atomic mismatch to ek orientation maan lete kuch is tarah se hum schematic se samajhte hain ki grain boundary actually hai kya to ek ye ek grain hai iska ek orientation hai aur ek yeh grain hai ismein kuch ek orientation hai abhi hum in dono ke beech ka jo region hai yeh meri grain boundary hai to aap aap dekhenge ki yahan pe kuch ordered structure hai yahan par kuch ordered structure hai par grain boundary jo region hai yahan par bonds broken hai aur yahan pe koi ek order nahi hai to grain boundary ek a disordered ya yahan pe koi ek preferential order yahan pe atoms ka hota nahi hai ye ek boundary region hai do grains ke beech ka to yeh jo boundary region hai ye kyunki hum isko to hum 2d mein dekh rahe hain aur grains hamare 3d mein hote hain to ye jo defective region hai ye a yeh hoga hamara ek plane ya ye region hoga ek area hoga to yeh jo defect hai ye kis type ka defect hoga ye hamara two dimensional defect ya surface defect ya planar defect hoga aur aap dekh paa rahe honge ki yahan pe number of broken bonds jyada honge aur iski wajah se yahan pe ye jo area hoga ye mere grain ki tulna mein high energy area hoga kyunki yahan pe broken bonds jyada honge to yeh ho gaya mera grain boundaries in crystalline material.



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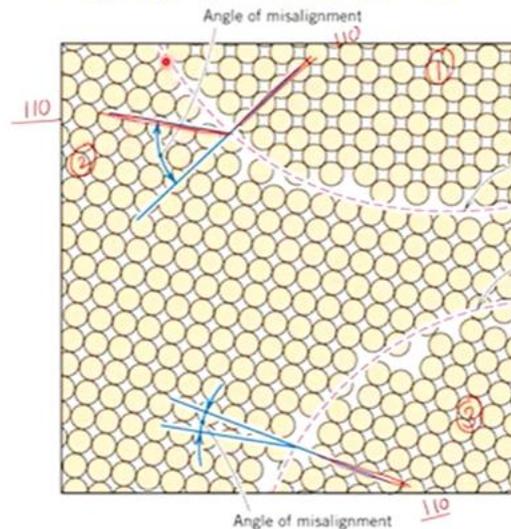
To grain boundary ki energy kya hogi grain boundary ki energy hogi meri milli joules per meter square aur abhi hum jab misorientation ki baat karte to pehle misorientation samajh lete hain to maan lete hain ki yeh mera ek kuch particular plane hai is plane ko main maan le raha hoon yeh mera (110) plane hai ek material mein agar material mein yaani ye grain one mein is grain one ko main naam deta hoon grain 1 grain 2 aur grain 3 to main dekhunga ki (110) planes yahan pe dusre grain mein kis tarah se to agar main dekhunga ye particular (110) plane hai (110) plane yahan pe bhi main dekhunga ki (110) plane kahan pe hai kuch is tarah se ye mere (110) planes hai abhi ye hum maan ke chal rahe to grain one mein is tarah se hai to main in jo (110) plane is grain ka hai aur dusre plane ka (110) inka agar angle nikaalu inke beech ka aap dekho ye dekhiyega yeh orientation is tarah se yeh orientation is tarah se to inke beech ka ek main angle nikaal sakta hoon isko kehta hoon main angle of misalignment aur angle of misorientation to yeh ho gaya mera angle of misalignment aur angle of misorientation similarly yahan pe aap dekh paa rahe honge ki ek angle of misalignment grain 2 aur grain 3 ke beech mein to aap dekh paa rahe honge ki ye jo boundary hai yahan pe grain 1 aur grain 2 ki ismein angle of misalignment jyada hai aur ismein ek angle of misalignment kam hai to iske hisaab se hum grain boundaries ko define karte hain angle of misalignment ya angle of misorientation se to agar yeh jo angle hai yeh less than 15 degree hai to main isko low or small angle grain boundary kehta hoon kisi books mein isko hum kisi kisi books mein isko less than 10 degree bhi define karte hain par yeh aapke upar depend hai ki aap kis tarah se low angle grain boundary ko define kar sakte hain to generally 10 to 15 consider karte hain yahan pe main 15 degree consider kar raha hoon yeh jo angle of misorientation ya angle of misalignment 15 degree se niche hai to woh ho jayegi meri low angle grain boundary agar wo yeh angle of misalignment jyada hai to yeh ho jayegi 15 a aur 15 degree se jyada hogi to isko hum high angle grain boundary kehte hain to yahan pe hum dekhenge ki yeh jo boundary hai yeh 15 degree se jyada dikh rahi hai to yeh ho jayegi meri high angle grain boundary is tarah se aur yeh jo angle hai yeh less than 15 degree dikh rahi hai mujhe to yeh jo boundary hogi in dono grain ke beech mein yeh low angle grain boundary ya small angle grain boundary hogi to yeh ho gayi meri

definition grain boundaries ki angle of misorientation ke hisaab se isko bhi likh leta hoon kisi kisi books mein misorientation bhi likhte hain.



Grain boundary: Angle of Misalignment

- ✓ Low (or small) angle grain boundary $< 10^\circ$ ($< 15^\circ$)
- ✓ High angle grain boundary ($> 15^\circ$)



To abhi jab hum baat karenge angles angle of misorientation ke baad to yeh jo grain boundaries hai ye mere material mein strengthening ka kaam karti hai to yeh sabse pehle studied kiya tha hall aur petch ne e.o. hall aur n.j. petch ne to ye do classic papers hai material science mein jo sabse pehle kaam the jinhone bataya ki grain size variation se yaani grain size agar aap change kar rahe to material ki strength ghata aur badha sakte hain to yeh do classic papers hai e.o. hall aur n.j. petch ke dwara aap interested hai yahan par kuch references diye aap isko padh sakte hain to aur yeh jo grain size strengthening iska aur ek naam diya jaata hai hall aur petch ke naam se hi isko hall-petch relation bhi kehte hain jab main grain size strengthening ki baat karunga to hum hall petch relationship ke baare mein bhi padhenge jo cover karta hai mere strength ko grain size ke saath aap dekhenge ki yeh connect karta hai yahan par proportional nahi likhunga to yahan par yeh connect karega mere grain size ke saath yeh relationship to aaiye dekhte hain ki yeh jo grain size hai meri strength kaise badhata hai to jab main strength ki baat karunga tab sabse pehle main elastic strength strain curve plot karunga to yeh maine true stress aur true strain is tarah se plot kiya hai aur main agar ye curve dekhunga true stress true strain curve to larger grain size ke liye mujhe kuch is tarah se variation mil raha hai agar same material mein main agar grain size ghataunga to mujhe kis tarah se strength milega yeh dekhte hain to maan lete hain ki kuch is strain pe mujhe yeh stress mil raha hai larger grain size par agar main grain size ghataunga to mujhe stress strain curve kuch is tarah se dikhta hai jahan par aap dekhenge ki isi strain ke liye aapko jo strength hai woh badh gayi hai yahan par aap dekh paa rahe honge ki yeh strain ke liye yeh jo strength lag rahi hai yahan pe yahan pe larger aur yeh smaller main is tarah se karunga to aap dekh paa rahe honge σ_s greater hai σ_{Large} se to ek hi strains pe at particular strain to yeh strength prapt karne ke liye mujhe small grain size mein jyada stress ki zarurat padegi larger grain size ke hisaab se to yeh jo difference hai yahi mera strengthening main keh sakta hoon ki mera material strengthen ho gaya jaise jaise main apna grain size small kiya to aap dekh paa rahe honge ki yahan par strength to badi

hai par thodi si ductility mein kami aayi hai to yeh jo strength badhta hai humne dekha tha ki yeh hum jab dislocation ki baat kar rahe tab dislocation grain boundaries par ya is smaller grain mein jyada roke jayenge as compared to larger grain size aur uski wajah se strength badhti hai yeh hum aage padhenge bhi.



Classic Papers: by Hall and Petch

Hall-Petch relationship
 $\sigma \propto \frac{1}{\sqrt{d}}$

The Deformation and Ageing of Mild Steel: III Discussion of Results

By E. O. HALL
Cavendish Laboratory, Cambridge

Communicated by W. L. Bragg; MS. received 8th March 1951

ABSTRACT An attempt is made here to explain the observed phenomena in the yielding and ageing of mild steel, described in two previous papers, in the general terms of a grain-boundary theory. On this hypothesis, a satisfactory explanation of the variation of the lower yield point with grain size may be developed. It is shown that strain-ageing must involve two processes: a healing of the grain-boundary films, coupled with a hardening in the grains themselves. A discussion of the possible nature of the grain-boundary film is also undertaken.

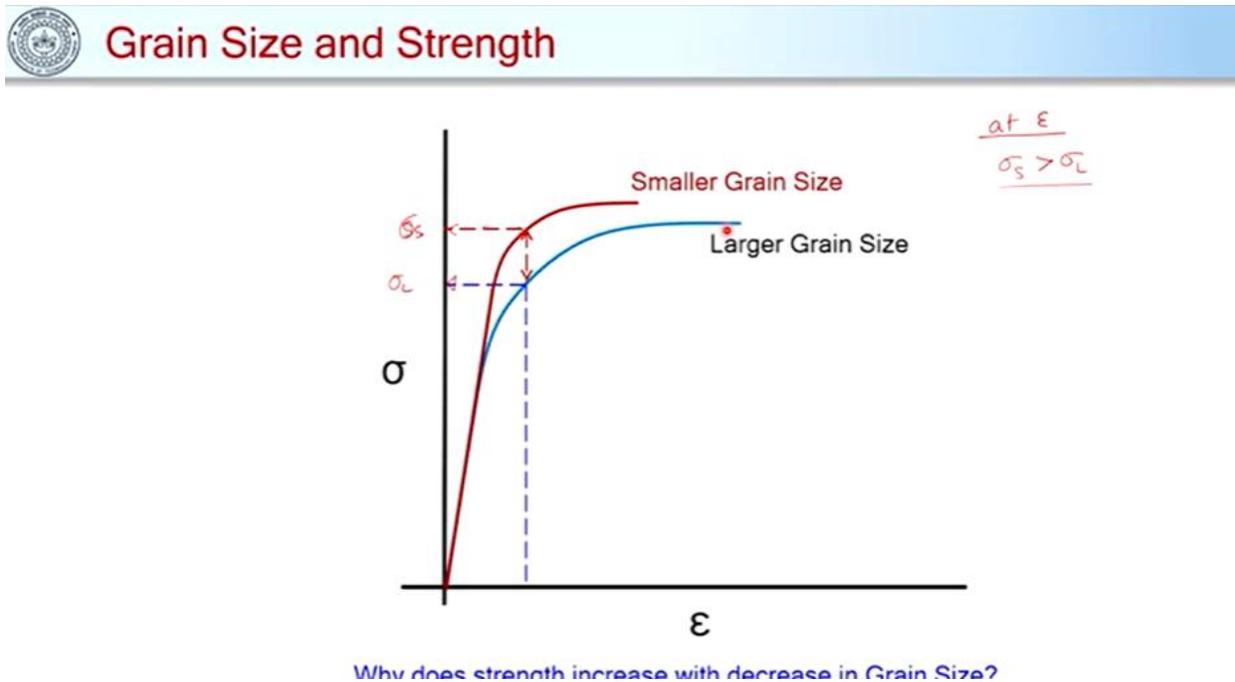




Petch N J. The cleavage strength of polycrystals. *J. Iron Steel Inst.* 174:25-8, 1953. [Department of Metallurgy, University of Leeds, Leeds, England]

Cleavage strength is shown to be related to grain size. A theory is given in which yielding and cleavage depend on the stress concentration generated where a slip band across a grain is blocked by the grain boundary. [The SCIP[®] indicates that this paper has been cited over 365 times since 1961.]

E. O. Hall, Proc. Phys. Soc., Sect. B, 1951, 64, (9), 747-755
 N. J. Petch, J. Iron Steel Inst., 1953, 174, (1), 25-28
<https://royalsocietypublishing.org/doi/pdf/10.1098/rstb.1995.0021>
<https://livingstones.newcastle.edu.au/nodes/view/53435>



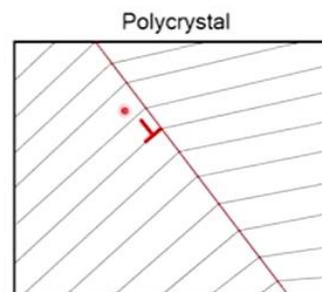
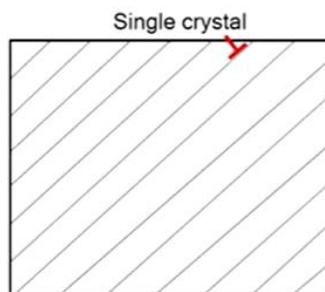
To hamare paas ek question hai ki yeh grain size change hone se material ki strength kyun badhti hai to iske liye is tarah se samajhte hain jab main strength ki baat kar raha hoon tab humein dislocation ki movements dekhni hai agar dislocation ki movement mein koi resistance hai agar

ya impedance hai ya usmein koi rukawat hai to aap dekhenge ki strength badhegi ya dislocation ki pinning ho rahi hai to strength badhegi ya impedance hai to de to material ki strength badhegi to agar main single crystal aur polycrystal material consider kar raha hoon to single crystal mein main consider karta hoon ki mera atomic planes kuch is tarah se aur polycrystalline material mein kuch is tarah se wahan pe humein ek boundary milegi to humein yahan par orientation change mil raha hai aur in dono ke beech mein ye grain boundary hai maan lete hain mere paas kuch dislocation hai kuch is tarah se ek slip plane pe aur main stress apply karta hoon to kya hoga is stress ke influence mein ye dislocation move hota hai humne dekha tha aur ye move hoke single crystal mein ye surface pe aayega to yahan pe is dislocation ke liye koi rukawat nahi thi par agar wahi dislocation mere polycrystalline material mein to ab hum dekhenge ki dislocation grain boundary tak aayega aur grain boundary ke aane ke baad ruk jayega kyunki yahan pe koi slip plane continuity nahi hai yahan pe ek mis angle of misorientation hai yaani orientation change hai to aap dekh paa rahe honge ki dislocation yahan se move nahi karega aage aake is boundary pe ruk jayega agar yeh is boundary pe ruk gaya to iske peeche wale jo aane wale dislocations hai in saaron ko woh rokega ya interact karega unke saath to uske wajah se mere material ki strength badh jayegi to aap dekhenge ki polycrystalline material mein grain boundaries meri strength badhane ka ya dislocation ko rokne ka kaam karte hai uske wajah se aap dekhenge ki mere material ki strength badh gayi hai to kuch is tarah se schematic se samajhte hain agar mera ye dislocation hai aap dekh paa rahe honge yahan pe ek slip plane hai aur yeh slip plane kuch is tarah se yaani yahan pe grain boundary hai aur orientation change hai to yeh jab dislocation boundary tak pahunchega to aap dekh paa rahe honge yahan pe orientation change hone ki wajah se dislocation is boundary ko cross nahi kar payega ya wahan ruk jayega to iski wajah se mere material ki strength badhegi grain boundary ki wajah se to aap dekh paa rahe honge ki dislocation a ka dislocation b mein move nahi kar payega kyunki yahan par orientation change hai crystallographic misorientation yahan par aur yahan par hum dekhte hain ki grain boundary jo mera region hai woh atomic disorder hai aur yahan par mere slip plane ki discontinuity hai to schematic se hum samajh payenge ki grain boundary mere material ki strength badhati hai kyunki wo defects jaise dislocation inko rokti hai jab plastic deformation ho rahi hai.



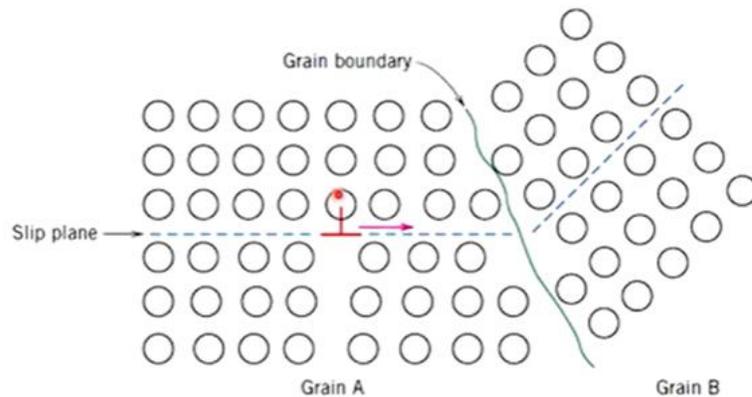
GB: Strengthening???

- Resistance to the dislocation movements
- Pinning of dislocations
- Impede dislocation motion





Grain Boundary Strengthening



- ✓ A dislocation passing into grain B will have to change its direction of motion
- ✓ Increase in crystallographic misorientation
- ✓ The atomic disorder within a GB region: a discontinuity of slip planes

To abhi kuch aur roles dekhte hain grain boundaries ke plastic deformation mein to hum jab deformation ki baat karte hain to main abhi low temperature jab baat karunga to main dekh paa raha hoon ki yeh jo temperature hai main less than $0.5T_m$ to yeh main kelvin mein define karta hoon jaise isko ek udaharan ke dwara bhi samajh sakte jaise aluminium ka melting point 660 degree celsius hai aur nickel close to 1500 hai maan lijiye aap check kar lijiyega ki kitna melting point hai yahan par to isko main kelvin mein pehle convert karunga to $660 + 273$ add karke dekhunga aur yahan pe bhi $1500 + 273$ is tarah se add karunga yeh ho gaya mera melting point in kelvin ho gaya ye al aur nickel ka abhi hum dekhte ki koi operating temperature hai let's say 300 degree celsius hai to aap dekh paa rahe honge agar main 300 degree celsius ko bhi kelvin mein convert karunga to mere paas kuch is tarah se operating temperature aayega aur is operating temperature ko main inke melting point se normalize karunga yaani divide karke dekhunga to aap dekhenge ki ye jo temperature hai ye greater than $0.5T_m$ aayega par iske liye less than $0.5T_m$ aayega to aap dekh paa rahe honge ki main jo operating temperature hai usko main compare karunga tulna karunga mere melting point ke hisaab se mere alloy ke melting point ke hisaab se to low temperature main kuch is tarah se define kar raha hoon ki less than $0.5T_m$ hai wo mera low temperature hai to is case mein jo grain boundaries hai wo barrier ya obstacle karke act karegi mere dislocation ke saath to aap dekhenge ki dislocation ke pile up honge grain boundaries ke upar yeh ho gaya mere low temperature deformation ke saath at high temperature high temperature main is tarah se define karunga ki temperature jo operating temperature agar jyada hai ya application temperature jyada hai $0.5T_m$ se to isko main high temperature karke consider karta hoon yahan par meri grain boundaries weaker ho jaati hai mere grain ke interior ke saath agar main kuch is tarah se consider karu mere paas do grains hai yahan pe maine grain is tarah se consider kar raha hoon to grain boundaries jo hai yahan par grain boundary at high temperature wo yeh jo meri grain boundary hai woh weak ho jayegi agar main kuch temperature $0.5T_m$ is tarah se consider karunga aur main yahan par boundary strength yaani grain boundary ki strength aur grain interior sigma σ_{grain} is tarah se mark kar raha hoon to aap dekhenge ki point 5 ke pehle agar main temperature is tarah se mark karunga badhte hue to yahan par jo grain boundary ki strength hai wo

badi rahegi mere grain interior ke saath aur at point $0.5T_m$ ya above $0.5T_m$ aap dekhenge ki yeh jo grain boundary ki strength hai a yeh ya grain ki strength hai woh badi ho jayegi mere grain boundary ke strength ke saath to hum dekh paa rahe hain ki grain boundaries weak ho jaati hai at high temperature to uske wajah se kya hoga agar grain boundaries weak hogi to wahan par grain boundary sliding hogi aur plastic flow hoga yahan pe grain boundary deform ho rahi hai to yahan pe voids bhi taiyaar karne ke chances jyada hai aur grain boundaries humne dekha hai ki wo source ya sink act karti hai vacancy ke liye yeh isko hum kehte hain Nabarro-herring creep to iske baare mein bhi hum padhenge jab hum creep ke baare mein padhenge abhi ke liye aap yeh samajh sakte ho ki grain boundaries meri source aur sink ke tarah kaam karti hai aur ek temperature ko main consider kar sakta hoon isko kehte hain equicohesive temperature equicohesive temperature yaani ek aisa temperature jahan par mere grain boundary aur grain interior yahan par main keh sakta hoon ki equicohesive temperature pe grain boundary yaani is tarah se main likh sakta hoon grain boundary aur grain interior ki strength jo hai wo saman hoti hai isko main kehta hoon equicohesive temperature below equicohesive temperature grain boundary ki strength badi hoti hai grain interior se aur above equicohesive temperature grain boundary ki strength kam hoti hai mere grain interior se to yahan par humne dekha ki equicohesive temperature close to mere $0.5T_m$ hota hai aur yahi definition hai mere high temperature aur low temperature ke demarcation ki to yeh ho gaya mera equicohesive temperature to hum dekh paa rahe hain ki jo fine grain material hai ismein hum dekhenge ki fine grain material mein mere grain boundaries jyada hogi to to fine grain material mere stronger rahenge coarse grain material ke tulna mein equicohesive temperature ke niche to yahan par dekhenge ki fine grain material fine grain size inki jo strength hogi ye badi hogi coarse grain se aur equicohesive temperature ke baad hum dekhenge ki coarse grain material ki strength jyada hogi mere fine grain size ki tulna mein to yahan par hum dekh paa rahe ho ki grain boundary ek important role play karta hai temperature ke saath aur deformation.

Roles of GB in plastic deformation

- At low temperature ($T < 0.5 T_m$, in K),
 - ✓ GBs act as a barrier (obstacle) to dislocation motion. Dislocations pile up against the GBs.
- At high temperature ($T > 0.5 T_m$),
 - ✓ GBs gets weaker than the bulk
 - ✓ GBs sliding leading to plastic flow and opening of voids along GBs
 - ✓ GBs can act as sources and sinks for vacancies (Nabarro-Herring creep)

Equi-Cohesive Temperature (ECT),

- ✓ GBs and grain interior have the same strength
- ✓ $ECT \sim 0.5 T_{mp}$ (in K)

$T < ECT$: Fine grain materials are stronger than coarse grain materials

$T > ECT$: GB is weaker than grain - coarse grain materials are stronger (think about Ni-based superalloys in turbines blade)

$\frac{300^\circ\text{C}}{(300+273)\text{K}}$ Al - 660°C Ni - 1520°C
 T_m ($660+273$) K T_m ($1520+273$) K

To jab main yeh baat kar raha hoon grain boundaries ki to aaiye jaante hain ki grain boundary kis tarah se dislocation ke saath interact karte hain maan lete ki mere paas ek slip plane hai yahan par

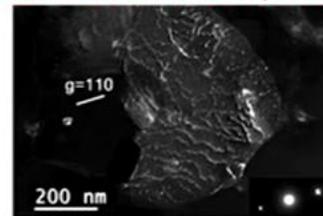
kuch dislocation yahan par pile up hai aur yeh grain boundary yahan par to ye dislocations stress ke under move kar rahe hain aur yahan pe aake ruk ja rahe hain kyunki yahan pe orientation change hoga to yeh dislocations isko pass nahi kar payenge to yahan pe pile up taiyaar ho jayega aur ek kuch back stress taiyaar karega mere dislocation ke pile up ki wajah se to main keh sakta hoon ki grain boundary ek barrier ki tarah kaam karti hai dislocation ko to yeh aap dekh sakte hain practically bhi dekh sakte hain to aap yahan par dekh paa rahe hain ki yahan pe boundaries hai aur yeh dislocation is direction mein move kar raha hai to yeh yahan pe aake ruk ja rahe hai similarly aap dekh paa rahe honge ki yeh boundaries hai to yahan pe ye dislocations aake boundaries pe aake ruk ja rahe hain yaani meri grain boundaries dislocation motion ko a ek barrier ki tarah kaam kar rahi hai to iski wajah se kya hoga humne dekha ki dislocation agar boundary se aake ruk ja rahe hai to ek pile up taiyaar hoga aur is pile up ki wajah se back stress taiyaar hoga jo yahan pe is slip plane pe jo dislocation aayenge inke motion ko oppose karega ye aap dekh bhi sakte hain jahan jaise jaise main grain boundary ke paas aa raha hoon to ye jo dislocations hai ye closely packed hai yaani yaani paas paas hai tightly packed hai yaani iska matlab in dono ke beech mein itna strong force of repulsion nahi hai kyunki same similar dislocation hai to agar inke paas jo spacing hai wo kam hai to itna strong repulsion nahi hai par jaise jaise inka number badhega to aap dekh paa rahe honge ki back stress badhega aur jaise jaise is slip plane par hum dekhenge yeh dislocation ya yeh dislocation inmein jo distance hai wo badhega yaani iska matlab yahan par back stress badhega jaise jaise number of dislocation ka slip plane par badhega ya pile up jaise jaise badhega to yeh dekhiye yahan par dislocation ye tightly packed nahi hai to isi ke anusar hum abhi ek hall petch relation ki baat karenge hall petch relation derive karne ki koshish karenge yahan pe source ke taraf ye jo dislocation hai ye widely spaced hai.



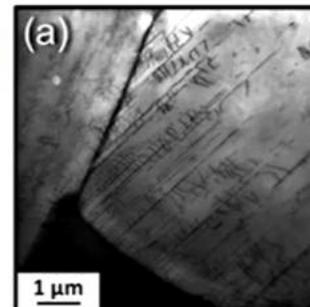
Grain boundary & Dislocation interaction

If dislocations are not able to traverse through obstacles such as GBs, second phase

- ✓ They pile up on the slip planes at barriers



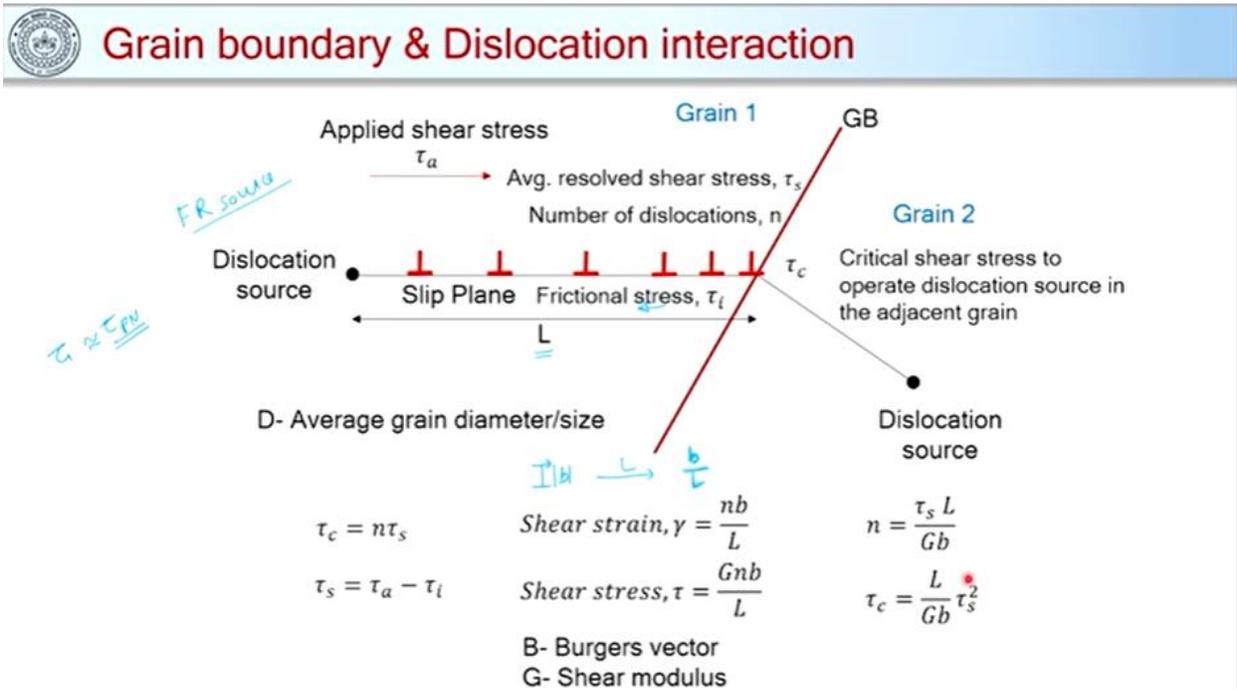
- ✓ Dislocations piled up against the barrier produces a "back stress" to oppose the motion of additional dislocations
- ✓ Dislocation will be tightly packed together near head
- ✓ More widely spaced towards the source



To abhi hum interactions ki baat karte hain grain boundary aur dislocations ki tab main consider karta hoon do grain yaani ek ye grain 1 aur ye grain 2 yaani in dono ke beech mein ek kisi orientation angle hai aur yeh meri grain boundary hai kuch is tarah se abhi main consider karta hoon ek slip plane yahan pe aur is slip plane pe main ek consider karta hoon ek dislocation source

hai jo is boundary se L distance apart hai to dislocation source ka jo distance hai boundary se wo L hai aur ye dislocation source operate karega jab main ek shear stress apply karunga τ_a main usko naam de raha hoon applied shear stress as τ_a ab ye shear stress ke karan dislocation source operate hoga aur dislocation emit honge to dislocation source humne dekhe the jaise frank-read source hai to frank-read source ko hum keh sakte hain ki is type ke source yahan par active ho sakte hain ab ye jab active honge to yahan par dislocation emit karenge aur main maan ke chal raha hoon ki yeh jo grain size hai mera yaani average grain size material mein ye mera D hai to isko main consider kar raha hoon grain diameter ya grain size to jab ye dislocation source dislocations ko emit karenge aur is shear stress ke karan abhi ye slip plane pe easily glide honge aap dekhenge ki ye glide hoke boundary par aake ruk jayenge phir se dislocation source active hoga aur phir se emit karega dislocation ko aur yeh yahan par abhi ye dislocation ki wajah se in dono dislocation mein interaction hoga aur ek yahan par abhi pile up taiyaar hoga dislocations ka to yahan par aap dekhenge ki dislocation aayenge aur ruk jayenge is slip plane pe us tarah se aap dekhenge ki dislocation jo hai yahan par yeh widely spaced hai aur yahan pe tightly spaced hai kyunki yahan pe ek back stress ka generation hoga ab ye jo back stress generate hoga wo depend karega mere kitne dislocation pile up hue yaani number of dislocation kitne pile up hue is slip plane pe aur is back stress ki wajah se kya hoga aap dekh rahe honge ki ek dislocation source main consider kar raha hoon grain 2 mein aur ye jo back stress yahan pe ya grain boundary pe jo stress generate hoga wo is shear stress ke saath add up hoke is dislocation source ko operate karega to main shear stress ki value consider kar raha hoon $\tau_{critical}$ usko main keh raha hoon ki critical shear stress hai jo operate karega mere dislocation source ko adjacent grain mein yaani is grain ke jo pile up hua hai uske wajah se jo dislocation source operate hoga is grain mein us stress jab ek critical value pahunchegi us critical shear stress ko main τ_c keh raha hoon abhi main ek average resolved shear stress ki baat karunga yaani jab ye dislocation move honge to humne dekha tha ki ek resolved shear stress reach hona chahiye slip plane pe aur us shear stress ko main consider kar raha hoon τ_s to is ek dislocation move karne ke liye slip plane pe jo shear stress average shear stress lagega usko main τ_s consider kar raha hoon to main kuch is tarah se bhi consider kar sakta hoon jab ye dislocation move honge to hum keh sakte hain frictional stress bhi lagta hai slip plane pe ye frictional stress kya hai ye frictional stress is nothing but main isko humne dekha tha isko main τ_{PN} yaani peierls nabarro stress ki tarah bhi consider kar sakta hoon yaani ek slip plane par ek jo frictional stress lagna chahiye yaani ek ye stress jab tak reach nahi hoga ya τ_i tak reach nahi hoga tab tak mera dislocation move nahi hoga isko main kehta hoon frictional stress to aap dekh pa rahe honge ki main kuch abhi relations likh sakta hoon ye τ_c yaani ye critical shear stress ye critical shear stress kya hai is dislocation source yaani adjacent grain mein jo dislocation source hai usko operate karne ke liye kitna critical she shear stress ki zarurat hai isko main consider kar sakta hoon $n \times \tau_s$ kyunki mere paas n number of dislocations hai aur ye create karenge kuch agar mere paas average resolved shear stress hai τ_s ek dislocation ke liye to n number of dislocation $n\tau_s$ shear stress yahan pe generate karenge to isko τ_c ko main consider kar sakta hoon $n\tau_s$ aur τ_s ko main likh sakta hoon τ_a yaani kitna shear stress applied kiya minus τ_i kyunki frictional stress to opposite direction mein act karega to isko main is tarah se consider kar sakta hoon frictional stress ko to τ_s ko main likh sakta hoon $\tau_a - \tau_i$ abhi main dekh sakta hoon ki shear strain aur shear stress kya taiyaar honge ki jab ek dislocation move hota hai mere grain mein to kya shear stress hona chahiye jaise mere paas ek dislocation hai jiska burgers vector is direction mein hai aur magnitude b hai aur length of grain ya length L hai to main shear strain ko is tarah se likh sakta hoon $\gamma = b/L$ ye humne dekha bhi hai ki ek dislocation jab move karta hai to kitna shear stress hona chahiye crystal to ye aa jayega γ is equal to agar mere paas n dislocations hai yaani total shear strain ki

main jab baat karunga to n dislocation se to $n \times b/L$ b/L yeh hai mera ek dislocation ke movement ki wajah se jo shear strain develop hoga woh quantity hai ab main shear strain ko shear stress mein directly convert kar sakta hoon agar mere paas shear modulus pata hai to mujhe to τ is equal to main Gnb/L $G \times$ shear strain is tarah se likh raha hoon shear stress is equal to shear modulus into shear stress to to ek τ ki value aa jayegi ab jab main n ki value nikaalne ki koshish karunga to n ki value ye jo τ_s hai yahan pe main consider karunga τ_s to is formula se mere paas total number of dislocation is slip plane pe kitne hone chahiye uski value aa jayegi $n = \tau_s L / Gb$ aur is n ki value main agar pehle equation mein rakhunga is is formula mein to mere paas τ_c ki value kuch is tarah se aayegi $L\tau_s^2 / Gb$ to yeh ek relation aa gaya mere paas yeh length jo hai slip dislocation source ka grain boundary tak ka yeh ek length shear modulus burgers vector aur ek τ_s yaani ek average resolved shear stress ki value hai yeh τ_c ki value aa gayi.



Abhi τ_c ki value yeh τ_s ki value mujhe pata hai $\tau_a - \tau_i$ yeh humne dekha tha to agar main τ_s ki jagah $\tau_a - \tau_i$ rakhunga to mere paas ye identity aayegi agar main isko solve karunga yaani τ_a ke dauran agar τ τ_a ko find out karne ke liye to τ_a jo hai wo mera applied shear stress hai yahi mujhe dhundhna hai grain size ke hisaab se to τ_a aayega $\tau_i + (\tau_c Gb / L)^{1/2}$ abhi main is L ko agar numerator mein is tarah se likhunga yaani is tarah se main isko transform kar sakta hoon is equation ko aur yeh jo term hai $\tau_c Gb$ ko main consider kar raha hoon k' ek constant kyunki ye jo critical shear stress rahegi dusre grain mein operate karne ke liye ye constant main maan ke chal sakta hoon to ye k' main consider kar raha hoon aur aap dekh paa rahe honge ki ye jo applied shear stress hai ye main teen quantities mein likh sakta hoon ek τ_i ek k' aur ek L ab is L ko humne dekha tha ki ye length hai mere dislocation source ki grain boundary tak ki to isko main convert kar sakta hoon grain size mein agar main sufficient constant yahan pe introduce karu to yahan pe yeh k' ko main k consider kar raha hoon yahan pe yaani ek dusra constant yahan pe aur yeh L ko main convert kar raha hoon grain average grain diameter ya grain size ke dauran to agar τ_a ko main is is tarah se likh sakta hoon $\tau_i + kd^{-1/2}$ to ye yahan pe hamare paas ek relation aa gaya to main is tarah se likh sakta hoon τ_a ko baaki do agar main constant maan ke chal raha hoon to τ_a inversely

proportional hai mere square root of grain size ke saath yahi mera jo relation hai yahi mera hall
 petch relation hai aap dekh paa rahe honge ki jaise jaise mera grain size badhega yahan pe ye jo
 applied shear stress hai deformation ke liye woh ghatega ya grain size jaise jaise ghatega waise
 applied shear stress badhega yeh mera hall petch relation hai to aap dekh paa rahe honge ki yahan
 pe kuch micrographs maine tem micrographs dikhaye yahan pe dislocations aaye yeh grain
 boundary pe ruke aur is grain boundary pe rukne ke baad ek back stress hoga aur uske wajah se
 dusre grain mein bhi dislocation source active honge to grain boundary is tarah se act karti hai
 mere dislocation a ke motion ke barrier ke liye.



Hall-Petch Relation....

$$\tau_c = \frac{L}{Gb} \tau_s^2$$

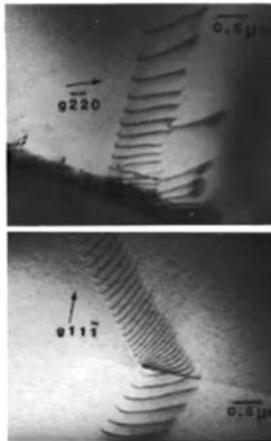
$$\tau_c = \frac{L}{Gb} (\tau_a - \tau_i)^2$$

$$\tau_a = \tau_i + \left(\frac{\tau_c Gb}{L} \right)^{1/2}$$

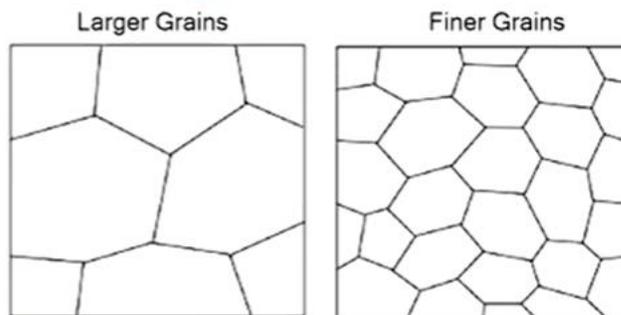
$$\tau_a = \tau_i + k'(L)^{-1/2}$$

$$\tau_a \propto \frac{1}{\sqrt{D}}$$

$$\tau_a = \tau_i + k(D)^{-1/2}$$



Shen et al., Scripta Metall., 20 (1986) 921-926.



Finer grains

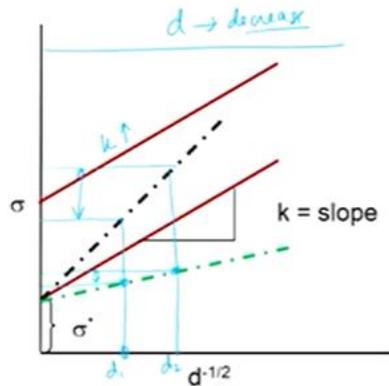
- More grain boundaries
- More obstacles to the dislocation motion
- More Strength

Abhi hum kuch points likh lete hain jaise larger grains aur finer grains ke baare mein aap larger
 grains mein dekh rahenge dekhenge ki yahan par grain boundary jo area hai ya number of grain
 boundaries jo hai woh kam hai finer grains ki tulna mein yahan par aap dekh paa rahe honge ki
 grain boundaries jo hai aur number of grain boundaries ya grain boundary fraction hai jo hai wo
 bade hai to agar yahan par agar dislocation move hoga to aap dekhenge ki yeh jo dislocation hai
 grains mein yeh boundaries ko yaani unke saath jo interaction hai ismein kam hoga aur yahan par
 agar dekhenge ki grain size jaise jaise kam ho gaya to grain ka jo distance hai ya grain ka jo free
 space hai travel ka boundary tak woh kam ho jayega aur yahan par aap dekhenge ki dislocation
 aur grain boundary interaction jyada honge to yahan par aap kuch points likh sakte hain finer grains
 mein mere paas grain boundary jyada hai to mere paas dislocation motion ke liye obstacles jyada
 hai aur uske wajah se meri strength badhegi aur yeh humne ek model ke saath bhi derive kiya ki
 isko hum hall petch relation kehte hain jahan par mera applied shear stress badhta hai jaise jaise
 mera grain size ghat-ta hai aur iska relation is tarah se diya hai abhi hum hall petch relation ki baat
 karenge to yahan pe jab maine τ_a likha hai to main isko convert kar sakta hoon σ_y yaani ek yield
 strength ya stress of polycrystalline material is tarah se aur ye σ^* yaani yahan pe internal stress ko
 main σ^* keh raha hoon yeh jo σ^* hai isko hum is tarah se samjhenge a jab main yeh relation plot
 karunga to yahan pe mujhe kuch linear relation milega jab main σ versus $d^{-1/2}$ plot karunga to ye
 linear relation hoga aur ye jo linear relation hoga iska slope hoga k isko hum kehte hain hall petch

coefficient aur yahan pe jo y intercept hai isko kehte hain hum frictional stress a yeh frictional stress kya hai frictional stress main jab kahunga jab stress offer karega mera grain a jab infinite grain size hoga yaani d agar infinite hoga to yeh value zero ki taraf aayegi aur yeh jo stress mile jo milega dislocation ko move karne ke liye yeh rahega mera frictional stress to yeh humne dekha tha isko hum τ_{PN} bhi consider karte hain yaani peierls nabarro stress ki tarah to aap dekh sakte hain ki yeh mera frictional stress hai aur abhi hum dekhenge ki yeh jo values agar change ho rahi hai k aur σ^* ki to mera strength kis tarah se change hota hai ya badhta hai ya ghat-ta hai maan lete ki k change ho raha hai yahan par k yahan par badh raha hai mera slope jyada hai aur yahan par slope kam hai to aap dekh paa rahe honge ki jaise jaise k badhta hai waise waise strengthening wahan pe badhti hai maan lete hain mere paas do grain size hai kuch is tarah se aur isko main kahunga d_1 isko main kahunga d_2 to agar jahan pe slope jyada hai to strength aap dekhenge kuch is tarah se badi hai ye meri strength is tarah se badi hai is case mein jahan pe k higher hai aur jahan pe k kam hai to agar main do points consider karunga to yahan par aap dekhenge ki ye jo strength hai woh us extent se nahi badhi hai jis extent se jab k mera higher hai to aap dekh paa rahe honge ki maine grain size yahan par aap dekhenge ki is direction mein jaunga to grain size change ho raha hai to yahan se d_1 se main d_2 aaya to aap dekhenge ki strength meri badh gayi hai to agar dekhenge ki yahan par yahan par $d^{-1/2}$ hai to yahan par D mera is direction mein decrease ho raha hai yaani mera grain size yahan par decrease ho raha hai to agar grain size decrease ho raha hai to aap dekhenge ki is case mein ja jab k ki value jyada hai tab change yaani delta sigma jo strength mujhe mili hai woh badh gayi hai kis tulna mein jab k ki value kam hai aur ek cheez dekh sakte hain ki k indicates mera jo dependency hai strength ki enhancement on grain size jaise jaise mera grain enhancement ho raha hai yaani refine ho raha hai us tarah se strength ki kaise change ho rahi hai ye batata hai meri k value to k value jyada hai to dependency grain size pe jyada hai strength ki aur k value kam hai to dependency kam hai a strength ki grain size pe abhi hum dekhenge ki ye jo intercept hai jo σ^* hai isko hum kehte hain frictional stress ye agar badh gaya to aap dekhenge ki mere material ki strength badhegi to humein chahiye ki ye σ^* agar humein strength badhani hai to σ^* bhi humein badhana padega yaani frictional stress badhana padega a aur usko hum badha sakte hain agar agar main consider kar sakta hoon ki τ_{PN} agar badh raha hai to to σ^* indicates intrinsic resistance.



Hall-Petch Relation



$$\sigma_y = \sigma^* + \frac{k}{\sqrt{d}}$$

where,

σ^* = friction stress or yield stress for infinitely large grain size (MPa)

k = Hall-Petch Coefficient (MPa m^{1/2})

d = Average grain diameter (m)

σ_y = Flow stress of the polycrystal (MPa)

k - indicates dependency of strength enhancement on grain size

σ^* - indicates intrinsic resistance



Hall-Petch Relation: Crystal Structures

$\sigma = \sigma_i + k(D)^{-1/2}$				k and σ_i for various elements			
Crystal Structure	Element	Group	D_{min}/D_{max} (μm)	σ_i (MPa)	K (MPa $\mu\text{m}^{1/2}$)	$Gb^{1/2}$ (MPa $\mu\text{m}^{1/2}$)	$k/(Gb^{1/2})$ (-)
BCC	V	5	0.1/520	150	380	760	0.5
	Nb	5	0.1/610	120	340	630	0.5
	Ta	5	0.04/3900	80	760	1170	0.7
	Cr	6	0.02/1100	320	800	1820	0.4
	Mo	6	0.02/511	270	630	2070	0.3
	W	6	0.16/7	800	1000	2660	0.4
	Fe	8	0.009/2000	130	310	1290	0.2
						MEAN	0.42 \pm 0.07
FCC	Ni	10	0.01/460	80	230	1200	0.2
	Cu	11	0.005/320	40	110	770	0.1
	Ag	11	0.01/250	60	100	500	0.2
	Au	11	0.02/200	150	80	440	0.2
	Al	13	0.08/1200	10	90	440	0.2
						MEAN	0.18 \pm 0.02
HCP	Be	2	0.03/1100	80	720	680	1.1
	Mg	2	0.2/1000	70	90	100	0.9
	Ti	4	0.01/250	250	190	640	0.3
	Zr	4	0.4/1000	240	280	210	1.3
	Hf	4	35/130	100	350	320	1.1
	Co	9	0.012/4.8	260	140	380	0.4
	Zn	12	0.02/500	20	220	230	1.0
						MEAN	1.5
						MEAN	0.9 \pm 0.2

2-Fe σ^*
 FCC B
 100um-1um
 K
 1

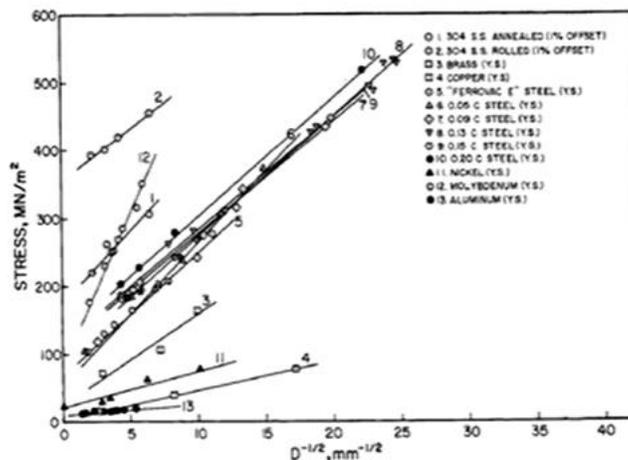
To aaiye hum jaante hain kuch crystal structures ke baare mein aur yeh hall petch relation ke baare mein to maine kuch hall petch relation is tarah se likha hai aur yahan pe kuch material hai aur crystal structure maine plot kiye bcc fcc aur hcp to aap dekh paa rahe honge ki yahan pe kuch bcc material hai fcc hai aur hcp material hai aur yahan par grain sizes hai σ_0 isko main σ_i bhi keh sakta hoon yahi mera frictional stress hai aur yeh k hai hall petch coefficient aur yahan par hum dekh paa rahenge ki kitni strength yahan par badi hai ki ghati hai to aap dekh paa rahe honge ki jo k value hai yahan par ek average k value agar hum dekhenge is tarah se to average k value mere bcc

ke case mein jyada hai aap dekhenge 0.42 hai yahan par aur fcc ke case mein 0.1 hai 2 hai aur hcp ke case mein yeh sabse highest hai 0.9 to aap dekh paa rahe honge mean k value jo hai mere bcc ke liye jyada hai iska matlab main agar fcc aur bcc ki tulna karunga to aap dekh paa rahe honge ki agar main grain size jaise mere paas yahan par 10 micron hai fcc mein 10 micron to 100 micron mein ja raha hoon ya ulta kar lete refinement ki baat kar rahe hain to main 100 micron se 10 micron grain size agar change kar raha hoon same case mein yahan par kar raha hoon 100 micron se 10 micron grain size agar change kar raha hoon to bcc mein jo delta sigma milega yeh bada rahega mere fcc ke tulna mein kyunki yahan par k constant hai jab main maan ke chal raha hoon ki σ^* dono ke case mein same hai maan lete ye mera gamma austenite hai aur yeh mera alpha iron hai ya ferrite hai to mujhe bcc ke case mein agar main grain size refine karunga to strength ki change mujhe jyada milegi aur hcp ke case mein to usse bhi jyada milegi yaani hum dekh sakte hain ki hcp material grain size refinement mein jo dependency hai strength ki wo jyada hai a fcc ke tulna mein aur bcc ki tulna mein aur bcc mein jo grain size dependence hai wo fcc ki tulna mein jyada hai jab main strength ki baat karta hoon to abhi dekhte hain ki hall petch ki utility kya hai to agar hall petch ki utility main consider karunga yahan par maine stress versus $d^{-1/2}$ plot kiya aur aap dekh paa rahe honge ki yeh bahut saare material ke liye yahan par bahut saare material yahan par plot kiye aur inke liye yeh valid hai to aap dekh paa rahe honge ki main agar kisi process mein grain size refine kar raha hoon to main material ki strength predict kar sakta hoon agar mujhe kuch strength pata hai ek grain size par is hall petch relation ke dwara to agar main isko convert karunga yeh hall petch relation ko kuch is tarah se main hardness ke saath likh sakta hoon to main hardness ke saath bhi likh sakta hoon $H = H_0 + k_H d^{-1/2}$ to main similar expression likh sakta hoon kyunki hardness jo hai wo industrial scales mein likh sakta hoon ki hardness jo hai wo aasaani se measure ho sakta hai easily measurable hai to aap turant dekh sakte hain ki material ki strength badhi hai ki ghati hai yeh relation ke dwara yahan par sirf jo k_H hai woh corresponding hall petch coefficient for hardness hai to aur H_0 hai wo mera frictional hardness main keh sakta hoon ki infinite grain size rahega yaani sufficiently large rahega wo hardness rahegi ye value to.



Hall-Petch Relation: Utility

Pure metals and alloys



Hardness
↓
early:

Roughly linear correlation of strength to hardness
→ Similar expression for hardness with different parameter k

$$H = H_0 + k_H(D)^{-1/2}$$

To abhi hum dekhte hain ek important question abhi hum dekh sakte hain ki yeh jo hall petch relation hai humne dekha ki jaise jaise grain size ghat-ta hai waise strength badhti hai to yeh saare grain size ke liye valid hai kya jaise main grain size agar change kar raha hoon isko likh sakte jaise main agar 1 nanometer grain size mujhe mil raha hai ya 10 nanometer consider karunga 1 nanometer possible nahi hai to 10 nanometer pe se main ja raha hoon 1 mm tak to ye mujhe strength hamesha badhti milegi jaise jaise main grain size refine kar raha hoon to yeh valid question hai to iska answer hai ki jaise jaise main grain size refine karta hoon hall petch relation hamesha ke liye valid nahi rahega kisi grain size par kisi particular grain size par wo breakdown hota hai to isko hum jaante hain yeh jo relation hai yeh hamesha ke liye valid nahi hai saare grain size ke liye valid nahi hai to yeh first observation yahan par dekha tha professor chokshi et al ne to unke co-workers ne to yahan pe aap dekh paa rahe honge ki jaise jaise grain size mein ghata raha hoon yahan pe 16 nanometer tha yahan pe 6.25 nanometer hai aap dekh rahe honge ki palladium aur copper mein ye jo strength hai yahan pe decrease ho rahi hai jaise main grain size refine kar raha hoon to yahan pe mujhe ye relation jo hai wo valid nahi hai beyond certain grain size to yahan pe bhi aap dekh paa rahe honge ki jo hardness hai aur $d^{-1/2}$ hai grain size ke saath relation jaise jaise main grain size refine kar raha hoon to copper ke liye to pehle to strength badhi kuch critical grain size tak aur uske baad woh decrease hui similarly palladium ke liye bhi aap dekh paa rahe honge ki jaise jaise main grain size refine kar raha hoon waise strength to badhi hai par kuch grain size ke baad woh strength decrease hui to hum dekh paa rahe ho ki yeh grain size jaise fine ho raha hai yaani nanometer range mein ja raha hai tab meri jo strength hai material ki wo ghat rahi hai aur iska ye bhi aap dekh sakte hain ki ye jo strength ghat rahi hai iska matlab hai ki jo strength coefficient hai to yahan pe uski value negative honi chahiye to mujhe milegi negative value of slope yaani jo value hai yahan pe k ki value wo negative rahegi yeh hum keh sakte hain phir ki hall petch relation ek universal law nahi hai.

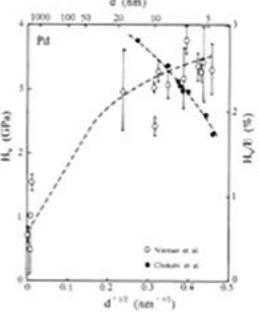
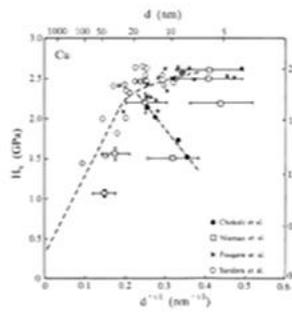
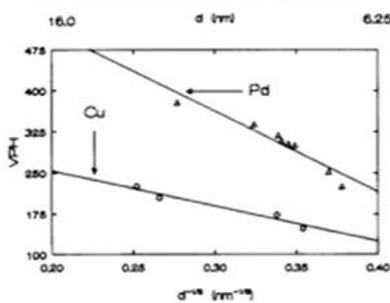
Is H-P relation valid for all grain sizes ??

10 nm → 1 μm

$$\sigma = \sigma_i + k(D)^{-1/2}$$

- Decrease in strength with decrease in grain size
- Negative value of slope, k

First observation: Chokshi et al.,

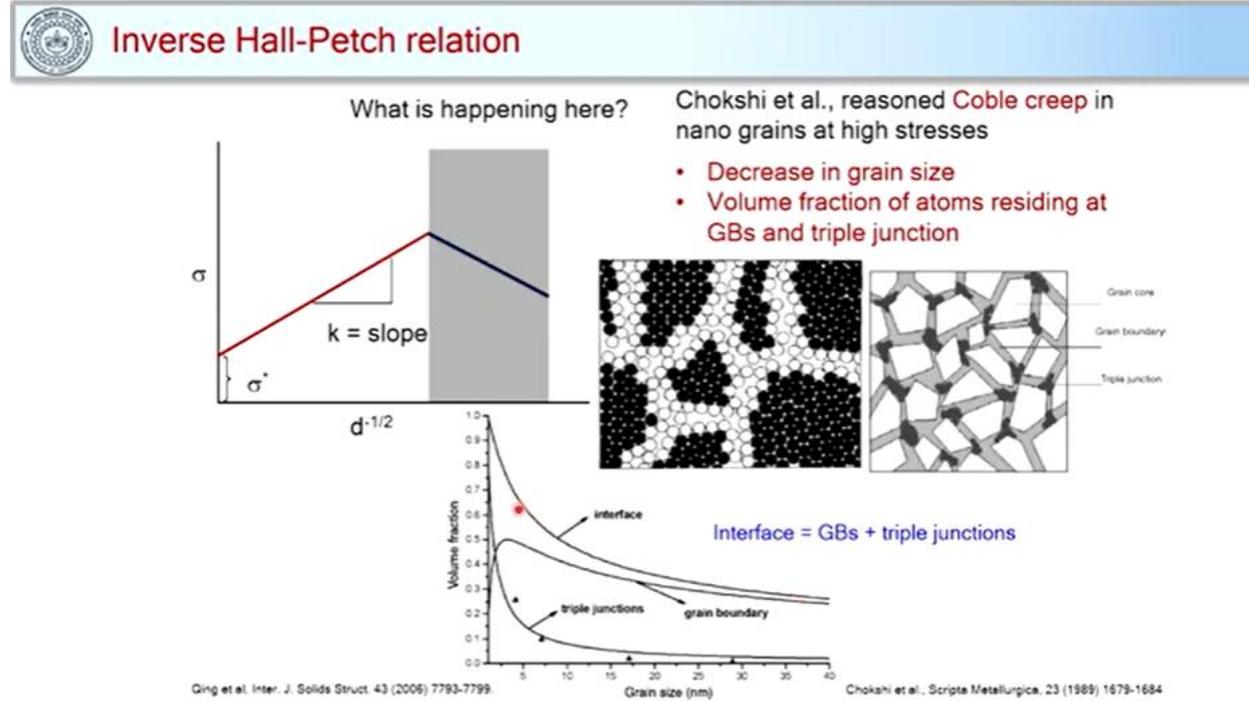


- H-P relation is not a universal law
- H-P relation is valid for a limited range of grain sizes

Chokshi et al., Scripta Metallurgica, 23 (1989) 1679-1684
© Tantalum Group, Mater. Sci. (1991) 1229-1237

Ek limited range of grain size ke liye hi wo valid hai jab main in isko main kehta hoon jab strength decrease hogi yeh mera normal hall petch relation hai aur yahan par hum dekhenge ki grain size ke baad jaise refine karunga strength decrease hogi yaani k ki value negative ho jayegi yahan par

humein dekhna hai ki kya ho raha hai isi isko hum kehte inverse hall petch kyunki humein ulta result mil raha hai yahan par jaise main grain size kam kar raha hoon waise strength ghat rahi hai to yeh jo region hai yahan par isko main kehta hoon inverse hall petch aur yeh mujhe milta hai nano grains aur high stresses mein jab hum baat karenge nano grains ki jab baat karenge yahan par hum dekhenge ki refine jab grain hue the to nano regime mein the aur chokshi et al ne chokshi aur unke co-workers ne dikhaya tha ki yeh coble creep active ho jaati hai material mein jab mere paas grain size nano regime mein hai.

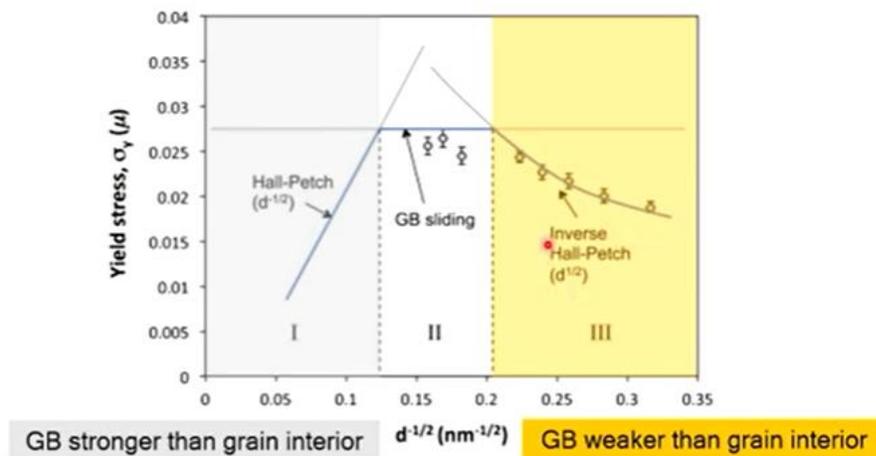


To coble creep ke baare mein bhi hum padhenge jab hum creep ke baare mein padhenge is course mein to yahan pe explanation ke liye yeh jaan lete hain ki jaise jaise main grain size refine kar raha hoon waise waise aap dekhenge ki yeh jo grain boundaries pe jo atoms hai fraction jo volume fraction hai atoms ka woh badhega yaani yeh meri grain boundary hai aur yeh mere triple junction hai triple junction kya hota hai triple junctions hote hain ki jahan pe teen grain meet karte hain to aap dekh paa rahe honge ki triple junction aur grain boundary pe jo atom ka volume fraction hai woh badhega grain interior ki tulna mein to yahan par aap dekh paa rahe honge ki ye triple junction hai aur yeh grain boundaries hai to kuch is tarah se hum samajh sakte ki volume fraction of atoms at grain boundaries ya triple junctions yeh badhenge jaise jaise main grain size ghata raha hoon yahan par aap dekhein agar main grain size ghata raha hoon to triple junction par jo atom ka volume fraction hai woh badhega grain interior ki tulna mein aur grain boundary ka volume fraction atoms ka volume fraction is tarah se badhega aur jab main interface baat karunga interface yaani main is tarah se define kar raha hoon main dono ka agar add karke baat karunga to main usko interface kahunga to interface mein jo atoms ka volume fraction hai woh badhega jaise jaise grain size main ghata raha hoon ab iske wajah se kya hoga ki yeh jo atoms hai grain boundaries ke jab main stress apply karunga deform karne ki koshish karunga tab yahan pe mujhe coble creep milega coble creep yaani atoms ka diffusion hota hai grain boundary pe atoms diffusion through grain boundary to grain boundary se jo atomic diffusion hota hai usko hum coble creep kehte hain to coble creep yahan par active ho jayega aur uske wajah se material ki strength decrease hogi to yahan pe

strengthening na milte hue humein strength decrease milegi kyunki yahan pe atoms ka volume fraction grain boundaries pe badh raha hai to yahan pe hum dekh sakte hain ki hall petch aur inverse hall petch ke baare mein to hall petch mein mujhe $d^{-1/2}$ milta hai aur inverse hall petch mein main keh sakta hoon ye $d^{1/2}$ hai to yahan pe yeh grain boundary stronger hai grain interior ke se aur yahan pe hum dekhenge ki grain boundaries meri weaker ho jaati hai grain interior se yaani jab main main refine kar raha hoon yahan pe is regime mein jahan pe hall petch region hall petch relation valid hai agar main grain size refine karunga to mujhe strength badhte hue milegi kyunki grain boundary stronger hai mere grain interior se par inverse hall petch mein jaise jaise main grain size refine karunga waise waise strength ghategi kyunki grain boundaries weaker ho jaati hai grain interior mein aur iska reason humne dekha ki yahan par jo atoms ka volume fraction hai grain boundaries par interface par woh badhta hai grain interior ki tulna mein.



Hall-Petch Vs Inverse Hall-Petch relation

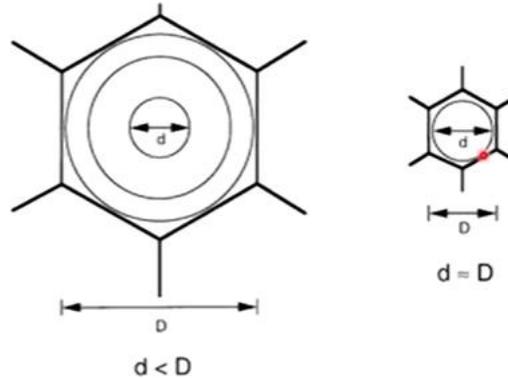


Ab dekhte hain ki yeh critical size hum kuch define kar sakte hain kya ki kab tak hum critical size maan sakte hain ki jiske niche humein strength decrease milegi ya humein inverse hall petch relation milega to hum dekh sakte hain ki agar main ek dislocation loop maan ke chal raha hoon aur uski main diameter d maan raha hoon aur meri ye grain size ki diameter capital D maan raha hoon to yahan par aap dekh paa rahe honge ki yeh jo d hai ya dislocation loop jo hai uski diameter hai woh small hai yaani kaafi small hai mere grain size ke diameter ke tulna mein to main critical grain size tak ja sakta hoon jahan par main consider karunga ki yeh jo ek dislocation loop ek grain mein fit ho jaaye woh mera critical grain size hoga wahan tak mujhe strengthening mil sakte hain to yahan par aap dekh sakte hain ki jo interaction of characteristic length yaani dislocation loop jo diameter hai aur size parameter yaani grain size ye dono fit ho jaaye yaani same ho jaaye wahan tak main dekh sakta hoon ki strength badhegi aur iske niche jab jayenge tab hamari strength ghategi.



Grain Size and Strength

"at least one dislocation loop must fit into an average grain"



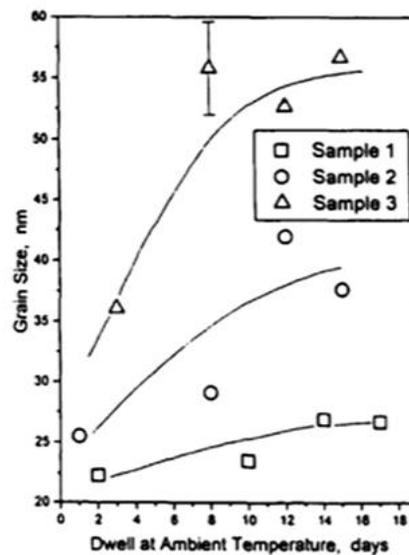
Interaction of characteristic length (dislocation loop diameter) and size parameter (grain size)

E Arzi, Acta mater. 46 (1998) 5611-5626

Aur ek cheez aapko batana chahta main grain size ko refine kar raha hoon agar main grain size ko refine kar raha hoon to ek cheez aapko dekhni padegi ki jo agar main nanometers range mein hoon grain size ke isko bhi likh lete hain agar main nanometers regime mein hoon to mujhe ek precaution leni padegi deformation waqt ki deformation ke waqt ya microstructure ko stable rakhne ke liye kyunki yahan par aap dekhenge ki kuch studies hai yahan par aap dekh rahe hain ki grain sizes a yeh hai mere time ke saath agar maine grain size is regime mein prapt kar liye nanometers mein aur yahan pe aap dekhenge ki grain microstructure stable nahi hai agar main sirf room temperature pe a ek ambient temperature pe rakh de raha hoon kuch samay ke liye to aap dekhenge ki naturally



Caution: Grain Size Vs Grain growth



- Nanograined materials can show grain-growth at room temperature too
- Microstructure may not be stable

Gertsman and Birringer, Scripta Metall. et Mater. 30 (1994) 577-581.

wahan pe grain growth is tarah se mil rahi hai yaani ek tendency hai nano grain material mein grain growth ki to aapko grain growth ko stabilize karna padega in nanometers range mein.

To is part mein humne dekha ki humne grain size strengthening kya hoti hai to humne grain size strengthening jab padh rahe to hum usko hall petch strengthening bhi kehte hain aur jab hall petch strengthening ki baat karenge to hum dekhte ki grain boundaries jo hai woh ek barrier karke act karti hai dislocation ke motion ko to yeh main grain ki area fraction main badhaunga material mein yaani main grain size small karte jaunga to mujhe strengthening milegi par ye jo hall petch relation hai yeh universal nahi hai ek particular grain size tak ye valid hai uske niche agar main jaunga to strength decrease hoti hai usko main inverse hall petch relation kehta hoon aur yeh jo nano grain size hai ya finer grain size hai yeh stable ho sakte hain ya nahi bhi ho sakte mostly ye dekha gaya ki inmein grain growth ki tendency bhi hoti hai even at room temperature to yeh abhi humne grain size strengthening dekhi hum kuch grain boundaries baare mein padhenge next part mein jahan par hum kuch dislocation models ke baare mein dekhenge ki main apne grain boundary ko kis tarah se define kar sakta hoon abhi ke liye rukta hoon dhanyavad